4 Cumulative Impacts

4.1 INTRODUCTION

The Council on Environmental Quality (CEQ) identifies the impacts that must be addressed and considered by federal agencies in satisfying the requirements of the National Environmental Policy Act (NEPA). This includes permanent, temporary, indirect, and cumulative impacts.

CEQ NEPA implementing regulations define "cumulative impact" as "the impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency (Federal or non-Federal) or person undertakes such other actions." 40 Code of Federal Regulations (CFR) § 1508.7. Cumulative impacts should be evaluated along with the overall impacts analysis of each alternative. The range of alternatives considered should include a No Action Alternative as a baseline against which to evaluate cumulative effects. The range of actions to be considered includes not only the proposed action but all connected and similar actions that could contribute to cumulative effects. Related actions should be addressed in the same analysis. CEQ recommends that an agency's analysis accomplish the following:

- Focus on the effects and resources within the context of the proposed action.
- Present a concise list of issues that have relevance to the anticipated effects of the proposed action or eventual decision.
- Reach conclusions based on the best available data at the time of the analysis.
- Rely on information from other agencies and organizations on reasonably foreseeable projects or activities that are beyond the scope of the analyzing agency's purview.
- Relate to the geographic scope of the proposed project.
- Relate to the temporal period of the proposed project.

A cumulative impacts analysis involves assumptions and uncertainties. Monitoring programs and research can be identified to supplement the available information and thus, enhance analyses for the future. The absence of an ideal database should not prevent the completion of a cumulative effects analysis.

This section addresses areas of the quantitative analyses presented in Chapter 3, with particular attention to energy, air, and climate. Chapter 4 describes the indirect cumulative effects of climate change on a global scale. This chapter is organized according to the conventions of the climate change literature rather than the conventions of an Environmental Impact Statement (EIS) format. To assist the reader, the chart on the following page maps topics found in U.S. Department of Transportation (DOT) NEPA documents (DOT Order 5610.1C) to the sections in this Final Environmental Impact Statement (FEIS).

4.1.1 Approach to Scientific Uncertainty and Incomplete Information

4.1.1.1 CEQ Regulations

CEQ regulations recognize that many federal agencies confront limited information and substantial uncertainties when analyzing the potential environmental impacts of their actions under NEPA

Typical NEPA Topics	EIS Subsections
Water	4.4 Climate; 4.5.3 Freshwater Resources; 4.5.5 Coastal Systems and Low-lying Areas
Ecosystems	4.5.3 Freshwater Resources; 4.5.4 Terrestrial Ecosystems; 4.5.5 Coastal Systems and Low-lying Areas; 4.5.6 Food, Fiber, and Forest Products; 4.7 Non-climate Cumulative Impacts of CO_2
Threatened and endangered species	4.5.4 Terrestrial Ecosystems; 4.5.5 Coastal Systems and Low-lying Areas; 4.7 Non-climate Cumulative Impacts of CO_2
Publicly owned parklands, recreational areas, wildlife and waterfowl refuges, and historic sites, Section 4(f) related issues	4.5.3 Freshwater Resources; 4.5.4 Terrestrial Ecosystems; 4.5.5 Coastal Systems and Low-lying Areas; 4.5.7 Industries, Settlements, and Society
Properties and sites of historic and cultural significance	4.5.7 Industries, Settlements, and Society
Considerations relating to pedestrians and bicyclists	4.5.7 Industries, Settlements, and Society
Social impacts	4.5.7 Industries, Settlements, and Society; 4.6 Environmental Justice
Noise	4.5.7 Industries, Settlements, and Society
Air	4.3 Air Quality
Energy supply and natural resource development	4.2 Energy; 4.5.4 Terrestrial Ecosystems; 4.5.6 Food, Fiber, and Forest Products; 4.5.7 Industries, Settlements, and Society
Floodplain management evaluation	4.5.3 Freshwater Resources; 4.5.5 Coastal Systems and Low-lying Areas
Wetlands or coastal zones	4.5.3 Freshwater Resources; 4.5.5 Coastal Systems and Low-lying Areas
Construction impacts	4.3 Air Quality; 4.4 Climate; 4.5.7 Industries, Settlements, and Society; 4.5.8 Human Health
Land use and urban growth	4.4 Climate; 4.5.6 Food, Fiber, and Forest Products; 4.5.7 Industries, Settlements, and Society
Human environment involving community disruption and relocation	4.3 Air Quality; 4.4 Climate; 4.5.5 Coastal Systems and Low-lying Areas; 4.6 Environmental Justice; 4.5.7 Industries, Settlements, and Society; 4.5.8 Human Health

(40 CFR § 1502.22). Accordingly, the regulations provide agencies with a means to formally acknowledge incomplete or unavailable information in NEPA documents. Where "information relevant to reasonably foreseeable significant adverse impacts cannot be obtained because the overall costs of obtaining it are exorbitant or the means to obtain it are not known," the regulations require an agency to include in its NEPA document:

1. A statement that such information is incomplete or unavailable;

2. A statement of the relevance of the incomplete or unavailable information to evaluating reasonably foreseeable significant adverse impacts on the human environment;

3. A summary of existing credible scientific evidence that is relevant to evaluating the reasonably foreseeable significant adverse impacts on the human environment; and

4. The agency's evaluation of such impacts based on theoretical approaches or research methods generally accepted in the scientific community.

Relying on these provisions is appropriate where an agency is performing a NEPA analysis that involves potential environmental impacts resulting from carbon dioxide (CO_2) emissions (*e.g., Mayo Found. v. Surface Transp. Bd.*, 472 F.3d 545, 555, 8th Cir. 2006). CEQ regulations also authorize agencies to incorporate material into a NEPA document by reference in order to "cut down on bulk without impeding agency and public review of the action" (40 CFR § 1502.21).

Throughout this EIS, the National Highway Transportation Safety Administration (NHTSA) uses these two mechanisms – acknowledging incomplete or unavailable information and incorporation by reference – to address areas where the agency cannot develop a credible estimate of the potential environmental impacts of the standards or reasonable alternatives. In particular, NHTSA recognizes that information about the potential environmental impacts of changes in emissions of CO_2 and other greenhouse gases (GHG) and associated changes in temperature, including those expected to result from the proposed rule, is incomplete. In this EIS, NHTSA often relies on the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (2007) as a recent "summary of existing credible scientific evidence which is relevant to evaluating the reasonably foreseeable significant adverse impacts on the human environment" (40 CFR § 1502.22(b)(3)).

4.1.1.2 Uncertainty within the IPCC Framework

The IPCC Reports communicate uncertainty and confidence bounds using descriptive words in italics, such as *likely* and *very likely*, to represent levels of confidence in conclusions. This is briefly explained in the IPCC Fourth Assessment Synthesis Report and the IPCC Fourth Assessment Report Summary for Policy Makers (IPCC 2007d, IPCC 2007c). A more detailed discussion of the IPCC's treatment of uncertainty can be found in the Guidance Notes for Lead Authors of the IPCC Fourth Assessment Report on Addressing Uncertainties (IPCC 2005).

This FEIS uses the IPCC uncertainty language (always noted in italics) throughout Chapters 3 and 4 when discussing qualitative environmental impacts on certain resources. The reader should refer to the documents referenced above to gain a full understanding of the meaning of those uncertainty terms, because they might be different from the meaning of language describing uncertainty in this FEIS as required by the CEQ regulations discussed above.

4.1.2 Temporal and Geographic Boundaries

When evaluating cumulative effects, the analyst must consider expanding the geographic study area beyond that of the proposed action, as well as expanding the temporal (time) limits to consider past, present, and reasonably foreseeable future actions that might affect the environmental resources of concern. The timeframe for this cumulative impacts analysis extends through year 2100 and considers potential cumulative impacts on a national, as well as global, basis.

4.2 ENERGY

A NEPA analysis must consider the cumulative impacts of the proposed action. For this EIS, such considerations involve evaluating the cumulative fuel consumption of the vehicle fleet from the onset of the new standards.

4.2.1 Affected Environment

According to the Energy Information Administration (EIA), net imports of total liquid fuels, including crude oil and refined products, will fall to 51 percent in 2022 and then increase to 54 percent in 2030. This change is attributed to changes in the Corporate Average Fuel Economy (CAFE) standards and in the increased use of biofuels. These imports will replace declining production in meeting the increasing demand for liquid fuels in the United States. The large volume of crude oil imports has a number of impacts on the domestic economy. Further decreases or increases in imports, likely under some of the CAFE alternatives, could affect the world price of crude oil. However, over time the U.S. share of global demand for liquid fuels will decline due to rapid increases in demand in developing economies, including China and India, reducing the relative impact of the CAFE standards on global markets.

Over time a larger share of liquid fuels is expected to be produced from unconventional sources such as biofuels, shale oil, coal-to-liquids, and gas-to-liquids. These alternate sources would affect CO_2 and other emission reductions from the CAFE alternatives. This shift would be driven by changes to the Renewable Fuels Standard (RFS) in the Energy Independence and Security Act (EISA), which forecasts that 36 billion gallons of renewable fuels will be required by 2022 for use primarily in the transportation sector. The EIA Annual Energy Outlook (AEO) 2008 forecasts that domestic production of non-hydro renewable energy will increase from less than 4 quadrillion British thermal units (BTUs) in 2006 to more than 10 quadrillion BTUs in 2030 (EIA 2008a). In the United States, liquid fuels from gas, coal, and biomass are projected to increase from 0.00 quadrillion BTUs in 2006 to 0.54 quadrillion BTUs. Overall, NHTSA expects in the short-term, the impact from these changes would net out. Over the long-term, the impact of these changes remains uncertain.

Changes to the CAFE standards are unlikely to affect domestic production, given the level of crude oil imports. The domestic environmental impacts over the life of the model year (MY) 2011-2020 vehicles are unlikely to change, regardless of the alternative elected. Impacts on production would occur outside of the United States, and would be determined by the balance between the decline in U.S. imports and the increase in demand from developing countries. Impacts on petroleum products would be mixed. U.S. imports of petroleum products are often targeted for specific product requirements, for logistical reasons, or to optimize the inputs and outputs from refineries. Petroleum imports depend on specific product demands and the mix of crudes processed in the refineries, which are projected to change considerably over time. Consequently, any decline in demand for petroleum products is likely to have some effect on both overseas and domestic refineries.

4.2.2 Environmental Consequences

Implementing alternative CAFE standards would result in different future levels of fuel use, total energy, and petroleum consumption, which in turn would have an impact on emissions of GHGs and criteria air pollutants. An important measure of the impact of alternative CAFE standards is the impact on the cumulative fuel consumption of the vehicle fleet from the onset of the new standards. Passenger cars and light trucks are considered separately; total fuel consumption encompasses gasoline and diesel. CAFE standards for MY 2011-2020 are assumed to apply to all subsequent additions to the vehicle fleet. The impact of alternative CAFE standards, by affecting petroleum consumption, total energy

consumption, and emissions, would ultimately determine many of the indirect environmental impacts of adopting higher CAFE standards.

Table 4.2-1 shows the cumulative fuel consumption of passenger cars under the No Action Alternative (Alternative 1) and the six action alternative CAFE standards with the Reference Case inputs, as described in Table 2.2-1 (*see* Section 2.2 of this FEIS). By 2060, when MY 2011 or later cars are likely to comprise the entire fleet, cumulative fuel consumption (from 2010) reaches 4.43 trillion gallons under the No Action Alternative. Cumulative consumption falls across the alternatives, from 4.03 trillion gallons under the Optimized Alternative (Alternative 3) to 3.47 trillion gallons under the Technology Exhaustion Alternative (Alternative 7).

Table 4.2-2 shows the cumulative fuel consumption of light trucks/sport utility vehicles (SUVs) under the CAFE alternatives examined. Cumulative fuel consumption by 2060 reaches 5.31 trillion gallons under the No Action Alternative. Cumulative consumption declines across the alternatives, from 4.73 trillion gallons under the Optimized Alternative to 3.93 trillion gallons under the Technology Exhaustion Alternative, which represent a cumulative savings of 1.38 trillion gallons relative to the No Action Alternative.

4.2.3 Input Scenarios

In response to public comments, and to test how different economic assumptions might affect estimates of fuel consumption, NHTSA ran a scenario using high cost assumptions and compared the results to the Reference Case. Tables 4.2-3 and 4.2-4 list the results for the High Scenario. The High Scenario assumes higher fuel prices than are assumed in the Reference Case, which results in lower fuel consumption across all of the CAFE alternatives examined. This is true even for the No Action Alternative, because higher fuel prices in the High Scenario would reduce fuel consumption (relative to the Reference Case) even in the absence of any change in CAFE standards.

Table 4.2-3 shows the cumulative fuel consumption of passenger cars under the No Action Alternative and the six action alternative CAFE standards in the High Scenario. By 2060, when MY 2011 or later cars are likely to comprise the entire fleet, cumulative fuel consumption (from 2010) reaches 3.97 trillion gallons under the No Action Alternative. Cumulative consumption declines across the alternatives, from 3.32 trillion gallons under the Optimized Alternative to 3.12 trillion gallons under the Technology Exhaustion Alternative, which represents cumulative savings of 851.1 billion gallons relative to the No Action Alternative.

Table 4.2-4 shows the cumulative fuel consumption of light trucks/SUVs under the various CAFE alternatives in the High Scenario. Cumulative fuel consumption by 2060 reaches 4.76 trillion gallons under the No Action Alternative. Cumulative consumption falls across the alternatives, from 3.87 trillion gallons under the Optimized Alternative to 3.54 trillion gallons under the Technology Exhaustion Alternative, which represents cumulative savings of 1.22 trillion gallons relative to the No Action Alternative.

To further assess how different economic assumptions might affect estimates of fuel consumption, NHTSA ran two additional scenarios in the Volpe model: the Mid-1 Scenario and the Mid-2 Scenario. As the names of the scenarios suggest, results from the two additional scenarios fall between those of the Reference Case and the High Scenario. For a summary of Mid-1 and Mid-2 scenario results, *see* tables in Appendix B.

Table 4.2-1

Reference Case Passenger Car Cumulative Annual Fuel Consumption and Cumulative Fuel Savings (billion gallons)

Calendar Year Range	Alternative CAFE Standards for MY 2011-2020						
	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt. 7
	No Action	25% Below Optimized	Optimized	25% Above Optimized	50% Above Optimized	Total Cost Equal Total Benefit	Technology Exhaustion
Cumulative Fuel Consumption							
2010-2020	697.6	688.3	688.0	687.7	687.3	686.5	653.0
2010-2030	1,437.7	1,372.3	1,370.3	1,369.1	1,366.5	1,364.1	1,239.9
2010-2040	2,292.6	2,136.1	2,131.3	2,129.0	2,122.9	2,119.0	1,880.2
2010-2050	3,282.8	3,017.5	3,009.6	3,005.9	2,995.6	2,989.9	2,618.3
2010-2060	4,427.9	4,036.9	4,025.2	4,020.0	4,004.9	3,997.1	3,471.9
Cumulative Fuel Savings Compared the No Action Alternative							
2010-2020	--	9.3	9.6	9.9	10.3	11.1	44.6
2010-2030	--	65.4	67.4	68.6	71.2	73.6	197.8
2010-2040	--	156.5	161.3	163.6	169.7	173.7	412.4
2010-2050	--	265.2	273.2	276.8	287.1	292.9	664.5
2010-2060	--	391.0	402.7	407.9	423.0	430.9	956.0

Table 4.2-2

Reference Case Light Truck Cumulative Annual Fuel Consumption and Cumulative Fuel Savings (billion gallons)

Calendar Year Range	Alternative CAFE Standards for MY 2011-2020						
	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt. 7
	No Action	25% Below Optimized	Optimized	25% Above Optimized	50% Above Optimized	Total Cost Equal Total Benefit	Technology Exhaustion
Cumulative Fuel Consumption							
2010-2020	903.7	894.9	893.8	891.8	890.4	888.0	858.0
2010-2030	1,791.9	1,711.4	1,705.7	1,694.0	1,685.5	1,674.4	1,546.5
2010-2040	2,800.0	2,595.3	2,582.7	2,555.4	2,535.7	2,511.4	2,245.6
2010-2050	3,962.4	3,602.6	3,581.5	3,535.1	3,501.5	3,461.2	3,029.6
2010-2060	5,305.3	4,763.2	4,732.3	4,663.5	4,613.7	4,554.6	3,929.6
Cumulative Fuel Savings Compared to the No Action Alternative							
2010-2020	--	8.7	9.8	11.9	13.2	15.6	45.7
2010-2030	--	80.6	86.2	98.0	106.5	117.6	245.4
2010-2040	--	204.7	217.3	244.5	264.3	288.6	554.3
2010-2050	--	359.8	380.9	427.3	460.9	501.2	932.8
2010-2060	--	542.1	573.0	641.8	691.7	750.8	1,375.7

Table 4.2-3

High Scenario Passenger Car Cumulative Fuel Consumption and Cumulative Fuel Savings (billion gallons)

Calendar Year Range	Alternative CAFE Standards for MY 2011-2020						
	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt. 7
	No Action	25% Below Optimized	Optimized	25% Above Optimized	50% Above Optimized	Total Cost Equal Total Benefit	Technology Exhaustion
Cumulative Fuel Consumption							
2010-2020	652.7	636.7	633.7	630.4	627.9	624.8	611.5
2010-2030	1,322.1	1,219.6	1,205.4	1,193.1	1,183.2	1,169.3	1,142.4
2010-2040	2,088.5	1,850.8	1,820.5	1,796.1	1,776.1	1,746.7	1,716.4
2010-2050	2,966.7	2,570.0	2,521.0	2,482.6	2,450.8	2,403.4	2,371.1
2010-2060	3,970.2	3,391.6	3,321.2	3,266.8	3,221.7	3,153.7	3,119.1
Cumulative Fuel Savings Compared to the No Action Alternative							
2010-2020	--	16.0	19.1	22.3	24.8	27.9	41.2
2010-2030	--	102.5	116.7	129.0	138.9	152.8	179.7
2010-2040	--	237.7	268.0	292.4	312.4	341.8	372.1
2010-2050	--	396.8	445.8	484.2	515.9	563.3	595.6
2010-2060	--	578.6	649.0	703.4	748.5	816.5	851.1

Table 4.2-4

High Scenario Light Truck Cumulative Fuel Consumption and Cumulative Fuel Savings (billion gallons)

Calendar Year Range	Alternative CAFE Standards for MY 2011-2020						
	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt. 7
	No Action	25% Below Optimized	Optimized	25% Above Optimized	50% Above Optimized	Total Cost Equal Total Benefit	Technology Exhaustion
Cumulative Fuel Consumption							
2010-2020	845.9	828.1	825.1	822.2	819.9	818.2	803.9
2010-2030	1,649.4	1,518.7	1,504.1	1,490.4	1,476.9	1,474.5	1,426.6
2010-2040	2,553.1	2,236.1	2,204.0	2,174.3	2,143.3	2,141.7	2,053.5
2010-2050	3,584.1	3,038.3	2,985.0	2,936.0	2,883.8	2,883.7	2,748.8
2010-2060	4,760.9	3,949.8	3,872.1	3,800.8	3,723.9	3,725.6	3,537.4
Cumulative Fuel Savings Compared to the No Action Alternative							
2010-2020	--	17.9	20.8	23.7	26.1	27.7	42.1
2010-2030	--	130.7	145.3	159.0	172.5	174.9	222.7
2010-2040	--	317.0	349.1	378.8	409.8	411.4	499.6
2010-2050	--	545.8	599.1	648.1	700.3	700.4	835.3
2010-2060	--	811.1	888.8	960.1	1,037.0	1,035.3	1,223.4

4.3 AIR QUALITY

4.3.1 Affected Environment

Section 3.3.1 describes the air quality affected environment.

4.3.2 Methodology

4.3.2.1 Overview

The analysis methodology for air quality cumulative impacts and consequent health outcomes is the same as described in Section 3.3.2, except that NHTSA added the potential CAFE standards for MY 2016-2020 because the EISA requires that passenger cars and light trucks achieve an average of at least 35 miles per gallon (mpg) by 2020. The MY 2016-2020 standards are thus a reasonably foreseeable future action that must be considered.

NHTSA analyzed the cumulative air quality impacts of the action alternatives by calculating the emissions from passenger cars and light trucks that would occur under each alternative and including the potential CAFE standards for MY 2016-2020, and assessing the changes in emissions in relation to the No Action Alternative. Many of the factors that affect air quality at any given location, such as meteorology and atmospheric processes, cannot be accounted for when evaluating human health and environmental impacts because this analysis cannot be done without a full-scale photochemical air quality modeling analysis. Full-scale photochemical air quality modeling was not conducted for this cumulative analysis; therefore, the ambient air quality impacts associated with each alternative cannot be analyzed for this FEIS. Full-scale photochemical air quality modeling is necessary to accurately project levels of particulate matter 2.5 microns in diameter or less ($PM_{2.5}$), ozone, and air toxics. A national-scale air quality modeling analysis would analyze the combined impacts of each alternative on $PM_{2.5}$, ozone, and MSATs. The atmospheric chemistry related to ambient concentrations of $PM_{2.5}$, ozone, and air toxics is very complex, and making predictions based solely on emissions changes is extremely difficult. The analysis of the alternatives is predicated on the common sense proposition that assessing emissions is a valid approach to assessing air quality impacts because emissions, ambient concentrations, and health effects are connected. Lower emissions should result in lower ambient concentrations of pollutants on an overall average basis, which should lead to decreased health effects of those pollutants.

The cumulative impacts analysis consists of three components analyzed together:

- CAFE implementation through MY 2010
- The MY 2011-2015 CAFE standard rules
- Assumed MY 2016-2020 rules based on EISA requirements for at least 35 mpg by 2020

For comparison, the non-cumulative impacts analysis (Section 3.3.2) consists of only two components:

- CAFE implementation through MY 2010
- The MY 2011-2015 CAFE standard rules

Because EISA directs NHTSA to increase CAFE standards to reach a combined fleet average CAFE level of at least 35 mpg by model year 2020, MY 2016-2020 CAFE standards are reasonably foreseeable and must be accounted for when analyzing the cumulative impacts of the MY 2011-2015 CAFE standards. For each alternative, NHTSA assumed that passenger-car and light-truck CAFE standards would continue to increase over MY 2016-2020 at their average annual rate of increase over

MY 2011-2015. This assumption results in passenger-car and light-truck CAFE standards under each action alternative that meet or exceed the EISA requirement of a combined fleet average of at least 35 mpg by model year 2020. NHTSA assumed further that the fuel economy standards for model year 2020 would remain in effect through the end of the analysis period. Because the CAFE standards apply to new vehicles, this assumption results in emissions reductions and fuel savings that continue to grow as new vehicles meeting the CAFE standards for MY 2020 and beyond are added to the fleet in each subsequent year, reaching their maximum values when all passenger cars and light trucks in the U.S. fleet meet these standards. For calendar years 2016-2020, the non-cumulative impacts analysis (Section 3.3.2) assumes that MY 2016-2020 and later passenger cars and light trucks would continue to meet the MY 2015 standards. By contrast, the cumulative impacts analysis assumes that MY 2016-2020 passenger cars and light trucks would meet the potential MY 2016-2020 standards and that MY 2021 and later passenger cars and light trucks would meet the potential MY 2020 standard.

The results presented in Section 4.3.3, Environmental Consequences, are for the Reference Case inputs as shown in Table 2.2-1 (*see* Section 2.2). Section 4.3.4, Input Scenarios, discusses the alternatives with three other input scenarios – High, Mid-1, and Mid-2.

4.3.2.2 Treatment of Incomplete or Unavailable Information

As noted in Section 3.3.2, the estimates of emissions rely on models and forecasts that contain numerous assumptions and data that are uncertain. Examples of areas in which information is incomplete or unavailable include future emission rates, vehicle manufacturers' decisions on vehicle technology and design, the mix of vehicle types and model years, emissions from fuel refining and distribution, and economic factors. Where information in the analysis included in the FEIS is incomplete or unavailable, the agency has relied on CEQ regulations regarding incomplete or unavailable information (40 CFR § 1502.22(b)). NHTSA used the best available models and supporting data in preparing this FEIS. The models used have been scientifically reviewed and have been approved by the agencies that sponsored their development. NHTSA believes that the assumptions made in the FEIS regarding uncertain conditions reflect the best available information and are valid and sufficient for this analysis.

4.3.3 Environmental Consequences

4.3.3.1 Results of Emissions Analysis – Reference Case

The Clean Air Act (CAA) has been successful in reducing emissions from on-road mobile sources. As discussed in Section 3.3.1, pollutant emissions from vehicles have been declining since 1970, and the U.S. Environmental Protection Agency (EPA) projects the decline will continue. However, as future trends show, vehicle travel is having increasingly less impact on emissions as a result of stricter EPA standards for vehicle emissions and the chemical composition of fuels, even with additional increases in vehicle miles traveled (VMT) (Smith 2002). This general trend would continue, more or less, with implementation of any alternative CAFE standard. The cumulative impacts analysis shows that some of the alternative CAFE standards would lead to reductions and some would lead to increases in emissions from passenger cars and light trucks, compared to current trends without the alternative CAFE standards. The amounts of the reductions and increases would vary by pollutant, calendar year, and alternative. The more restrictive alternatives generally would result in greater emission reductions compared to the No Action Alternative. This trend is shown in the analysis of the MY 2011-2015 CAFE standards in Section 3.3.3.

This section analyzes the cumulative impacts of the standards and the assumed MY 2016-2020 standards. The analysis shows that the CAFE standards would lead to further reductions in emissions from passenger cars and light trucks, although the amount of the reductions would vary by the alternative

CAFE standards. Some exceptions, however, are: carbon monoxide (CO) emissions would increase with Alternative 2 (25 Percent Below Optimized), Alternative 3 (Optimized), and (in 2025 and 2035) Alternative 4 (25 Percent Above Optimized). VOC emissions would increase with Alternatives 2 and 3 in 2015. The more restrictive alternatives would result in greater emission reductions compared to Alternative 1 (No Action).

4.3.3.2 Alternative 1: No Action

4.3.3.2.1 Criteria Pollutants

With the No Action Alternative, the CAFE standards would remain at the MY 2010 level in future years. Emissions for this alternative would follow the same trends as shown in the environmental consequences analysis (*see* Section 3.3.3.2). Nationwide emissions changes would be uneven with respect to pollutant and alternative, reflecting projected changes in VMT, emission factors, and diesel share of the vehicle fleet. Cumulative emissions would be less than non-cumulative emissions for the same combination of pollutant, year, and alternative, with the exception of CO.

Table 4.3-1 summarizes the total national cumulative emissions from passenger cars and light trucks for Alternative 1 (No Action) for each criteria pollutant and analysis year. Alternatives 2 through 7 are presented from left to right in the table in order of increasing fuel economy requirements. Alternative 1 would generally have the highest emissions for all criteria pollutants. Emissions of CO under Alternatives 2 and 3 are exceptions, showing increases compared to the No Action Alternative. Appendix B-1 presents the cumulative emissions of criteria pollutants for each nonattainment area.

Table 4.3-1

Reference Case Alternative CAFE Standards
Nationwide Criteria Pollutant Emissions from Passenger Cars and Light Trucks (tons/year)
Cumulative Effects with MY 2011-2015 Standards and Potential MY 2016-2020 Standards

Pollutant and Year	Alt. 1 No Action	Alt. 2 25% Below Optimized	Alt. 3 Optimized	Alt. 4 25% Above Optimized	Alt. 5 50% Above Optimized	Alt. 6 Total Costs Equal Total Benefits	Alt. 7 Technology Exhaustion
CO							
2015	20,241,797	20,253,445	20,257,987	20,228,139	20,224,744	20,189,464	19,529,680
2020	18,133,965	18,186,406	18,206,784	18,075,188	18,060,051	17,968,700	15,338,352
2025	18,103,174	18,247,050	18,288,999	18,023,431	17,994,420	17,842,582	12,918,978
2035	19,745,847	20,068,580	20,145,455	19,664,457	19,615,715	19,406,046	11,524,825
NO_x							
2015	2,305,222	2,303,582	2,303,373	2,303,034	2,302,869	2,301,994	2,287,081
2020	1,670,131	1,659,367	1,658,963	1,656,253	1,655,168	1,651,757	1,587,272
2025	1,426,220	1,403,976	1,403,684	1,396,298	1,394,058	1,387,882	1,248,660
2035	1,369,135	1,335,125	1,335,545	1,318,678	1,314,728	1,305,570	1,048,518
$PM_{2.5}$							
2015	80,400	80,254	80,242	80,153	80,124	80,062	78,981
2020	82,456	81,374	81,331	81,026	80,910	80,859	78,190
2025	87,471	85,076	84,999	84,469	84,265	84,228	80,710
2035	99,707	95,588	95,468	94,650	94,333	94,305	89,788
SO_x							
2015	208,833	207,880	207,784	207,448	207,302	206,804	196,728
2020	217,490	210,826	210,470	209,405	208,750	207,666	182,940
2025	232,179	217,440	216,796	214,942	213,736	212,094	175,787
2035	265,792	240,446	239,437	236,567	234,662	232,370	183,541

Table 4.3-1 (cont'd)

Reference Case Alternative CAFE Standards
Nationwide Criteria Pollutant Emissions from Passenger Cars and Light Trucks (tons/year)
Cumulative Effects with MY 2011-2015 Standards and Potential MY 2016-2020 Standards

Pollutant and Year	Alt. 1 No Action	Alt. 2 25% Below Optimized	Alt. 3 Optimized	Alt. 4 25% Above Optimized	Alt. 5 50% Above Optimized	Alt. 6 Total Costs Equal Total Benefits	Alt. 7 Technology Exhaustion
VOCs							
2015	2,261,550	2,259,712	2,259,680	2,257,453	2,256,856	2,253,598	2,185,838
2020	1,896,683	1,882,585	1,882,513	1,875,117	1,872,667	1,864,598	1,666,245
2025	1,817,495	1,787,653	1,787,778	1,773,541	1,769,015	1,755,492	1,407,415
2035	1,906,119	1,861,129	1,862,621	1,832,904	1,825,138	1,803,935	1,196,950

Table 4.3-2 lists the net changes in nationwide cumulative emissions from passenger cars and light trucks for the No Action Alternative for each criteria pollutant and analysis year. Alternatives 2 through 7 are presented in the table from left to right in order of increasing fuel economy requirements. The reductions in nationwide cumulative emissions generally increase from left to right, except as noted above for CO emissions. This reflects the increasing fuel economy requirements that are assumed under successive alternatives.

Table 4.3-2

Reference Case Alternative CAFE Standards
Nationwide Criteria Pollutant Emission Changes from Passenger Cars and Light Trucks (tons/year)
Cumulative Effects with MY 2011-2015 Standards and Potential MY 2016-2020 Standards a/

Pollutant and Year	Alt. 1 No Action b/	Alt. 2 25% Below Optimized	Alt. 3 Optimized	Alt. 4 25% Above Optimized	Alt. 5 50% Above Optimized	Alt. 6 Total Costs Equal Total Benefits	Alt. 7 Technology Exhaustion
CO							
2015	0	11,649	16,190	-13,658	-17,053	-52,332	-712,117
2020	0	52,441	72,819	-58,778	-73,914	-165,265	-2,795,614
2025	0	143,876	185,825	-79,743	-108,754	-260,592	-5,184,196
2035	0	322,733	399,608	-81,390	-130,132	-339,801	-8,221,022
NO_x							
2015	0	-1,640	-1,849	-2,188	-2,353	-3,228	-18,141
2020	0	-10,764	-11,168	-13,878	-14,963	-18,374	-82,859
2025	0	-22,244	-22,536	-29,922	-32,162	-38,338	-177,560
2035	0	-34,010	-33,590	-50,457	-54,407	-63,566	-320,618
$PM_{2.5}$							
2015	0	-147	-158	-247	-276	-338	-1,419
2020	0	-1,083	-1,126	-1,431	-1,546	-1,597	-4,266
2025	0	-2,395	-2,472	-3,002	-3,206	-3,243	-6,761
2035	0	-4,119	-4,239	-5,057	-5,374	-5,402	-9,919
SO_x							
2015	0	-952	-1,049	-1,385	-1,530	-2,029	-12,105
2020	0	-6,664	-7,020	-8,085	-8,740	-9,824	-34,550
2025	0	-14,740	-15,383	-17,237	-18,443	-20,085	-56,393
2035	0	-25,346	-26,356	-29,225	-31,131	-33,422	-82,252
VOCs							
2015	0	-1,838	-1,870	-4,097	-4,694	-7,952	-75,712
2020	0	-14,098	-14,170	-21,566	-24,016	-32,085	-230,438
2025	0	-29,842	-29,717	-43,954	-48,480	-62,003	-410,080
2035	0	-44,990	-43,498	-73,215	-80,981	-102,184	-709,169

a/ Negative emissions changes indicate reductions; positive emissions changes are increases.
b/ Emissions changes for the No Action Alternative are shown as zero because the No Action Alternative is the baseline to which the emissions for the other alternatives are compared.

4.3.3.2.2 Air Toxics

As with the criteria pollutants, current trends in the levels of air toxics emissions from vehicles would continue, with emissions of most air toxics continuing to decline, despite a growth in total VMT, as a result of the EPA emission standards. Exceptions to this trend are emissions of benzene and formaldehyde, which increase in 2035 over 2025 levels with the No Action Alternative. Further, with current trends, emissions of diesel particulate matter (DPM) increase in every analysis year with the No Action Alternative. Alternative 1 (No Action) would result in no other increase or decrease in toxic air pollutant emissions in nonattainment and maintenance areas throughout the United States.

Table 4.3-3 summarizes the cumulative national toxic air pollutant emissions from passenger cars and light trucks for Alternative 1 (No Action) for each toxic air pollutant and analysis year. Alternatives 2 through 7 are presented in order of increasing fuel economy requirements from left to right. Unlike criteria pollutants, emissions of many toxic air pollutants would increase in several alternatives. The changes in air toxic emissions, whether positive or negative, would generally be small relative to Alternative 1 emissions levels. An exception is Alternative 7, which would result in changes in emissions of some toxic air pollutants that would be large relative to Alternative 1 emissions levels.

Changes in cumulative emissions for toxic air pollutants reflect decreases with reductions in upstream emissions, and increases due to the rebound effect and changes in the proportion of diesel vehicles. Cumulative emissions of acetaldehyde would increase under Alternatives 4 and 5 for all analysis years, and under Alternatives 2, 3, 6, and 7 for some analysis years. Cumulative emissions of acrolein would increase with all the action alternatives because data on upstream emissions reductions were not available. Cumulative emissions of benzene would decrease under all the action alternatives compared to the No Action Alternative. Cumulative emissions of 1,3-butadiene would generally decrease slightly from Alternative 1 under successive alternatives. Cumulative emissions of DPM would decline under all alternatives relative to the No Action Alternative. Cumulative emissions of formaldehyde would decrease with Alternatives 2 and 3 but increase with Alternative 7; changes in formaldehyde emissions under Alternatives 4, 5, and 6 vary depending on analysis year.

Cumulative emissions would generally be less than non-cumulative emissions for the same combination of pollutant, year, and alternative, for acetaldehyde (except in 2035 and with Alternative 7 in all years), benzene (except Alternative 7 in 2035), DPM, and formaldehyde (except Alternative 7). Cumulative emissions would generally be greater than non-cumulative emissions for the same combination of pollutant, year, and alternative, for acrolein and 1,3-butadiene (in 2020-2035). Appendix B-1 presents the cumulative emissions of toxic air pollutants for each nonattainment area for the No Action Alternative.

Table 4.3-4 lists the net changes in nationwide cumulative emissions from passenger cars and light trucks compared to Alternative 1 (No Action) for each air toxic and analysis year. Alternatives 2 through 7 are presented from left to right in order of increasing fuel economy requirements. In Table 4.3-4 the nationwide emissions changes are uneven with respect to pollutant and alternative, reflecting the changes in VMT and emissions by cars versus trucks and gasoline versus diesel engines that are projected to occur with the increasing fuel economy requirements assumed under successive alternatives.

Table 4.3-3

Reference Case Alternative CAFE Standards
Nationwide Toxic Air Pollutant Emissions from Passenger Cars and Light Trucks (tons/year)
Cumulative Effects with MY 2011-2015 Standards and Potential MY 2016-2020 Standards

	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt. 7
Pollutant and Year	**No Action**	**25% Below Optimized**	**Optimized**	**25% Above Optimized**	**50% Above Optimized**	**Total Costs Equal Total Benefits**	**Technology Exhaustion**
Acetaldehyde							
2015	11,982	11,978	11,976	11,985	11,987	11,991	12,093
2020	9,420	9,408	9,406	9,425	9,428	9,420	9,610
2025	8,401	8,390	8,389	8,402	8,406	8,386	8,468
2035	8,209	8,224	8,229	8,211	8,214	8,183	7,974
Acrolein a/							
2015	569	569	569	571	571	574	626
2020	429	431	430	438	439	444	602
2025	371	376	375	386	389	396	652
2035	351	362	361	377	381	392	758
Benzene							
2015	64,524	64,510	64,514	64,458	64,447	64,374	62,953
2020	51,781	51,645	51,664	51,431	51,385	51,200	46,206
2025	47,378	47,125	47,171	46,690	46,602	46,291	36,932
2035	47,515	47,256	47,364	46,405	46,251	45,791	29,613
1,3-butadiene							
2015	6,134	6,133	6,133	6,133	6,134	6,133	6,141
2020	4,698	4,688	4,687	4,686	4,685	4,680	4,625
2025	4,092	4,071	4,071	4,065	4,064	4,050	3,850
2035	3,885	3,852	3,854	3,839	3,839	3,803	3,331
Diesel particulate matter (DPM)							
2015	94,873	94,356	94,292	94,197	94,130	94,033	92,005
2020	98,292	94,693	94,463	94,189	93,880	93,678	89,049
2025	104,603	96,630	96,218	95,732	95,157	94,850	88,442
2035	119,499	105,773	105,131	104,372	103,457	102,999	94,643
Formaldehyde							
2015	17,382	17,358	17,351	17,388	17,393	17,421	18,018
2020	14,106	13,998	13,977	14,092	14,103	14,129	15,995
2025	12,930	12,719	12,688	12,859	12,876	12,906	15,817
2035	13,035	12,717	12,677	12,899	12,924	12,961	17,034

a/ Data on upstream emissions reductions were not available for acrolein. Thus, the emissions for acrolein reflect only the change in tailpipe emissions.

Table 4.3-4

Reference Case Alternative CAFE Standards
Nationwide Changes in Toxic Air Pollutant Emissions from Passenger Cars and Light Trucks (tons/year)
Cumulative Effects with MY 2011-2015 Standards and Potential MY 2016-2020 Standards a/

Pollutant and Year	Alt. 1 No Action b/	Alt. 2 25% Below Optimized	Alt. 3 Optimized	Alt. 4 25% Above Optimized	Alt. 5 50% Above Optimized	Alt. 6 Total Costs Equal Total Benefits	Alt. 7 Technology Exhaustion
Acetaldehyde							
2015	0	-4	-6	3	5	9	111
2020	0	-12	-15	4	7	-1	189
2025	0	-11	-12	1	4	-16	66
2035	0	15	20	3	5	-26	-235
Acrolein c/							
2015	0	0	0	2	2	5	57
2020	0	2	1	8	10	14	173
2025	0	5	4	15	18	25	281
2035	0	11	10	26	30	40	407
Benzene							
2015	0	-14	-10	-66	-77	-150	-1,570
2020	0	-137	-117	-350	-396	-582	-5,576
2025	0	-253	-207	-688	-776	-1,087	-10,446
2035	0	-259	-151	-1,110	-1,264	-1,724	-17,902
1,3-butadiene							
2015	0	-1	-1	-1	-1	-1	7
2020	0	-10	-11	-12	-13	-18	-73
2025	0	-22	-21	-27	-28	-43	-242
2035	0	-33	-31	-46	-46	-82	-555
Diesel particulate matter (DPM)							
2015	0	-517	-581	-676	-743	-840	-2,868
2020	0	-3,599	-3,828	-4,103	-4,412	-4,613	-9,243
2025	0	-7,973	-8,384	-8,870	-9,446	-9,753	-16,160
2035	0	-13,726	-14,368	-15,127	-16,042	-16,500	-24,857
Formaldehyde							
2015	0	-24	-32	6	11	39	636
2020	0	-108	-129	-14	-2	24	1,890
2025	0	-211	-242	-71	-54	-24	2,887
2035	0	-319	-358	-136	-111	-74	3,999

a/ Negative emissions changes indicate reductions; positive emissions changes are increases.

b/ Emissions changes for the No Action Alternative are shown as zero because the No Action Alternative is the baseline to which the emissions for the other alternatives are compared.

c/ Data on upstream emissions reductions were not available for acrolein. Thus, the emissions for acrolein reflect only the change in tailpipe emissions.

4.3.3.2.3 Health Outcomes and Costs

With Alternative 1 (No Action), the CAFE standards would remain at the MY 2010 level in future years. Emissions of criteria pollutants and air toxics would change as described above. Human health effects of emissions are tied to specific pollutants, and will vary as emissions of these pollutants vary. The No Action Alternative would result in no other increase or decrease in human health effects throughout the United States, compared to current trends.

Table 4.3-5 lists the net changes in health outcomes due to nationwide cumulative emissions in each analysis year. Alternatives 1 through 7 are presented from left to right in order of increasing fuel economy requirements. The health impacts of vehicle emissions decrease for all alternatives compared to the No Action Alternative, and decrease successively in each analysis year.

Table 4.3-5

Reference Case Alternative CAFE Standards
Nationwide Changes in Health Outcomes from Criteria Air Pollutant Emissions from Passenger Cars and Light Trucks (cases/year)
Cumulative Effects with MY 2011-2015 Standards and Potential MY 2016-2020 Standards a/

Health Outcome and Year	Alt. 1 No Action b/	Alt. 2 25% Below Optimized	Alt. 3 Optimized	Alt. 4 25% Above Optimized	Alt. 5 50% Above Optimized	Alt. 6 Total Costs Equal Total Benefits	Alt. 7 Technology Exhaustion
Mortality (ages 30 and older)							
2015	0	-11	-12	-19	-21	-26	-109
2020	0	-83	-86	-110	-119	-122	-327
2025	0	-184	-190	-230	-246	-249	-518
2035	0	-316	-325	-388	-412	-414	-760
Chronic bronchitis							
2015	0	-10	-11	-16	-18	-23	-95
2020	0	-72	-75	-95	-103	-106	-284
2025	0	-160	-165	-200	-214	-216	-451
2035	0	-275	-283	-337	-358	-360	-661
Emergency room visits for asthma							
2015	0	-2	-3	-4	-4	-5	-23
2020	0	-17	-18	-23	-25	-26	-68
2025	0	-38	-40	-48	-51	-52	-108
2035	0	-66	-68	-81	-86	-86	-159
Work-loss days							
2015	0	-2,006	-2,162	-3,377	-3,772	-4,619	-19,392
2020	0	-14,796	-15,383	-19,552	-21,126	-21,824	-58,309
2025	0	-32,732	-33,787	-41,024	-43,814	-44,325	-92,403
2035	0	-56,293	-57,939	-69,110	-73,443	-73,833	-135,560

a/ Negative changes indicate reductions; positive emissions changes are increases.
b/ Changes in health outcomes for the No Action Alternative are shown as zero because the No Action Alternative is the baseline to which the emissions for the other alternatives are compared.

The economic value of health impacts would vary proportionately with changes in health outcomes, under the methodology defined in Section 3.3.2.4.2. The economic impacts analyzed here are the result of changes in ambient particulate matter (PM) and ozone concentrations as caused by changes in precursor criteria pollutants NO_x, VOCs, SO_2 and $PM_{2.5}$. Alternative 1 (No Action) would result in no other change in health-related costs throughout the United States, compared to current trends.

Table 4.3-6 lists the nationwide changes in health costs from cumulative emissions from passenger cars and light trucks. Results for each analysis year are shown for the No Action Alternative in the left column, and for other alternatives from left to right in order of increasing fuel economy requirements. As with health outcomes, the economic impacts of each alternative decrease across successive alternatives and years compared to the health costs of emissions under the No Action Alternative.

Table 4.3-6

Reference Case Alternative CAFE Standards
Nationwide Changes in Health Costs from Criteria Air Pollutant Emissions from Passenger Cars and Light Trucks (U.S. million dollars/year)
Cumulative Effects with MY 2011-2015 Standards and Potential MY 2016-2020 Standards a/

	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt. 7
Year	No Action b/	25% Below Optimized	Optimized	25% Above Optimized	50% Above Optimized	Total Costs Equal Total Benefits	Technology Exhaustion
2015	0	-20	-23	-29	-32	-42	-240
2020	0	-192	-201	-241	-260	-302	-1,177
2025	0	-414	-426	-515	-552	-622	-2,228
2035	0	-680	-694	-871	-933	-1,034	-3,703

a/ Negative changes indicate economic benefit; positive emissions changes are economic costs.
b/ Changes for the No Action Alternative are shown as zero because the No Action Alternative is the baseline to which the emissions for the other alternatives are compared.

4.3.3.3 Alternative 2: 25 Percent Below Optimized

4.3.3.3.1 Criteria Pollutants

CAFE standards under the 25 Percent Below Optimized Alternative (Alternative 2) would require increased fuel economy compared to the No Action Alternative (Alternative 1). Alternative 2 would increase fuel economy less than would Alternatives 3 through 7. Under Alternative 2, cumulative emissions are generally less than Alternative 1, but greater than all other alternatives. However, Alternative 2 would have greater cumulative emissions of CO than the No Action Alternative.

Emissions in individual nonattainment areas might follow different patterns than nationwide emissions. Emissions of criteria pollutants vary due to interrelations among upstream emissions, VMT increases, and diesel share of fuel. Compared to Alternative 1, cumulative emissions of NO_x, SO_x, and VOCs under Alternative 2 decrease in all nonattainment areas. In contrast, CO emissions increase in almost all nonattainment areas, while PM emissions vary. Tables in Appendix B-2 list the emissions reductions for each nonattainment area.

Cumulative fuel economy standards would lead to lower emissions of most pollutants compared to non-cumulative standards, due to the impact of more stringent standards in the cumulative case. In

Alternative 2, cumulative emissions of all pollutants are lower than non-cumulative emissions. However, emissions of CO are higher under the cumulative case than the non-cumulative case.

4.3.3.3.2 Air Toxics

Under Alternative 2, cumulative emissions would generally be less than non-cumulative emissions for the same combinations of pollutant and year.

There would be reductions in cumulative nationwide emissions of all toxic air pollutants (except acrolein and acetaldehyde in 2035) under Alternative 2 compared to the No Action Alternative. Compared to Alternative 3, Alternative 2 would have higher emissions of DPM and formaldehyde but lower emissions of benzene. Compared to Alternatives 4 through 7, Alternative 2 would generally have higher emissions of benzene, 1,3-butadiene, and DPM, but lower emissions of acrolein and formaldehyde, and mixed results for acetaldehyde depending on the year and alternative.

At the nationwide level, the reduction in upstream emissions of toxic air pollutants tends to offset the increase in VMT and emissions due to the rebound effect. However, as noted above, the reductions in upstream emissions are not uniformly distributed to individual nonattainment areas. Net emission reductions can occur if the reduction in upstream emissions in the nonattainment area more than offsets the increase within the area due to the rebound effect. Under Alternative 2, many nonattainment areas would experience net increases in emissions of one or more toxic air pollutants in at least one of the analysis years (*see* Appendix B-2). However, the emission increases would be quite small, as shown in Appendix B-2, and emissions increases would be distributed throughout each nonattainment area.

4.3.3.3.3 Health Outcomes and Costs

Compared to Alternative 1 (No Action), the cumulative impact of Alternative 2 would result in 316 fewer mortalities and 56,293 fewer work-loss days in 2035. Cumulative health benefits would exceed non-cumulative benefits, reducing mortalities by an additional 238 cases and lost-work days by an additional 42,415 cases in 2035. In that same year, Alternative 2 would reduce health costs by $680 million, an additional $507 million over non-cumulative benefits.

4.3.3.4 Alternative 3: Optimized

4.3.3.4.1 Criteria Pollutants

CAFE standards under the Optimized Alternative (Alternative 3) would require increased fuel economy compared to Alternatives 1 and 2, but less than Alternatives 4 through 7. Under Alternative 3, cumulative emissions are generally less than Alternative 1, but greater than all other alternatives. However, Alternative 3 would have greater cumulative emissions of CO than any other alternative. Alternative 3 would also have slightly greater cumulative emissions of NO_x and VOCs than Alternative 2.

Emissions in individual nonattainment areas could follow different patterns than nationwide emissions. Emissions of criteria pollutants vary due to interrelations among upstream emissions, VMT increases, and diesel share of fuel. Compared to Alternative 1, cumulative emissions of NO_x, SO_x, and VOCs under Alternative 3 decrease in almost all nonattainment areas. In contrast, CO emissions increase in almost all nonattainment areas, while PM emissions vary. Tables in Appendix B-2 list the emissions reductions for each nonattainment area.

As with previously discussed alternatives, cumulative fuel economy standards would lead to lower emissions of most pollutants compared to non-cumulative standards. In Alternative 3, cumulative emissions of all pollutants are lower than non-cumulative emissions.

4.3.3.4.2 Air Toxics

Under Alternative 3, cumulative emissions would generally be less than non-cumulative emissions for the same combinations of pollutant and year.

Alternative 3 would reduce air toxics emissions compared to the No Action Alternative for all air toxics (except acetaldehyde in 2035, and acrolein). Alternative 3 would have higher emissions of benzene, 1,3-butadiene (2015 and 2020), and DPM compared to Alternatives 4 through 7. Alternative 3 would have lower emissions of acrolein and formaldehyde compared to Alternatives 4 through 7, and mixed results for acetaldehyde depending on the year and alternative.

Nationwide, emissions of toxic air pollutants can decrease because the reduction in upstream emissions more than offsets the increase in VMT and emissions due to the rebound effect. However, the reductions in upstream emissions are not uniformly distributed to individual nonattainment areas. Under Alternative 3, many nonattainment areas would experience net increases in emissions of one or more toxic air pollutants in at least one of the analysis years (*see* Appendix B-2). However, the emission increases would be quite small, as shown in Appendix B-2, and emission increases would be distributed throughout each nonattainment area.

4.3.3.4.3 Health Outcomes and Costs

Compared to Alternative 1 (No Action), the cumulative impact of Alternative 3 would result in 325 fewer mortalities and 57,939 fewer work-loss days in 2035. Cumulative health benefits would exceed non-cumulative benefits, reducing mortalities by an additional 242 cases and lost-work days by an additional 43,150 cases in 2035. In that same year, Alternative 3 would reduce health costs by $694 million, an additional $515 million over non-cumulative benefits.

4.3.3.5 Alternative 4: 25 Percent Above Optimized

4.3.3.5.1 Criteria Pollutants

CAFE standards under the 25 Percent Above Optimized Alternative (Alternative 4) would require increased fuel economy compared to Alternatives 1 through 3, but less than Alternatives 5 through 7. Under Alternative 4, cumulative emissions would be less than under Alternatives 1, 2, and 3, but greater than all other alternatives.

Emissions in individual nonattainment areas could follow different patterns than nationwide emissions. Emissions of criteria pollutants vary due to interrelations among upstream emissions, VMT increases, and diesel share of fuel. Compared to Alternative 1, cumulative emissions of CO, NO_x, SO_x, VOCs, and PM under Alternative 4 decrease in almost all nonattainment areas. However, PM emissions could increase or decrease depending on nonattainment area. Tables in Appendix B-2 list the emissions reductions for each nonattainment area.

As with previously discussed alternatives, cumulative fuel economy standards would lead to lower emissions of most pollutants compared to non-cumulative standards. In Alternative 4, cumulative emissions of all pollutants are lower than non-cumulative emissions.

4.3.3.5.2 Air Toxics

Under Alternative 4, cumulative emissions would generally be less than non-cumulative emissions for the same combinations of pollutant and year.

Alternative 4 would reduce air toxics emissions compared to the No Action Alternative for all air toxics except acetaldehyde, acrolein, and formaldehyde in 2015. Compared to Alternatives 5 through 7, Alternative 4 would have higher emissions of benzene, 1,3-butadiene (except in 2015), and DPM. Alternative 4 would have lower emissions of acrolein and formaldehyde compared to Alternatives 5 through 7, and mixed results for acetaldehyde depending on the year and alternative.

At the nationwide level, emissions of toxic air pollutants can decrease because the reduction in upstream emissions more than offsets the increase in VMT and emissions due to the rebound effect. However, the reductions in upstream emissions are not uniformly distributed to individual nonattainment areas. Under Alternative 4, many nonattainment areas would experience net increases in emissions of one or more toxic air pollutants in at least one of the analysis years (*see* Appendix B-2). However, the emission increases would be quite small, as shown in Appendix B-2, and emission increases would be distributed throughout each nonattainment area.

4.3.3.5.3 Health Outcomes and Costs

Compared to Alternative 1 (No Action), the cumulative impact of Alternative 4 would result in 388 fewer mortalities and 69,110 fewer work-loss days in 2035. Cumulative health benefits would exceed non-cumulative benefits, reducing mortalities by an additional 262 cases and lost-work days by an additional 46,654 cases in 2035. In that same year, Alternative 4 would reduce health costs by $871 million, an additional $564 million over non-cumulative benefits.

4.3.3.6 Alternative 5: 50 Percent Above Optimized

4.3.3.6.1 Criteria Pollutants

CAFE standards under the 50 Percent Above Optimized Alternative (Alternative 5) would require increased fuel economy compared to Alternatives 1 through 4, but less than Alternatives 6 and 7. Under Alternative 5, cumulative emissions would be less than Alternatives 1 through 4, but greater than all other alternatives.

Emissions in individual nonattainment areas could follow different patterns than nationwide emissions. Emissions of criteria pollutants vary due to interrelations among upstream emissions, VMT increases, and diesel share of fuel. Compared to Alternative 1, cumulative emissions of CO, NO_x, SO_x, and VOCs under Alternative 5 decrease in all nonattainment areas. PM emissions increase or decrease depending on nonattainment area. Tables in Appendix B-2 list the emissions reductions for each nonattainment area.

As with previously discussed alternatives, cumulative fuel economy standards would lead to lower emissions of most pollutants compared to non-cumulative standards. In Alternative 5, cumulative emissions of all pollutants are lower than non-cumulative emissions.

4.3.3.6.2 Air Toxics

Under Alternative 5, cumulative emissions would generally be less than non-cumulative emissions for the same combinations of pollutant and year, with the exception of acrolein, butadiene, and acetaldehyde in 2035.

Alternative 5 would reduce air toxics emissions of benzene, 1,3-butadiene, formaldehyde (except in 2015), and DPM compared to the No Action Alternative, but would increase emissions of acetaldehyde and acrolein compared to the No Action Alternative. Alternative 5 would have higher emissions of benzene, 1,3-butadiene (except for Alternative 7 in 2015), and DPM compared to Alternatives 6 and 7. Alternative 5 would have lower emissions of acrolein and formaldehyde compared to Alternatives 6 and 7, and mixed results for acetaldehyde depending on year and alternative.

At the nationwide level, emissions of toxic air pollutants can decrease because the reduction in upstream emissions more than offsets the increase in VMT and emissions due to the rebound effect. However, the reductions in upstream emissions are not uniformly distributed to individual nonattainment areas. Under Alternative 5, many nonattainment areas would experience net increases in emissions of one or more toxic air pollutants in at least one of the analysis years (*see* Appendix B-2). However, the emission increases would be quite small, as shown in Appendix B-2, and emission increases would be distributed throughout each nonattainment area.

4.3.3.6.3 Health Outcomes and Costs

Compared to Alternative 1 (No Action), the cumulative impact of Alternative 5 would result in 412 fewer mortalities and 73,443 fewer work-loss days in 2035. Cumulative health benefits would exceed non-cumulative benefits, reducing mortalities by an additional 270 cases and lost-work days by an additional 48,104 cases in 2035. In that same year, Alternative 5 would reduce health costs by $993 million, an additional $584 million over non-cumulative benefits.

4.3.3.7 Alternative 6: Total Costs Equal Total Benefits

4.3.3.7.1 Criteria Pollutants

CAFE standards under the Total Costs Equal Total Benefits Alternative (Alternative 6) would require increased fuel economy compared to Alternatives 1 through 5, but less than Alternative 7. Under Alternative 6, cumulative emissions would be less than Alternatives 1 through 5, but greater than Alternative 7.

Emissions in individual nonattainment areas could follow different patterns than nationwide emissions. Emissions of criteria pollutants vary due to interrelations among upstream emissions, VMT increases, and diesel share of fuel. Compared to Alternative 1, cumulative emissions of CO, NO_x, SO_x, and VOCs under Alternative 6 decrease in all nonattainment areas. PM emissions increase or decrease depending on nonattainment area. Tables in Appendix B-2 list the emissions reductions for each nonattainment area.

As with previously discussed alternatives, cumulative fuel economy standards would lead to lower emissions of most pollutants compared to non-cumulative standards. In Alternative 6, cumulative emissions of all pollutants are lower than non-cumulative emissions.

4.3.3.7.2 Air Toxics

Under Alternative 6, cumulative emissions would generally be less than non-cumulative emissions for the same combinations of pollutant and year, with the exception of acrolein, 1,3-butadiene, and acetaldehyde in 2035.

Alternative 6 would reduce air toxics emissions of acetaldehyde (in 2025-2035), benzene, 1,3-butadiene, and DPM compared to the No Action Alternative, but would increase emissions of acetaldehyde (in 2015), acrolein, and formaldehyde compared to the No Action Alternative. Alternative 6 would have higher emissions of acetaldehyde (in 2035), benzene, 1,3-butadiene (except in 2015), and DPM compared to Alternative 7. Alternative 6 would have lower emissions of acetaldehyde (in 2015-2025), acrolein, 1,3-butadiene (in 2015), and formaldehyde compared to Alternative 7.

At the nationwide level, emissions of toxic air pollutants can decrease because the reduction in upstream emissions more than offsets the increase in VMT and emissions due to the rebound effect. However, the reductions in upstream emissions are not uniformly distributed to individual nonattainment areas. Under Alternative 6, many nonattainment areas would experience net increases in emissions of one or more toxic air pollutants in at least one of the analysis years (*see* Appendix B-2). However, the emission increases would be quite small, as shown in Appendix B-2, and emission increases would be distributed throughout each nonattainment area.

4.3.3.7.3 Health Outcomes and Costs

Compared to Alternative 1 (No Action), the cumulative impact of Alternative 6 would result in 414 fewer mortalities and 73,833 fewer work-loss days in 2035. Cumulative health benefits would exceed non-cumulative benefits, reducing mortalities by an additional 272 cases and lost-work days by an additional 48,600 cases in 2035. In that same year, Alternative 6 would reduce health costs by $1.034 billion, an additional $599 million over non-cumulative benefits.

4.3.3.8 Alternative 7: Technology Exhaustion

4.3.3.8.1 Criteria Pollutants

Of all the alternatives analyzed, the Technology Exhaustion Alternative (Alternative 7) would increase fuel economy the most. In this alternative, the cumulative fuel economy standard has more impact than in any other alternative. Cumulative standards would lead to greater reductions in emissions of all criteria pollutants. The greatest impact would be on SO_x emissions, which in 2035 would be reduced by an additional 12.4 percent to a 25.8 percent reduction in cumulative emissions below No Action Alternative levels, compared to a 13.4 percent reduction in non-cumulative emissions below No Action Alternative levels. Also in 2035, NO_x, PM, and VOC emissions would be reduced by an additional 4.9 percent, 4.3 percent, and 5.6 percent, respectively, in cumulative emissions compared to the non-cumulative emissions reductions. Alternative 7 is the only alternative in which CO emissions would decrease under cumulative standards, by an additional 3.7 percent.

Emissions in individual nonattainment areas might follow different patterns than nationwide emissions. Emissions of criteria pollutants vary due to interrelations among upstream emissions, VMT increases, and diesel share of fuel. Compared to Alternative 1, cumulative emissions of CO, NO_x, SO_x, and VOCs under Alternative 6 decrease in all nonattainment areas. PM emissions increase or decrease depending on nonattainment area. Tables in Appendix B-2 list the emissions reductions for each nonattainment area.

As with previously discussed alternatives, cumulative fuel economy standards would lead to lower emissions of most pollutants compared to non-cumulative standards. Unlike the prior alternatives, most (but not all) cumulative emissions in Alternative 7 are less than non-cumulative emissions. The exceptions are CO and VOCs, which are slightly higher for the cumulative standards in 2035.

4.3.3.8.2 Air Toxics

Under Alternative 7, cumulative emissions would generally be greater than non-cumulative emissions for the same combinations of pollutant and year, with the exception of benzene in 2020 and 2025 and DPM in all analysis years.

Alternative 7 would reduce air toxics emissions of acetaldehyde (in 2035 only), benzene, 1,3-butadiene (2020-2035), and DPM compared to the No Action Alternative, but would increase emissions of acetaldehyde (in 2015-2025), acrolein, and formaldehyde compared to the No Action Alternative.

At the nationwide level, emissions of toxic air pollutants can decrease because the reduction in upstream emissions more than offsets the increase in VMT and emissions due to the rebound effect. However, the reductions in upstream emissions are not uniformly distributed to individual nonattainment areas. Under Alternative 7, many nonattainment areas would experience net increases in emissions of one or more toxic air pollutants in at least one of the analysis years (see Appendix B-2). However, the emission increases would be quite small, as shown in Appendix B-2, and emission increases would be distributed throughout each nonattainment area.

4.3.3.8.3 Health Outcomes and Costs

Compared to Alternative 1 (No Action), the cumulative impact of Alternative 7 would result in 760 fewer mortalities and 135,560 fewer work-loss days in 2035. Cumulative health benefits would exceed non-cumulative benefits, reducing mortalities by an additional 100 cases and lost-work days by an additional 17,943 cases in 2035. In that same year, Alternative 7 would reduce health costs by $3.703 billion, an additional $374 million over non-cumulative benefits.

4.3.4 Input Scenarios

4.3.4.1 Results of the Emissions Analysis

The High Scenario analysis in this section shows that the alternatives would lead to further reductions in cumulative emissions from passenger cars and light trucks. The amount of the reductions would vary by alternative. The more restrictive High Scenario alternatives would result in greater cumulative emission reductions compared to the No Action Alternative.

4.3.4.2 Alternative 1: No Action

4.3.4.2.1 Criteria Pollutants

For the High Scenario analysis of the No Action Alternative, the CAFE standards would remain at the MY 2010 level in future years. Current trends in the levels of emissions from vehicles would continue, with emissions continuing to decline due to the EPA emission standards despite a growth in total VMT. Therefore, there would be no cumulative impacts due to future actions.

Table 4.3-7 summarizes the cumulative national criteria pollutant emissions from passenger cars and light trucks for the High Scenario No Action Alternative for each of the criteria pollutants and

analysis years. The table presents the other High Scenario alternatives (Alternatives 2 through 7) left to right in order of increasing fuel economy requirements. The No Action Alternative has the highest cumulative emissions of all the High Scenario alternatives for all criteria pollutants. Also, the High Scenario cumulative emissions are lower than the Reference Case cumulative emissions for all criteria pollutants.

Table 4.3-7

High Scenario Alternative CAFE Standards
Nationwide Criteria Pollutant Emissions from Passenger Cars and Light Trucks (tons/year)
Cumulative Effects with MY 2011-2015 Standards and Potential MY 2016-2020 Standards

	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt. 7
Pollutant and Year	**No Action**	**25% Below Optimized**	**Optimized**	**25% Above Optimized**	**50% Above Optimized**	**Total Costs Equal Total Benefits**	**Technology Exhaustion**
CO							
2015	18,861,709	18,819,939	18,808,141	18,754,373	18,733,183	18,676,707	18,198,144
2020	16,619,854	16,415,502	16,425,986	16,213,912	16,097,921	15,910,952	14,057,662
2025	16,403,499	16,020,001	16,080,959	15,651,538	15,408,409	15,050,866	11,706,038
2035	17,713,991	17,102,067	17,249,166	16,551,203	16,107,699	15,482,276	10,338,916
NO_x							
2015	2,148,052	2,144,324	2,143,260	2,141,447	2,140,565	2,139,441	2,131,148
2020	1,530,682	1,508,585	1,505,911	1,498,908	1,495,495	1,491,055	1,454,741
2025	1,292,315	1,245,534	1,242,387	1,227,626	1,219,549	1,209,840	1,131,426
2035	1,228,251	1,147,887	1,145,748	1,120,053	1,102,988	1,082,932	940,625
$PM_{2.5}$							
2015	74,919	74,510	74,386	74,356	74,275	74,100	73,596
2020	75,571	73,546	73,270	73,293	72,959	72,684	71,661
2025	79,258	75,295	74,870	74,948	74,361	74,025	73,132
2035	89,447	83,017	82,423	82,542	81,642	81,247	80,549
SO_x							
2015	194,594	192,140	191,511	190,550	189,957	189,131	183,315
2020	199,331	186,854	185,311	183,031	181,350	179,659	167,666
2025	210,380	185,622	183,100	179,565	176,762	174,331	159,282
2035	238,442	198,158	194,471	189,553	185,397	182,149	164,654
VOCs							
2015	2,107,357	2,098,520	2,096,656	2,089,966	2,087,196	2,082,243	2,036,807
2020	1,738,318	1,697,234	1,694,410	1,675,994	1,667,362	1,653,626	1,527,120
2025	1,646,853	1,567,100	1,564,214	1,531,051	1,514,867	1,490,440	1,275,275
2035	1,709,979	1,575,147	1,574,616	1,518,089	1,486,823	1,440,609	1,073,784

Table 4.3-8 lists the net change in nationwide cumulative emissions from passenger cars and light trucks for each alternative and analysis year for the High Scenario. The table presents Alternatives 1 through 7 left to right in order of increasing fuel economy requirements. In Table 4.3-8, the nationwide cumulative emissions reductions tend to increase from left to right, reflecting the increasing fuel economy requirements that are assumed for the High Scenario.

Table 4.3-8

High Scenario Alternative CAFE Standards
Nationwide Criteria Pollutant Emission Changes from Passenger Cars and Light Trucks (tons/year)
Cumulative Effects with MY 2011-2015 Standards and Potential MY 2016-2020 Standards a/

Pollutant and Year	Alt. 1 No Action b/	Alt. 2 25% Below Optimized	Alt. 3 Optimized	Alt. 4 25% Above Optimized	Alt. 5 50% Above Optimized	Alt. 6 Total Costs Equal Total Benefits	Alt. 7 Technology Exhaustion
CO							
2015	0	-41,769	-53,567	-107,336	-128,526	-185,002	-663,565
2020	0	-204,352	-193,867	-405,942	-521,932	-708,902	-2,562,191
2025	0	-383,498	-322,540	-751,962	-995,090	-1,352,633	-4,697,461
2035	0	-611,923	-464,825	-1,162,788	-1,606,291	-2,231,714	-7,375,075
NO_x							
2015	0	-3,727	-4,792	-6,605	-7,487	-8,610	-16,904
2020	0	-22,097	-24,771	-31,774	-35,187	-39,627	-75,941
2025	0	-46,781	-49,927	-64,688	-72,766	-82,475	-160,889
2035	0	-80,363	-82,503	-108,198	-125,262	-145,319	-287,626
$PM_{2.5}$							
2015	0	-408	-532	-562	-643	-819	-1,322
2020	0	-2,026	-2,302	-2,278	-2,612	-2,888	-3,910
2025	0	-3,964	-4,389	-4,311	-4,898	-5,234	-6,126
2035	0	-6,430	-7,024	-6,905	-7,805	-8,200	-8,898
SO_x							
2015	0	-2,455	-3,084	-4,045	-4,637	-5,463	-11,280
2020	0	-12,477	-14,020	-16,300	-17,980	-19,671	-31,665
2025	0	-24,758	-27,281	-30,816	-33,619	-36,050	-51,098
2035	0	-40,284	-43,971	-48,889	-53,046	-56,294	-73,788
VOCs							
2015	0	-8,838	-10,701	-17,391	-20,161	-25,115	-70,550
2020	0	-41,083	-43,908	-62,324	-70,955	-84,691	-211,198
2025	0	-79,753	-82,639	-115,802	-131,986	-156,414	-371,578
2035	0	-134,832	-135,363	-191,890	-223,156	-269,370	-636,195

a/ Negative emissions changes indicate reductions; positive emissions changes are increases.
b/ Emissions changes for the No Action Alternative are shown as zero because the No Action Alternative is the baseline to which the emissions for the other alternatives are compared.

4.3.4.2.2 Air Toxics

With the No Action Alternative, the CAFE standards would remain at the MY 2010 level in future years. As with the criteria pollutants, the High Scenario analysis indicates that current trends in the levels of air toxics emissions from vehicles would continue, with emissions continuing to decline due to the EPA emission standards despite a growth in total VMT. Exceptions to this trend are emissions of benzene and formaldehyde, which increase in 2035 over 2025 levels with the No Action Alternative. Further, with current trends, emissions of diesel particulate matter (DPM) increase in every analysis year with the No Action Alternative. The High Scenario analysis of Alternative 1 (No Action) would result in no other increase or decrease in cumulative toxic air pollutant emissions in nonattainment and maintenance areas throughout the United States.

Table 4.3-9 summarizes the High Scenario total national cumulative emissions of air toxics from passenger cars and light trucks with the No Action Alternative for each pollutant and analysis year.

Unlike with the criteria pollutants, the No Action Alternative does not have the highest cumulative emissions of all the alternatives for all toxic air pollutants. Table 4.3-9 shows increases for acrolein with Alternatives 2 through 7 because data on upstream emissions reductions were not available. The cumulative emissions for acrolein in Table 4.3-9 reflect only the increases due to the rebound effect and technology changes that manufacturers would introduce in response to CAFE standards. Because the upstream emissions reductions result from the decline in the amount of fuel processed, it is reasonable that upstream acrolein emissions should decrease as the upstream emissions for other pollutants do. Thus, the cumulative acrolein emissions given in Table 4.3.9 are an upper bound estimate.

Table 4.3-9

High Scenario Alternative CAFE Standards
Nationwide Toxic Air Pollutant Emissions from Passenger Cars and Light Trucks (tons/year)
Cumulative Effects with MY 2011-2015 Standards and Potential MY 2016-2020 Standards

Pollutant and Year	Alt. 1 No Action	Alt. 2 25% Below Optimized	Alt. 3 Optimized	Alt. 4 25% Above Optimized	Alt. 5 50% Above Optimized	Alt. 6 Total Costs Equal Total Benefits	Alt. 7 Technology Exhaustion
Acetaldehyde							
2015	11,165	11,174	11,177	11,176	11,180	11,194	11,268
2020	8,634	8,649	8,648	8,631	8,648	8,666	8,808
2025	7,613	7,619	7,623	7,576	7,593	7,603	7,673
2035	7,364	7,351	7,372	7,282	7,278	7,255	7,153
Acrolein a/							
2015	530	535	536	540	542	546	583
2020	393	413	414	425	433	444	552
2025	336	373	372	393	406	424	591
2035	315	374	374	406	424	450	680
Benzene							
2015	60,125	59,974	59,937	59,809	59,755	59,640	58,661
2020	47,458	46,725	46,690	46,274	46,045	45,686	42,348
2025	42,930	41,487	41,498	40,686	40,211	39,533	33,465
2035	42,626	40,169	40,301	38,917	37,990	36,721	26,566
1,3-butadiene							
2015	6,134	6,134	6,133	6,133	6,134	6,134	6,141
2020	4,698	4,689	4,687	4,683	4,679	4,672	4,625
2025	4,092	4,067	4,069	4,053	4,037	4,016	3,850
2035	3,885	3,833	3,846	3,810	3,766	3,713	3,331
Diesel particulate matter (DPM)							
2015	88,405	87,306	86,998	86,858	86,658	86,379	85,732
2020	90,085	84,216	83,324	83,159	82,584	82,197	81,614
2025	94,782	82,884	81,373	81,199	80,232	79,801	80,139
2035	107,203	87,624	85,380	85,166	83,729	83,295	84,904
Formaldehyde							
2015	16,197	16,228	16,236	16,264	16,282	16,345	16,789
2020	12,928	12,999	12,980	13,047	13,146	13,291	14,660
2025	11,716	11,792	11,753	11,866	12,031	12,252	14,332
2035	11,694	11,783	11,730	11,897	12,127	12,433	15,281

a/ Data on upstream emissions reductions were not available for acrolein. Thus, the emissions for acrolein reflect only the change in tailpipe emissions.

High Scenario cumulative emissions of formaldehyde are lowest under the No Action Alternative. In contrast, cumulative emissions of benzene, DPM, and 1,3-butadiene are highest in the No Action Alternative, and are generally higher for the less restrictive alternatives than the more restrictive alternatives. An exception is 1,3-butadiene in 2015 under Alternative 7. Cumulative emissions of acetaldehyde are highest for Alternative 7 except in 2035.

Table 4.3-10 lists the net change in High Scenario cumulative nationwide emissions from passenger cars and light trucks in relation to the No Action Alternative for each air toxic pollutant and analysis year. The High Scenario results for Alternatives 2 through 7 are presented from left to right in order of increasing fuel economy requirements. In Table 4.3-10, the nationwide emissions reductions or increases tend to become greater from left to right, reflecting the increasing fuel economy requirements that are assumed under successive alternatives, except for the cases noted above.

Table 4.3-10

High Scenario Alternative CAFE Standards
Nationwide Changes in Toxic Air Pollutant Emissions from Passenger Cars and Light Trucks (tons/year)
Cumulative Effects with MY 2011-2015 Standards and Potential MY 2016-2020 Standards a/

Pollutant and Year	Alt. 1 No Action b/	Alt. 2 25% Below Optimized	Alt. 3 Optimized	Alt. 4 25% Above Optimized	Alt. 5 50% Above Optimized	Alt. 6 Total Costs Equal Total Benefits	Alt. 7 Technology Exhaustion
Acetaldehyde							
2015	0	9	11	11	15	29	103
2020	0	16	15	-3	14	33	174
2025	0	6	11	-37	-20	-10	60
2035	0	-13	8	-82	-86	-109	-211
Acrolein c/							
2015	0	5	6	10	12	16	53
2020	0	20	20	32	39	50	158
2025	0	37	36	57	70	88	255
2035	0	59	58	90	109	135	365
Benzene							
2015	0	-150	-187	-316	-369	-485	-1,463
2020	0	-733	-767	-1,184	-1,413	-1,771	-5,110
2025	0	-1,443	-1,432	-2,244	-2,719	-3,397	-9,465
2035	0	-2,456	-2,324	-3,709	-4,636	-5,905	-16,060
1,3-butadiene							
2015	0	0	-1	-1	0	-1	7
2020	0	-10	-11	-16	-19	-26	-73
2025	0	-26	-24	-40	-55	-76	-242
2035	0	-52	-39	-75	-120	-172	-555
Diesel particulate matter (DPM)							
2015	0	-1,099	-1,407	-1,547	-1,747	-2,025	-2,673
2020	0	-5,868	-6,761	-6,926	-7,500	-7,888	-8,471
2025	0	-11,898	-13,408	-13,583	-14,550	-14,981	-14,643
2035	0	-19,579	-21,823	-22,036	-23,474	-23,908	-22,299
Formaldehyde							
2015	0	31	39	66	85	148	592
2020	0	72	52	119	218	363	1,732
2025	0	76	37	150	315	536	2,616
2035	0	89	36	203	433	739	3,587

a/ Negative emissions changes indicate reductions; positive emissions changes are increases.
b/ Emissions changes for the No Action Alternative are shown as zero because the No Action Alternative is the baseline to which the emissions for the other alternatives are compared.
c/ Data on upstream emissions reductions were not available for acrolein. Thus, the emissions for acrolein reflect only the change in tailpipe emissions.

4.3.4.2.3 Health Outcomes and Costs

With the No Action Alternative (Alternative 1), the CAFE standards would remain at the MY 2010 level in future years. Current trends in the levels of criteria pollutants and air toxics emissions from vehicles would continue, with emissions continuing to decline due to the EPA emission standards despite an increase in total VMT. The human health effects and health-related costs that occur under current trends would continue, and are expected to decline in the future as a result of declines in pollutant emissions. The No Action Alternative under the High Scenario would result in no other increase or decrease in human health effects and health-related costs.

Table 4.3-11 list the net changes in health outcomes due to High Scenario analysis of cumulative emissions in each analysis year. Alternatives 1 through 7 are presented from left to right in order of increasing fuel economy requirements. The health impacts of vehicle emissions decrease for nearly all alternatives compared to the No Action Alternative and decrease successively in each analysis year.

Table 4.3-11

High Scenario Alternative CAFE Standards
Nationwide Changes in Health Outcomes from Criteria Air Pollutant Emissions from Passenger Cars and Light Trucks (cases/year)
Cumulative Effects with MY 2011-2015 Standards and Potential MY 2016-2020 Standards a/

Health Outcome and Year	Alt. 1 No Action b/	Alt. 2 25% Below Optimized	Alt. 3 Optimized	Alt. 4 25% Above Optimized	Alt. 5 50% Above Optimized	Alt. 6 Total Costs Equal Total Benefits	Alt. 7 Technology Exhaustion
Mortality (ages 30 and older)							
2015	0	-31	-41	-43	-49	-63	-101
2020	0	-155	-176	-175	-200	-221	-300
2025	0	-304	-336	-330	-375	-401	-470
2035	0	-493	-539	-529	-598	-629	-682
Chronic bronchitis							
2015	0	-27	-35	-37	-43	-55	-88
2020	0	-135	-153	-152	-174	-193	-261
2025	0	-264	-293	-287	-327	-349	-408
2035							
Emergency room visits for asthma							
2015	0	-7	-9	-9	-10	-13	-21
2020	0	-32	-37	-36	-42	-46	-63
2025	0	-63	-70	-69	-78	-84	-98
2035	0	-103	-112	-110	-125	-131	-142
Work-loss days							
2015	0	-5,582	-7,277	-7,686	-8,790	-11,191	-18,070
2020	0	-27,684	-31,458	-31,134	-35,698	-39,466	-53,440
2025	0	-54,173	-59,978	-58,915	-66,935	-71,529	-83,728
2035	0	-87,883	-96,001	-94,366	-106,665	-112,073	-121,611

a/ Negative changes indicate reductions; positive emissions changes are increases.
b/ Changes in health outcome for the No Action Alternative are shown as zero because the No Action Alternative is the baseline to which the emissions for the other alternatives are compared.

The economic value of health impacts would vary proportionately with changes in health outcomes under the methodology defined in Section 3.3.2.4.2. The economic impacts analyzed here are the result of changes in ambient particulate matter (PM) and ozone concentrations as caused by changes in precursor criteria pollutants NO_x, VOCs, SO_2, and $PM_{2.5}$. Alternative 1 (No Action) would result in no other change in health-related costs throughout the United States, as compared to current trends.

Table 4.3-12 lists the nationwide changes in health costs in the High Scenario analysis of cumulative emissions from passenger cars and light trucks. Results for each analysis year are shown for the No Action Alternative in the left column, and for other alternatives from left to right in order of increasing fuel economy requirements. As with health outcomes, the economic impacts of each alternative decrease across nearly all successive alternatives and all successive years, compared to the health costs of emissions with the No Action Alternative.

Table 4.3-12

High Scenario Alternative CAFE Standards
Nationwide Changes in Health Costs from Criteria Air Pollutant Emissions from Passenger Cars and Light Trucks (U.S. million dollars/year)
Cumulative Effects with MY 2011-2015 Standards and Potential MY 2016-2020 Standards a/

	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt. 7
Year	No Action b/	25% Below Optimized	Optimized	25% Above Optimized	50% Above Optimized	Total Costs Equal Total Benefits	Technology Exhaustion
2015	0	-50	-64	-84	-96	-112	-223
2020	0	-374	-420	-505	-559	-621	-1,079
2025	0	-763	-829	-988	-1,097	-1,209	-2,019
2035	0	-1,273	-1,351	-1,610	-1,809	-2,010	-3,322

a/ Negative changes indicate economic benefit; positive emissions changes are economic costs.
b/ Changes for the No Action Alternative are shown as zero because the No Action Alternative is the baseline to which the emissions for the other alternatives are compared.

4.3.4.3 Alternative 2: 25 Percent Below Optimized

4.3.4.3.1 Criteria Pollutants

With the High Scenario analysis for the 25 Percent Below Optimized Alternative (Alternative 2), the CAFE standards would require increased fuel economy compared to the No Action Alternative. The 25 Percent Below Optimized Alternative would increase fuel economy less than would Alternatives 3 through 7. Cumulative nationwide emissions of all criteria pollutants would be reduced compared to the Reference Case; the magnitude of the reductions increase with analysis year. Reductions in cumulative emissions under Alternative 2 are less than reductions under successive alternatives, except for CO and $PM_{2.5}$ for which the reductions are slightly less for Alternative 3.

Cumulative emissions in individual nonattainment areas could follow different patterns than nationwide emissions. Emissions of criteria pollutants decrease in part because the reduction in upstream emissions, among other effects related to technology changes introduced by manufacturers in response to CAFE standards, more than offsets the increase in VMT and emissions due to the rebound effect in every nonattainment area. While cumulative emissions of CO, NO_x, SO_x, and VOCs decrease in each nonattainment area for all years, emissions of $PM_{2.5}$ are projected to increase in some nonattainment areas. Appendix B-2 contains tables that list the emission reductions for each nonattainment area.

In Alternative 2, the reduction in cumulative emissions under the High Scenario is greater than that under the Reference Case, for each criteria pollutant and year.

4.3.4.3.2 Air Toxics

With the High Scenario analysis of the 25 Percent Below Optimized Alternative (Alternative 2), cumulative nationwide air toxics emissions would increase for some pollutants and decrease for others, as compared to the No Action Alternative. Benzene, 1,3-butadiene, and DPM cumulative emissions would decline, with reductions increasing with analysis year. Compared to the No Action Alternative, cumulative emissions would increase for acetaldehyde (except in 2035), acrolein, and formaldehyde.

High Scenario Alternative 2 would have generally higher cumulative emissions of benzene, 1,3-butadiene, and DPM compared to Alternatives 3 through 7. High Scenario Alternative 2 would have generally lower cumulative emissions of acrolein and formaldehyde compared to Alternatives 3 through 7. Results for acetaldehyde would be mixed depending on alternative and year. Cumulative emissions with High Scenario Alternative 2 would be less than with Reference Case Alternative 2 except for acrolein in 2035 and 1,3-butadiene in 2015 and 2020.

Under High Scenario Alternative 2, many nonattainment areas would experience net increases, and some would experience net decreases, in cumulative emissions of one or more toxic air pollutants in at least one analysis year (Appendix B-2). The cumulative emission increases are quite small, as shown in Appendix B-2. Air quality impacts from these increases would not be notable because the VMT and emission increases would be distributed throughout each nonattainment area.

4.3.4.3.3 Health Outcomes and Costs

The High Scenario analysis shows a decrease in cumulative adverse health effects nationwide for the Alternative 2 compared to Alternative 1 (No Action). These reductions primarily reflect the projected $PM_{2.5}$ reductions, as $PM_{2.5}$ tends to be the largest contributor to adverse health effects. Compared to Alternative 1 (No Action), the cumulative impact of Alternative 2 would result in 493 fewer mortalities and 87,883 fewer work-loss days in 2035. Cumulative health benefits are greater under the High Scenario than under the Reference Case, reducing mortalities by an additional 177 cases and lost-work days by an additional 31,590 cases in 2035. In that same year, Alternative 2 would reduce health costs by $1.273 billion, an additional $593 million compared to Reference Case benefits.

4.3.4.4 Alternative 3: Optimized

4.3.4.4.1 Criteria Pollutants

With the High Scenario analysis of Optimized Alternative (Alternative 3), the CAFE standards would require increased fuel economy compared to Alternatives 1 and 2, but less than Alternative 4 through 7. Reductions in cumulative nationwide emissions are similar to reductions under Alternative 2. Cumulative emissions reductions of CO and $PM_{2.5}$ are slightly less than under Alternative 2. In other cases, the cumulative emissions reductions are greater than under Alternative 2.

Cumulative emissions in individual nonattainment areas could follow different patterns than nationwide emissions. Emissions of criteria pollutants decrease in part because the reduction in upstream emissions, among other effects related to technology changes introduced by manufacturers in response to CAFE standards, more than offsets the increase in VMT and emissions due to the rebound effect in every nonattainment area. While cumulative emissions of CO, NO_x, SO_x, and VOCs decrease in each

nonattainment area for all years, emissions of $PM_{2.5}$ are projected to increase in some nonattainment areas. Appendix B-2 contains tables that list the emission reductions for each nonattainment area.

In Alternative 3, the reduction in cumulative emissions under the High Scenario is greater than that under the Reference Case, for each criteria pollutant and year.

4.3.4.4.2 Air Toxics

Under High Scenario Alternative 3, nationwide cumulative emissions of benzene, 1,3-butadiene, and DPM would be lower compared to the High Scenario No Action Alternative. Nationwide cumulative emissions would be higher for acetaldehyde, acrolein, and formaldehyde compared to the High Scenario No Action Alternative.

High Scenario Alternative 3 would have generally higher emissions than would High Scenario Alternatives 4 through 7 for benzene, butadiene, and DPM. High Scenario Alternative 3 would have generally lower emissions than would High Scenario Alternatives 4-7 for acrolein and formaldehyde, and mixed results for acetaldehyde depending on alternative and year. Cumulative emissions under the High Scenario are lower than those under the Reference Case for Alternative 3 (except for acrolein in 2035).

Under High Scenario Alternative 3, many nonattainment areas would experience net increases, and some would experience net decreases, in cumulative emissions of one or more toxic air pollutants in at least one analysis year (Appendix B-2). The cumulative emission increases are quite small, as shown in Appendix B-2. Air quality impacts from these increases would not be notable because the VMT and emission increases would be distributed throughout each nonattainment area.

4.3.4.4.3 Health Outcomes and Costs

The High Scenario analysis shows a decrease in cumulative adverse health effects nationwide for Alternative 3 compared to Alternative 1 (No Action). These reductions primarily reflect the projected $PM_{2.5}$ reductions, because $PM_{2.5}$ tends to be the largest contributor to adverse health effects. Compared to Alternative 1 (No Action), the cumulative impact of Alternative 3 would result in 539 fewer mortalities and 96,001 fewer work-loss days in 2035. Cumulative health benefits are greater under the High Scenario than under the Reference Case, reducing mortalities by an additional 214 cases and lost-work days by an additional 38,062 cases in 2035. In that same year, Alternative 3 would reduce health costs by $1.351 billion, an additional $657 million compared to Reference Case benefits.

4.3.4.5 Alternative 4: 25 Percent Above Optimized

4.3.4.5.1 Criteria Pollutants

For the High Scenario analysis of the 25 Percent Above Optimized Alternative (Alternative 4), the CAFE standards would require increased fuel economy compared to Alternatives 1 through 3, but less than Alternatives 5 through 7. Cumulative nationwide emissions of all criteria pollutants for Alternative 4 would be reduced compared to Alternative 3. Compared to the No Action Alternative, the reductions increase for all analysis years.

Cumulative emissions in individual nonattainment areas could follow different patterns than nationwide emissions. Emissions of criteria pollutants decrease in part because the reduction in upstream emissions, among other effects related to technology changes introduced by manufacturers in response to CAFE standards, more than offsets the increase in VMT and emissions due to the rebound effect in every nonattainment area. While cumulative emissions of CO, NO_x, SO_x, and VOCs decrease in each

nonattainment area for all years, emissions of $PM_{2.5}$ are projected to increase in some nonattainment areas Appendix B-2 contains tables that list the emission reductions for each nonattainment area.

In Alternative 4, the reduction in cumulative emissions under the High Scenario is greater than that under the Reference Case, for each criteria pollutant and year.

4.3.4.5.2 Air Toxics

Under High Scenario Alternative 4, nationwide cumulative emissions of acetaldehyde (except in 2015), benzene, 1,3-butadiene, and DPM would be lower compared to the High Scenario No Action Alternative. Nationwide cumulative emissions would be higher for acetaldehyde (in 2015), acrolein, and formaldehyde compared to the High Scenario No Action Alternative.

High Scenario Alternative 4 would have generally higher emissions than would High Scenario Alternatives 5 through 7 for acetaldehyde (in 2035), benzene, 1,3-butadiene, and DPM. High Scenario Alternative 3 would have generally lower emissions than would High Scenario Alternatives 5 through 7 for acetaldehyde (except in 2035), acrolein, and formaldehyde. Cumulative emissions under the High Scenario are lower than those under the Reference Case for Alternative 4 (except for acrolein in 2025 and 2035 and 1,3-butadiene in 2015).

Under High Scenario Alternative 4, many nonattainment areas would experience net increases, and some would experience net decreases, in cumulative emissions of one or more toxic air pollutants in at least one analysis year (Appendix B-2). The cumulative emission increases are quite small, as shown in Appendix B-2. Air quality impacts from these increases would not be notable because the VMT and emission increases would be distributed throughout each nonattainment area.

4.3.4.5.3 Health Outcomes and Costs

The High Scenario analysis shows a decrease in cumulative adverse health effects nationwide for Alternative 4 compared to Alternative 1 (No Action). These reductions primarily reflect the projected $PM_{2.5}$ reductions, because $PM_{2.5}$ tends to be the largest contributor to adverse health effects. Compared to Alternative 1 (No Action), the cumulative impact of Alternative 4 would result in 529 fewer mortalities and 94,366 fewer work-loss days in 2035. Cumulative health benefits are greater under the High Scenario than under the Reference Case, reducing mortalities by an additional 141 cases and lost-work days by an additional 25,256 cases in 2035. In that same year, Alternative 4 would reduce health costs by $1.610 billion, an additional $739 million compared to Reference Case benefits.

4.3.4.6 Alternative 5: 50 Percent Above Optimized

4.3.4.6.1 Criteria Pollutants

For the High Scenario analysis of the 50 Percent Above Optimized Alternative (Alternative 5), the CAFE standards would require increased fuel economy compared to Alternatives 1 through 4, but less than Alternatives 6 and 7. Cumulative nationwide emissions of all criteria pollutants for Alternative 5 would be reduced compared to Alternative 4. Compared to the No Action Alternative, the percent reductions increase for all analysis years.

Cumulative emissions in individual nonattainment areas could follow different patterns than nationwide emissions. Emissions of criteria pollutants decrease in part because the reduction in upstream emissions, among other effects related to technology changes introduced by manufacturers in response to CAFE standards, more than offsets the increase in VMT and emissions due to the rebound effect in every

nonattainment area. While cumulative emissions of CO, NO_x, SO_x, and VOCs decrease in each nonattainment area for all years, emissions of $PM_{2.5}$ are projected to increase in some nonattainment areas. Appendix B-2 contains tables that list the emission reductions for each nonattainment area.

In Alternative 5, the reduction in cumulative emissions under the High Scenario is greater than that under the Reference Case, for each criteria pollutant and year.

4.3.4.6.2 Air Toxics

Under High Scenario Alternative 5, nationwide cumulative emissions of acetaldehyde (in 2025 and 2035), benzene, 1,3-butadiene, and DPM would be lower compared to the High Scenario No Action Alternative. Nationwide cumulative emissions would be higher for acetaldehyde (in 2015 and 2020), acrolein, and formaldehyde compared to the High Scenario No Action Alternative.

High Scenario Alternative 5 would have higher emissions than would High Scenario Alternatives 6 and 7 for acetaldehyde (in 2035), benzene, 1,3-butadiene (except Alternative 7 in 2015), and DPM (except Alternative 7 in 2035). High Scenario Alternative 5 would have lower emissions than would High Scenario Alternatives 6 and 7 for acetaldehyde (except in 2035), acrolein, 1,3-butadiene (Alternative 7 in 2015 only), and DPM (Alternative 7 in 2035 only), and formaldehyde. Cumulative emissions under the High Scenario are lower than cumulative emissions under the Reference Case for Alternative 5 (except for acrolein in 2025 and 2035, and 1,3-butadiene in 2015).

Under High Scenario Alternative 5, many nonattainment areas would experience net increases, and some would experience net decreases, in cumulative emissions of one or more toxic air pollutants in at least one analysis year (Appendix B-2). The cumulative emission increases are quite small, as shown in Appendix B-2. Air quality impacts from these increases would not be notable because the VMT and emission increases would be distributed throughout each nonattainment area.

4.3.4.6.3 Health Outcomes and Costs

The High Scenario analysis shows a decrease in cumulative adverse health effects nationwide for the Alternative 5 compared to Alternative 1 (No Action). These reductions primarily reflect the projected $PM_{2.5}$ reductions, because $PM_{2.5}$ tends to be the largest contributor to adverse health effects. Compared to Alternative 1 (No Action), the cumulative impact of Alternative 5 would result in 598 fewer mortalities and 106,665 fewer work-loss days in 2035. Cumulative health benefits are greater under the High Scenario than under the Reference Case, reducing mortalities by an additional 315 cases and lost-work days by an additional 56,220 cases in 2035. In that same year, Alternative 5 would reduce health costs by $1.809 billion, an additional $782 million compared to Reference Case benefits.

4.3.4.7 Alternative 6: Total Costs Equal Total Benefits

4.3.4.7.1 Criteria Pollutants

For the High Scenario analysis of the Total Costs Equal Total Benefits Alternative (Alternative 6), the CAFE standards would require increased fuel economy compared to Alternatives 1 through 5, but less than Alternative 7. Cumulative nationwide emissions of all criteria pollutants for Alternative 6 would be reduced compared to Alternative 5. Compared to the No Action Alternative, the percent reductions increase for all analysis years.

Cumulative emissions in individual nonattainment areas might follow different patterns than nationwide emissions. Emissions of criteria pollutants decrease in part because the reduction in upstream

emissions, among other effects related to technology changes introduced by manufacturers in response to CAFE standards, more than offsets the increase in VMT and emissions due to the rebound effect in every nonattainment area. While cumulative emissions of CO, NO_x, SO_x, and VOCs decrease in each nonattainment area for all years, emissions of $PM_{2.5}$ are projected to increase in some nonattainment areas. Appendix B-2 contains tables that list the emission reductions for each nonattainment area.

In Alternative 6, the reduction in cumulative emissions under the High Scenario is greater than that under the Reference Case, for each criteria pollutant and year.

4.3.4.7.2 Air Toxics

Under High Scenario Alternative 6, nationwide cumulative emissions of acetaldehyde (in 2025 and 2035), benzene, 1,3-butadiene, and DPM would be lower compared to the High Scenario No Action Alternative. Nationwide cumulative emissions with High Scenario Alternative 6 would be higher for acetaldehyde (in 2015 and 2020), acrolein, and formaldehyde compared to the High Scenario No Action Alternative.

High Scenario Alternative 6 would have higher emissions than would High Scenario Alternative 7 for acetaldehyde (in 2035), benzene, 1,3-butadiene (except in 2015), and DPM (except in 2025 and 2035). High Scenario Alternative 6 would have lower emissions than would High Scenario Alternative 7 for acetaldehyde (except in 2035), acrolein, 1,3-butadiene (in 2015 only), and DPM (in 2025 and 2035), and formaldehyde. Cumulative emissions under the High Scenario are lower than cumulative emissions under the Reference Case for Alternative 6 (except for acrolein in 2020-2035 and 1,3-butadiene in 2015).

Under High Scenario Alternative 6, many nonattainment areas would experience net increases, and some would experience net decreases, in cumulative emissions of one or more toxic air pollutants in at least one analysis year (Appendix B-2). The cumulative emission increases are quite small, as shown in Appendix B-2. Air quality impacts from these increases would not be notable because the VMT and emission increases would be distributed throughout each nonattainment area.

4.3.4.7.3 Health Outcomes and Costs

The High Scenario analysis shows a decrease in cumulative adverse health effects nationwide for Alternative 6 compared to Alternative 1 (No Action). These reductions primarily reflect the projected $PM_{2.5}$ reductions, because $PM_{2.5}$ tends to be the largest contributor to adverse health effects. Compared to Alternative 1 (No Action), the cumulative impact of Alternative 6 would result in 629 fewer mortalities and 112,073 fewer work-loss days in 2035. Cumulative health benefits are greater under the High Scenario than under the Reference Case, reducing mortalities by an additional 215 cases and lost-work days by an additional 38,340 cases in 2035. In that same year, Alternative 6 would reduce health costs by $2.010 billion, an additional $976 million compared to Reference Case benefits.

4.3.4.8 Alternative 7: Technology Exhaustion

4.3.4.8.1 Criteria Pollutants

For the High Scenario analysis of the Technology Exhaustion Alternative (Alternative 7), the CAFE standards would require higher fuel economy than for all other alternatives. Cumulative nationwide emissions of all criteria pollutants for Alternative 7 would be reduced compared to Alternative 6. Compared to the No Action Alternative, the percent reductions increase for all analysis years. Cumulative emissions reductions would be greater in Alternative 7 than in any other alternative.

Cumulative emissions in individual nonattainment areas could follow different patterns than nationwide emissions. Emissions of criteria pollutants decrease in part because the reduction in upstream emissions, among other effects related to technology changes introduced by manufacturers in response to CAFE standards, more than offsets the increase in VMT and emissions due to the rebound effect in every nonattainment area. While cumulative emissions of CO, NO_x, SO_x, and VOCs decrease in each nonattainment area for all years, emissions of $PM_{2.5}$ are projected to increase in some nonattainment areas. Appendix B-2 contains tables that list the emission reductions for each nonattainment area.

In Alternative 7, the reduction in cumulative emissions under the High Scenario is greater than or equal to that under the Reference Case, for each criteria pollutant and year.

4.3.4.8.2 Air Toxics

Under High Scenario Alternative 7, nationwide cumulative emissions of benzene, 1,3-butadiene (except in 2015), and DPM would be lower compared to the High Scenario No Action Alternative. Nationwide cumulative emissions with High Scenario Alternative 7 would be higher for acetaldehyde (except in 2035), acrolein, and formaldehyde compared to the High Scenario No Action Alternative.

All cumulative air toxics emissions under the High Scenario are lower than or equivalent to cumulative emissions under the Reference Case for Alternative 7.

Under High Scenario Alternative 7, some nonattainment areas would experience net increases, and some would experience net decreases, in emissions of one or more toxic air pollutants in at least one analysis year (Appendix B-2). The emission increases are quite small, as shown in Appendix B-2. Potential air quality impacts from these increases would not be notable because the VMT and emission increases would be distributed throughout each nonattainment area.

4.3.4.8.3 Health Outcomes and Costs

The High Scenario analysis shows a decrease in cumulative adverse health effects nationwide for Alternative 7 compared to Alternative 1 (No Action). These reductions primarily reflect the projected $PM_{2.5}$ reductions, because $PM_{2.5}$ tends to be the largest contributor to adverse health effects. Compared to Alternative 1 (No Action), the cumulative impact of Alternative 7 would result in 682 fewer mortalities and 121,611 fewer work-loss days in 2035. In that same year, Alternative 7 would reduce health costs by $3.320 billion.

Unlike other Alternatives, cumulative health benefits are less under the High Scenario than under the Reference Case, increasing mortalities by 78 cases and lost-work days by 13,949 cases in 2035. Similarly, health costs would be $381 million greater under the High Scenario than under the Reference Case.

4.3.4.9 Mid-1 and Mid-2 Scenarios

Compared to the Reference Case, total cumulative emissions of criteria pollutants under the Mid-1 Scenario were lower for all alternatives. For toxic air pollutants, compared to the Reference Case, total cumulative emissions under the Mid-1 Scenario were lower except for emissions of acrolein and 1,3-butadiene for some alternatives and years. The cumulative emissions differences between the Reference Case and the Mid-1 Scenario reflect the differences in the forecasted levels of fuel economy, VMT, and diesel vehicle share of the vehicle fleet.

Compared to the Reference Case, total cumulative emissions of criteria pollutants under the Mid-2 Scenario were lower for all alternatives. For toxic air pollutants, compared to the Reference Case, total cumulative emissions under the Mid-2 Scenario were lower except for emissions of acrolein with Alternative 6 in 2035. The cumulative emissions differences between the Reference Case and the Mid-2 Scenario reflect the differences in the forecasted levels of fuel economy, VMT, and diesel vehicle share of the vehicle fleet.

Cumulative emissions of criteria pollutants would be generally higher with the Mid-2 Scenario than with the Mid-1 Scenario for Alternatives 2 through 6, and equivalent for Alternative 7. Cumulative emissions of toxic air pollutants would be generally higher with the Mid-2 Scenario than with the Mid-1 Scenario for benzene, 1,3-butadiene, and DPM for Alternatives 2 through 6. Cumulative emissions of toxic air pollutants would be generally lower with the Mid-2 Scenario than with the Mid-1 Scenario for acetaldehyde, acrolein, and formaldehyde. Cumulative emissions of toxic air pollutants with the Mid-1 and Mid-2 Scenarios would be equivalent for Alternative 7.

Appendix B presents the full results from analysis of the Mid-1 and Mid-2 Scenarios.

4.4 CLIMATE

Although the proposed rule covers model years only up to 2015, the Energy Policy and Conservation Act (EPCA) has directed the Secretary, after consultation with the Secretary of the U.S. Department of Energy (DOE) and the Administrator of EPA, to establish separate average fuel economy standards for passenger cars and for light trucks manufactured in each model year beginning with model 2011 "to achieve a combined fuel economy average for model year 2020 of at least 35 mpg for the total fleet of passenger and non-passenger automobiles manufactured for sale in the United States for that model year" (49 United States Code [U.S.C.] § 32902(b)(2)(A)).

In April 2008, NHTSA issued a supplemental notice of public scoping providing additional guidance for participating in the scoping process and additional information about the standards and the alternatives NHTSA expected to consider in its NEPA analysis. In that notice, NHTSA stated that it would consider the cumulative impacts of the standards for MY 2011-2015 automobiles together with estimated impacts of NHTSA's historic implementation of the CAFE Program through MY 2010 and NHTSA's future CAFE rulemaking for MY 2016-2020, as prescribed by EPCA, as amended by EISA.

Again, a cumulative impact is defined as "the impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency … or person undertakes such other actions. Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time" (40 CFR § 1508.70).

This section on the cumulative impacts of the CAFE alternatives on climate covers many of the same topics as Section 3.4. However, Chapter 4 is broader than Chapter 3 because it compares foreseeable effects of both the MY 2011-2015 and future MY 2016-2020 CAFE standards to the MY 2020 levels affecting all passenger cars and light trucks built from 2020 through 2100 (Chapter 3 covers only the effects of the MY 2011-2015 standards).[1] Chapter 4 also addresses the consequences of emissions and effects on the climate system (both Section 4.4 and Section 3.4 address these topics), and the impacts of climate change on key resources (*e.g.*, freshwater resources, terrestrial ecosystems, and coastal ecosystems).

Understanding that many users of EIS documents do not read through in linear fashion, but instead focus on the sections of most interest, this section repeats some of the information in Section 3.4 with only minor modifications reflecting the slightly different scope (cumulative impacts versus the direct and indirect effects of the alternatives).

[1] Because EISA directs NHTSA to increase CAFE standards to reach a combined fleet average CAFE level of at least 35 mpg by model year 2020, MY 2016-2020 CAFE standards are reasonably foreseeable and must be accounted for when analyzing the cumulative impacts of the MY 2011-2015 CAFE standards. For each alternative, NHTSA assumed that passenger-car and light-truck CAFE standards would continue to increase over MY 2016-2020 at their average annual rate of increase over MY 2011-2015. This assumption results in passenger-car and light-truck CAFE standards under each action alternative that meet or exceed the EISA requirement of a combined fleet average of at least 35 mpg by model year 2020. NHTSA assumed further that the fuel economy standards for model year 2020 would remain in effect through the end of the analysis period. Because the CAFE standards apply to new vehicles, this assumption results in emissions reductions and fuel savings that continue to grow as new vehicles meeting the CAFE standards for MY 2020 and beyond are added to the fleet in each subsequent year, reaching their maximum values when all passenger cars and light trucks in the U.S. fleet meet these standards.

4.4.1 Introduction – Greenhouse Gases and Climate Change

A series of intensive and extensive analyses has been conducted by the IPCC, the scientific body tasked by the United Nations to evaluate the risk of human-induced climate change), the United States Climate Change Science Program (USCCSP), and many other programs sponsored by government, non-governmental organizations (NGO), and industry. Our discussion relies heavily on the most recent, thoroughly peer-reviewed, and credible assessments of global and U.S. climate change: the IPCC Fourth Assessment Report (*Climate Change 2007*), and reports by the USCCSP that include the *Scientific Assessment of the Effects of Global Change on the United States* and Synthesis and Assessment Products (SAPs). These sources and the studies they review are frequently quoted throughout this FEIS. Because new evidence is continuously emerging on the subject of climate change impacts, the discussions on climate impacts in this FEIS also draw on more recent studies, where possible.

Global climate change refers to long-term fluctuations in global surface temperatures, precipitation, ice cover, sea levels, cloud cover, ocean temperatures and currents, and other climatic conditions. Scientific research has shown that, in the past century, Earth's surface temperature and sea levels have risen, and most scientists attribute this to GHGs released by human activities, primarily the combustion of fossil fuels. The IPCC recently asserted that, "Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations" (IPCC 2007c).

The primary GHGs – CO_2, methane (CH_4), and nitrous oxide (N_2O) – are created by both natural and human activities. Human activities that emit GHGs to the atmosphere include the combustion of fossil fuels, industrial processes, solvent use, land use change and forestry, agricultural production, and waste management. These gases trap heat in Earth's atmosphere, changing the climate, which then impacts resources such as ecosystems, water resources, agriculture, forests, and human health. As the world population grows and developing countries industrialize, fossil fuel use and resulting GHG emissions and their concentrations in the atmosphere are expected to grow substantially over the next century. For a more in-depth discussion of the science of climate change, *see* Section 3.4.1.

4.4.2 Affected Environment

The affected environment can be characterized in terms of GHG emissions and climate. Section 3.4.2 provides a discussion of both topics, including a description of conditions in both the United States and the global environment. Because there is no distinction between the affected environment for purposes of the direct/indirect effects analysis and the cumulative impacts analysis, the reader is referred to Section 3.4.1.

4.4.3 Methodology

The methodology used to characterize the effects of the alternative CAFE standards on climate has two key elements:

1. Analyzing the effects of the alternatives on GHG emissions, and
2. Analyzing how the GHG emissions affect the climate system (climate effects).

Each element is discussed below.

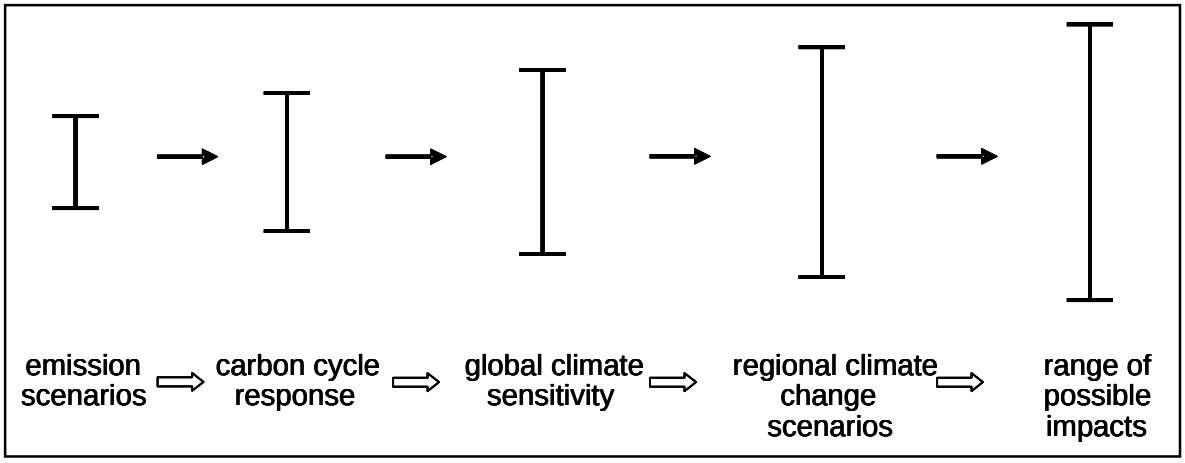
This FEIS expresses results for each alternative in terms of the environmental attribute being characterized (emissions, CO_2 concentrations, temperature, precipitation, sea level). It also presents the

change between the No Action Alternative and each of the other six alternatives to illustrate the differences in environmental impacts across the CAFE alternatives.

The methods used to characterize emissions and climate change impacts involve considerable uncertainty. Sources of uncertainty include the pace and effects of technology change in both the transportation sector and other sectors that emit GHGs; changes in the future fuel supply that could affect emissions; the sensitivity of climate to increased GHG concentrations; the rate of change in the climate system in response to changing GHG concentrations; the potential existence of thresholds in the climate system (which could be difficult to predict and simulate); regional differences in the magnitude and rate of climate changes; and many other factors.

Moss and Schneider (2000) characterize the "cascade of uncertainty" in climate change simulations (Figure 4.4-1). As indicated in the figure, the emissions estimates used in this FEIS are less uncertain than the global climate effects (as illustrated by the heights of the bars), which in turn are less uncertain than the regional climate change effects. The effects on climate are in turn less uncertain than the impacts of climate changes on affected resources (terrestrial and coastal ecosystems, human health, and other resources discussed in Section 4.5).

Figure 4.4-1. Cascade of Uncertainty in Climate Change Simulations a/



a/ Source: Moss and Schneider (2000) – "Cascade of uncertainties typical in impact assessments showing the 'uncertainty explosion' as these ranges are multiplied to encompass a comprehensive range of future consequences, including physical, economic, social, and political impacts and policy responses."

Where information in the analysis included in this FEIS is incomplete or unavailable, NHTSA has relied on CEQ regulations regarding incomplete or unavailable information (40 CFR § 1502.22(b)). The understanding of the climate system is incomplete; like any analysis of complex, long-term changes to support decisionmaking, the analysis described below involves many assumptions and uncertainties in the course of evaluating reasonably foreseeable significant adverse impacts on the human environment. This FEIS uses methods and data that represent the best available information on this topic, and which have been subject to peer review and scrutiny. In fact, the information cited throughout this section that is extracted from the IPCC and USCCSP has endured a more thorough and systematic review process than information on virtually any other topic in environmental science and policy. The Model for Assessment of Greenhouse Gas-induced Climate Change (MAGICC) and the IPCC emissions scenarios described below are generally accepted in the scientific community.

NHTSA notes that the USCCSP recently released for comment a draft SAP 3.1 regarding the strengths and limitations of climate models (CCSP 2008a). The reader might find the discussions in this

draft SAP useful in understanding the methodological limitations regarding modeling the environmental impacts of the proposed action and the range of alternatives on climate change.

4.4.3.1 Methodology for Greenhouse Gas Emissions Modeling

GHG emissions were estimated using the Volpe model, described in Section 3.1.4. These emissions estimates include CO_2, CH_4, and N_2O emissions from both direct fuel consumption and upstream sources. The following non-GHGs were also estimated by the Volpe model and taken into account in the climate modeling: SO_2, NO_x, CO, and VOCs.

The Volpe model assumes that major manufacturers will exhaust all available technology before paying noncompliance civil penalties. In the more stringent alternatives, the Volpe model predicts that increasing numbers of manufacturers will run out of technology to apply and, theoretically, resort to penalty payment. Setting standards this high might not be technologically feasible, nor might it serve the need of the Nation to conserve fuel and reduce emissions.

Fuel savings from stricter CAFE standards also result in lower emissions of CO_2, the main GHG emitted as a result of refining, distribution, and use of transportation fuels.[2] Lower fuel consumption reduces carbon dioxide emissions directly, because the primary source of transportation-related CO_2 emissions is fuel combustion in internal combustion engines. NHTSA estimates reductions in CO_2 emissions resulting from fuel savings by assuming that the entire carbon content of gasoline, diesel, and other fuels is converted to CO_2 during the combustion process (*See* 73 *FR* 24352, 24412-24413, May 2, 2008). Reduced fuel consumption also reduces CO_2 emissions that result from the use of carbon-based energy sources during fuel production and distribution. NHTSA currently estimates the reductions in CO_2 emissions during each phase of fuel production and distribution using CO_2 emissions rates obtained from the Greenhouse Gases Regulated Emissions and Energy Use in Transportation (GREET) model. The previous assumptions about how fuel savings are reflected in reductions in each phase. The total reduction in CO_2 emissions from the improvement in fuel economy under each alternative CAFE standard is the sum of the reductions in emissions from reduced fuel use and reductions in emissions from lower fuel production and distribution.

4.4.3.2 Methodology for Estimating Climate Effects

This FEIS estimates and reports on four direct and indirect effects of climate change, driven by alternative scenarios of GHG emissions, including:

- Changes in CO_2 concentrations,
- Changes in global temperature,
- Changes in regional temperature and precipitation, and
- Changes in sea level.

The change in CO_2 concentration is a direct effect of the changes in GHG emissions, and influences each of the other factors.

[2] For purposes of this rulemaking, NHTSA estimated emissions of vehicular CO_2, CH_4, and N_2O emissions, but did not estimate vehicular emissions of hydrofluorocarbons (HFCs). Methane and nitrous oxide account for less than 3 percent of the tailpipe GHG emissions from passenger cars and light trucks, and CO_2 emissions account for the remaining 97 percent. Of the total (including non-tailpipe) GHG emissions from passenger cars and light trucks, tailpipe CO_2 represents about 93.1 percent, tailpipe methane and nitrous oxide represent about 2.4 percent, and hydrofluorocarbons (from air conditioner leaks) represent about 4.5 percent. Calculated from *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2006* (EPA 2008a).

This FEIS uses a climate model to estimate the key direct and indirect effects of the alternative CAFE standards. NHTSA chose to employ MAGICC Version 5.3 (Wigley 2008) to estimate changes in key direct and indirect effects. The application of MAGICC Version 5.3 uses the emissions estimates for CO_2, CH_4, and N_2O from the Volpe model. Sensitivity analyses examined the relationship among various CAFE alternatives, climate sensitivities, and scenarios of global emissions paths and the associated direct and indirect effects for each combination. These relationships can be used to infer the effect of the emissions associated with the regulatory alternatives on direct and indirect climate effects.

MAGICC , the modeling runs and sensitivity analyses, and the emissions scenarios used in the analysis are described in the three sections below.

4.4.3.3 MAGICC Version 5.3

The selection of MAGICC for this analysis was driven by a number of factors:

- MAGICC has been used in the peer-reviewed literature to evaluate changes in global mean surface temperature and sea-level rise. In the IPCC Fourth Assessment Report for Working Group I (WGI) (IPCC 2007a), it was used to scale the results from the atmospheric-ocean general circulation models (AOGCMs)[3] to estimate the global mean surface temperature and the sea-level rise for global emissions scenarios that the AOGCMs did not run.
- MAGICC is publicly available and is already populated with the Special Report on Emission Scenarios (SRES). The SRES scenarios are long-term emissions scenarios representing different assumptions about key drivers of GHG emissions. They are described in more detail below.
- MAGICC was designed for the type of analysis performed in this FEIS.
- More complex AOGCMs are not designed for the type of sensitivity analysis performed here and are best used to provide results for groups of scenarios with much greater differences in emissions such as the B1 (low), A1B (medium), and A2 (high) scenarios.[4]
- MAGICC has been updated to version 5.3 to incorporate the science from the IPCC Fourth Assessment Report (Wigley 2008).

For the primary analysis using MAGICC, NHTSA assumed that global emissions consistent with the No Action Alternative would follow the trajectory provided by the SRES A1B (medium) scenario.

4.4.3.4 Modeling Runs and Input Scenarios

The modeling runs and input scenarios are designed to use information on the alternatives, climate sensitivities, and SRES emissions scenarios provided by the IPCC WGI (IPCC 2007a)[5] to model relative changes in atmospheric concentrations, global mean surface temperature, precipitation, and sea-level rise.

[3] For a discussion of AOGCMs, *see* Chapter 8 in IPCC (2007a).
[4] The IPCC SRES scenarios were developed in the late 1990s and published in 2000 (Nakicenovic et al. 2000). The SRES scenarios were developed around four storylines. The A1 storyline included a strong commitment to market-based solutions, high savings, high economic growth, and globalization. The A2 storyline differs from A1 with lower trade flows and slower rates of technological improvement. The B1 storyline includes a global integrated approach to sustainable development. The B2 storyline includes increased local awareness of environmental issues with strong efforts at the local level and less reliance on international institutions.
[5] The use of three emission scenarios provides insight into the impact of alternative global emission scenarios on the effect of the action alternatives.

The primary modeling runs are based on the results provided for the seven alternatives using the Reference Case Volpe model assumptions, a climate sensitivity of 3 °C for a doubling of CO_2 concentrations in the atmosphere, and the SRES A1B (medium) scenario. These are referred to as the Reference Case results below, in contrast with various sensitivity runs that test high and low values of the key parameters.

The approach uses the following steps to estimate these changes for the Reference Case and an analysis that examined the alternatives using the high-level Volpe assumptions (*e.g.*, higher fuel prices and a higher social cost of carbon) referred to as the "High Scenario":

1. NHTSA assumed that global emissions consistent with the No Action Alternative (Alternative 1) follow the trajectories provided by the SRES A1B (A1B) scenario, providing results illustrating the uncertainty due to factors influencing future global emissions of GHGs.

2. NHTSA assumed that global emissions for the action alternatives (Alternatives 2 through 7) are equal to the global emissions from the No Action Alternative minus the emissions reductions from the Volpe model for CO_2, CH_4, N_2O, SO_2, NO_x, CO, and VOCs. All SO_2 reductions were applied to Aerosol Region 1 of MAGICC, which includes North America.

3. MAGICC 5.3 was used to estimate the changes in CO_2 concentrations, global mean surface temperature, and sea-level rise through 2100 using the No Action Alternative and the action alternatives developed in steps 1 and 2 above.

4. For the Reference Case results, the increase in global mean surface temperature was used along with factors that relate increase in global average precipitation to this increase in global mean surface temperature to estimate the increase in global averaged precipitation for each alternative for the A1B (medium) scenario.

The approach uses the following steps to estimate the sensitivity of the results to the selection of the SRES global emissions scenario:

1. NHTSA assumed that global emissions consistent with the No Action Alternative (Alternative 1) follow four potential trajectories represented by the SRES A2, B1, B2, and A1FI scenarios. The results of these simulations illustrate the uncertainty due to factors influencing future global emissions of GHGs (factors other than the CAFE rulemaking).

2. For each SRES scenario from step 1, NHTSA assumed that global emissions for the action alternatives are equal to the global emissions from the No Action Alternative minus the emissions reductions from the Volpe model for CO_2, CH_4, N_2O, SO_2, NO_x, CO, and VOCs. All SO_2 reductions were applied to Aerosol Region 1 of MAGICC, which includes North America.

3. MAGICC 5.3 was used to estimate the changes in CO_2 concentrations, global mean surface temperature, and sea-level rise through 2100 using the No Action Alternative (Alternative 1) and action alternatives developed in steps 1 and 2 above.

Section 3.4.4 reports the results of the primary modeling runs. Section 3.4.5 reports the results from similar runs in which the alternatives use the high-level Volpe assumptions (*e.g.*, higher fuel prices and a higher social cost of carbon), in effect providing a "CAFE assumption sensitivity analysis."

4.4.3.5 Emissions Scenarios

As described above, MAGICC uses long-term emissions scenarios representing different assumptions about key drivers of GHG emissions. All scenarios used are based on the IPCC effort to develop a set of long-term (1990-2100) emissions scenarios to provide some standardization in climate change modeling. The most widely used scenarios are those from SRES (Nakicenovic *et al.* 2000).

Both the Reference Case and the Input Scenarios analyses rely primarily on the SRES scenario referred to as "A1B" to represent a baseline emissions scenario, that is, emissions for the No Action Alternative. NHTSA selected this scenario because it is regarded as a moderate emissions case and has been widely used in AOGCMs, including several AOGCM runs developed for the IPCC WGI Fourth Assessment Report (IPCC 2007a).

NHTSA's choice of the A1B scenario is based on the following factors:

- IPCC WGI evaluated the climate effects from A1B extensively in the Fourth Assessment Report (IPCC 2007a), which provides a basis for comparing the results from the analysis using MAGICC to the IPCC Fourth Assessment Report.
- The A1B and B2 scenarios are "middle-of-the road" scenarios and provide the best comparison (see below) to the EIA AEO 2008 and International Energy Outlook (IEO) 2008 forecast of liquid energy use. The AEO-2008/IEO-2008 provide the base assumptions for key parameters in the Volpe model scenarios.

The A1B (medium) scenario provides a global context for emissions of a full suite of GHGs and ozone precursors for the Reference Case. There are some inconsistencies between the overall assumptions used by IPCC in its SRES (Nakicenovic *et al.* 2000) to develop global emissions scenarios and the assumptions used in the Volpe model in terms of economic growth, energy prices, energy supply, and energy demand. However, these inconsistencies affect the characterization of each CAFE alternative in equal proportion, so the relative estimates provide a reasonable approximation of the differences in environmental impact among the alternatives. NHTSA used the A1B scenario as the primary scenario for evaluating climate effects, but used the A2, B1, B2, and the A1FI scenarios to evaluate the sensitivity of the results to alternative emissions scenarios.[6]

Separately, each of the other alternatives was simulated by calculating the difference in annual GHG emissions with respect to the No Action Alternative, and subtracting this change in the A1B (medium) scenario to generate modified global-scale emissions scenarios, which each show the effect of the various regulatory alternatives on the global emissions path. For example, the emissions from U.S. passenger cars and light trucks in 2020 for the No Action Alternative (Alternative 1) are 1,651 million metric tons of carbon dioxide ($MMTCO_2$); the emissions in 2020 for the Optimized Alternative (Alternative 3) are 1,581 $MMTCO_2$. The difference is 70 $MMTCO_2$. Global emissions for the A1B (medium) scenario in 2020 are 46,339 $MMTCO_2$, and represent the emissions under the No Action Alternative. Global emissions for the Optimized Alternative are 70 $MMTCO_2$ less, or 46,269 $MMTCO_2$.

NHTSA's assumptions in the Volpe model for growth in the number of vehicles and miles driven for cars and light trucks in the United States are based on the AEO assumptions for 2008 (EIA, 2008a). These alone cannot be compared to the SRES assumptions because the IPCC SRES results are reported

[6] From SRES, NHTSA used the A1B scenario to represent the A1B storyline, the A2-ASF scenario to represent the A2 storyline, the B1-IMAGE scenario to represent the B1 storyline, the B2-MESSAGE scenario to represent the B2 storyline, and the A1G-MINICAM scenario to represent the A1FI storyline.

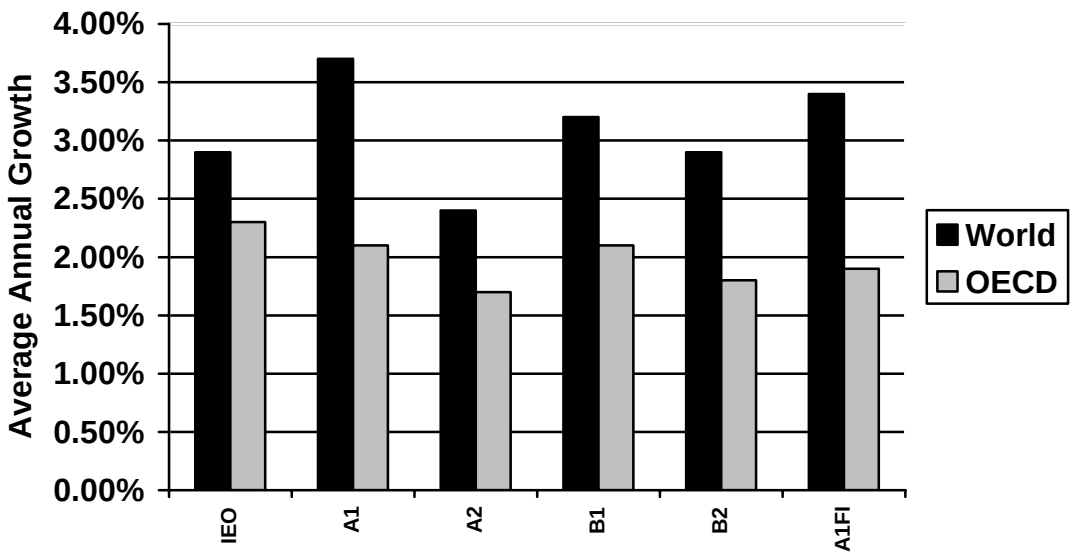
for four global regions including the Organization for Economic Cooperation and Development (OECD) and not for the United States separately. The EIA also published the IEO 2008 (EIA 2008c), which provides a global forecast of energy use and CO_2 from energy use through 2030 and which is consistent in assumptions to the IEO 2008.[7]

Figures 4.4-2 to 4.4-5 provide the forecast of gross domestic product (GDP), CO_2 emissions from energy use, primary energy use from the IEO-2008, and the five SRES scenarios for the World and the OECD 90 region.[8] The GDP growth assumptions for A1B for the OECD are close to those of the IEO-2008, but the A1B scenario has much higher GDP growth outside the OECD. This leads to higher global primary energy use by 2030, as shown in Figure 4.4-4, with much of the increase in natural gas use and higher emissions of CO_2, as shown in Figure 4.4-3. The global primary liquids energy use in A1B and the IEO-2008 compare well, considering that the IEO forecast for liquid fuels includes about 10 percent of the total in unconventional sources which are accounted for elsewhere in the SRES scenarios.

The forecast estimates for the OECD 90 region vary differently than the global numbers. The EIA shows a similar increase in primary energy use in the OECD 90 region but much greater increase in the use of primary liquid fuels even considering the reporting differences between the IEO and SRES.

Where information in the analysis included in this FEIS is incomplete or unavailable, NHTSA has relied on CEQ regulations regarding incomplete or unavailable information (40 CFR § 1502.22(b)). For this analysis, despite the inconsistencies between the IPCC assumptions on global trends across all GHG-emitting sectors (and the drivers that affect them) and the particularities of the Volpe model on the U.S. transportation sector, the approach used is valid; these inconsistencies affect all alternatives equally, and thus they do not hinder a comparison of the alternatives in terms of their relative effects on climate.

Figure 4.4-2. Average GDP Growth Rates (1990 to 2030)



[7] The IEO 2008 uses the energy supply and consumption from the AEO 2008 for the United States and uses the same forecast for world oil prices.
[8] The IEO nuclear primary energy forecast numbers were adjusted to account for differences in reporting primary energy use for nuclear energy and all IEO energy use estimates were converted to exajoules (EJ).

Figure 4.4-3. Global CO_2 Emissions from Fossil Fuel Use

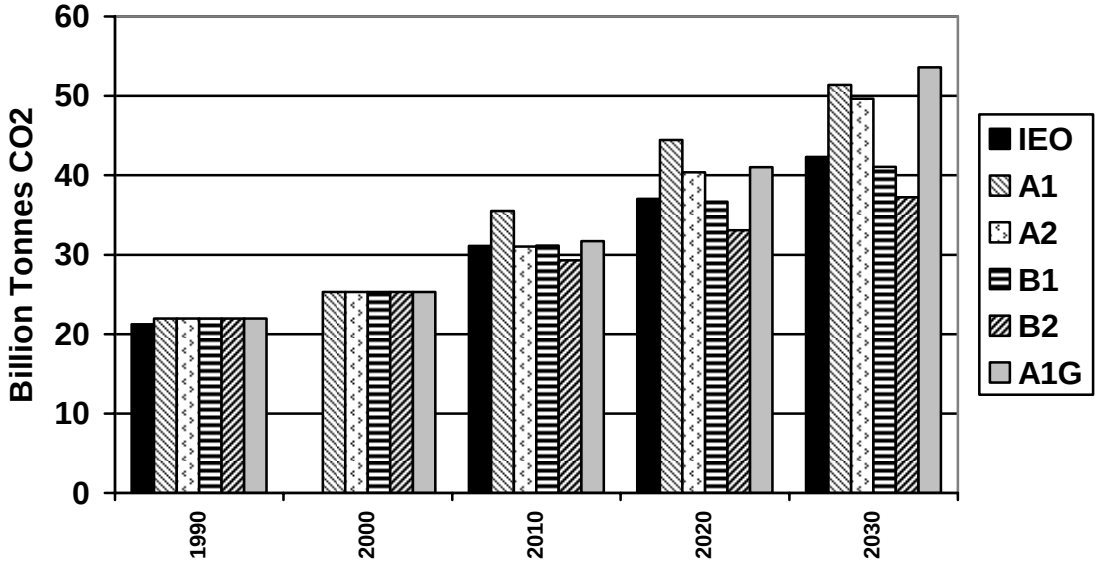


Figure 4.4-4. World Primary Energy Use Forecast

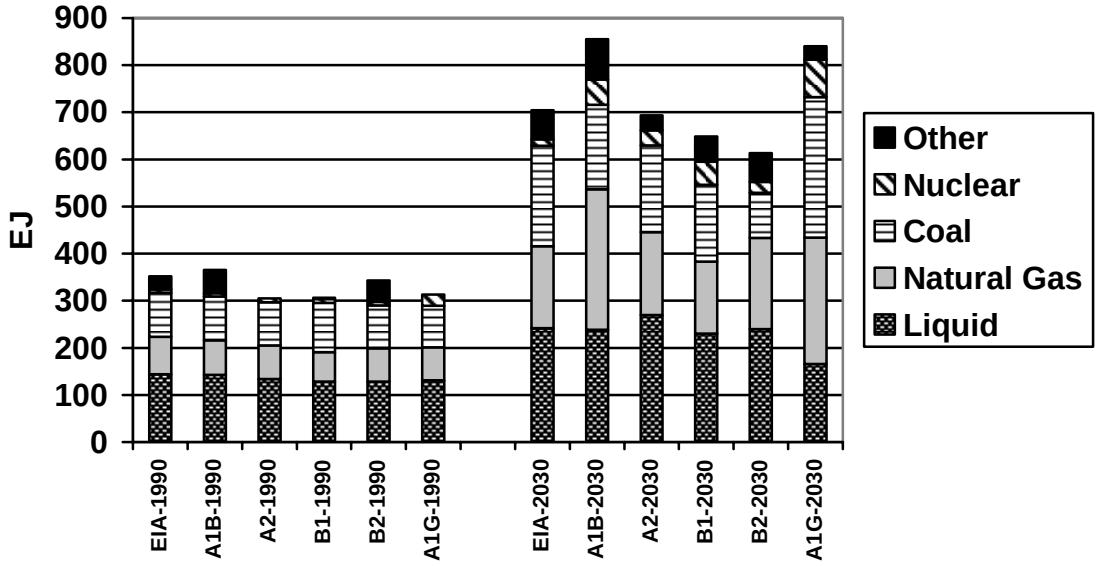
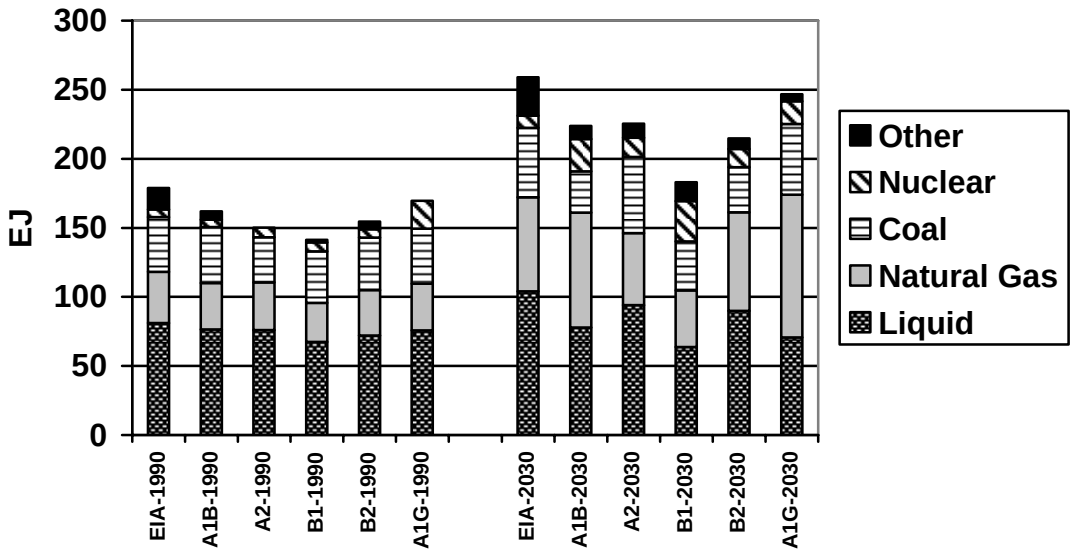


Figure 4.4-5. OECD 90 Primary Energy Use Forecast a/



a/ The SRES results provide forecasts for countries that were members of the OECD in 1990 only and the IEO 1990 and 2030 estimates have been scaled to reflect only countries in the OECD in 1990.

The approaches focus on the marginal climate effects of marginal changes in emissions. Thus, they generate a reasonable characterization of climate changes for a given set of emissions reductions, regardless of the underlying details associated with those emissions reductions. The discussion that follows characterizes projected climate change under the No Action Alternative and the changes associated with each action alternative.

The SRES and climate sensitivity variants (*see* Section 4.4.4.2.5) analysis also uses the B1 (low), B2, A2 (high), and A1F1 emissions scenarios (Nakicenovic *et al.* 2000) as "reference" scenarios. This provides a basis for determining climate responses to varying levels of emissions and climate sensitivities for the Optimized Alternative (Alternative 3). Some responses of the climate system are believed to be non-linear; by using a range of emissions cases and climate sensitivities, it is possible to estimate the effects of the alternatives in relation to different reference cases.

4.4.3.5.1 Tipping Points and Abrupt Climate Change

The phrase "tipping point" is most typically used, in the context of climate change and its consequences, to describe situations in which the climate system (the atmosphere, oceans, land, cryosphere,[9] and biosphere) reaches a point at which there is a disproportionately large or singular response in a climate-affected system as a result of only a moderate additional change in the inputs to that system (such as an increase in the CO_2 concentration). Exceeding one or more tipping points, which "occur when the climate system is forced to cross some threshold, triggering a translation to a new state at a rate determined by the climate system itself and faster than the cause" (Committee on Abrupt Climate Change 2002), could result in abrupt changes in the climate or any part of the climate system. These changes would likely produce impacts at a rate and intensity far greater than the slower, steady changes currently being observed (and in some cases, planned for) in the climate system.

[9] The cryosphere describes the portion of Earth's surface that is frozen water, such as snow, permafrost, floating ice, and glaciers.

The phrase tipping point is also used outside the climate modeling community. In addition to climate scientists, many others – including biologists, marine chemists, engineers, and policymakers – are concerned about tipping points, because it is not just the climate that can change abruptly. The same type of non-linear responses exist in physical, environmental, and societal systems that climate affects. For example, ocean acidity resulting from an elevated atmospheric concentration of CO_2 might reach a point at which there would be a dramatic decline in coral ecosystems. Consideration of possible tipping points could therefore encompass sharp changes in climate-affected resources and not be restricted to climate change alone.

Using the broad definition of the term tipping point to include both climate change and its consequences, the scale of spatial responses can range from global (e.g., a "supergreenhouse" atmosphere with higher temperatures worldwide) to continental or subcontinental changes (such as dramatically altering the Asian monsoon), to regional (e.g., drying in the southwestern United States leading to increases in the frequency of fires, to local (such as loss of the Sierra Nevada snowpack). The definition of tipping point used by Lenton *et al.* (2008) (discussed below) specifically applies only to subcontinental or larger features, whereas public policy is concerned with a wider range of scales, as the IPCC analysis (discussed below) suggests.

The temporal scales considered are also important. On crossing a tipping point, the evolution of the climate-affected system is no longer controlled by the time scale of the climate forcing (such as the heat absorption by GHGs), but rather is determined by its internal dynamics, which can either be much faster than the forcing, or substantially slower. The much faster case – abrupt climate change – might be said to occur when the:

- Rate of change is sharply greater than (or a different sign than) what has been prevailing over previous decades;
- State of the system exceeds the range of variations experienced in the past; or
- Rate has accelerated to a pace that substantially exceeds the resources and ability of nations to respond to it.

Climate changes could occur in many ways as tipping points are reached. These mechanisms range from the appearance or unusual strengthening of positive feedbacks – self-reinforcing cycles – and reversible-phase transitions in climate-affected systems to irreversible-phase transitions – where a threshold has been crossed that could lead to either abrupt or unexpected changes in the rate or direction of change in climate-affected systems. Although climate models incorporate many positive (and negative, or dampening) feedback mechanisms, the magnitude of these effects and the threshold at which the feedback-related tipping points are reached are only roughly known, especially regarding global impacts. In addition, models of climate and climate-affected systems do not contain all feedback processes. Although substantial progress has been made in understanding the qualitative processes associated with tipping points, there are limits to the quantitative understanding of many of these systems.

In recent years, the concept of a tipping point – or a set of tipping points – in Earth's climate system has been attracting increased attention among climate scientists and policy makers. The following sections draw on perspectives from four key analyses of the issue and other relevant research: the IPCC,

the USCCSP, paleoclimate[10] evidence, and Lenton *et al.* (2008). The section concludes with a brief comparative evaluation.

IPCC Perspectives on Tipping Points

In its Fourth Assessment Report, the IPCC addresses the issue of tipping points in the discussion of "major or abrupt climate changes" and highlights three large systems: the meridional overturning circulation (MOC) system that drives Atlantic Ocean circulation, the collapse of the West Antarctic ice sheet, and the loss of the Greenland ice sheet (Meehl *et al.* 2007). The IPCC states that there is uncertainty in the understanding of these systems but concludes that these systems are unlikely to reach their tipping points within the 21st Century (Meehl *et al.* 2007). The IPCC also mentions additional systems, as noted below, that might have tipping points, but does not include estimates for them.

The IPCC WGI report (Meehl *et al.* 2007) describes various climate and climate-affected systems that might undergo abrupt change, contribute to "climate surprises," or experience irreversible impacts. The systems that the IPCC described include:

- Atlantic MOC (AMOC) and other ocean circulation changes
- Arctic sea ice
- Glaciers and ice caps
- Greenland and West Antarctic ice sheets
- Vegetation cover
- Atmospheric and ocean-atmosphere regimes

The IPCC Working Group II (WGII) report provides insight on the uncertainties surrounding tipping points, their systemic and impact thresholds, and the value judgments required to select a critical level of warming (Carter *et al.* 2007). The presence of these thresholds can also present their own physical and ecological limits and informational and cognitive barriers to adaptation (Adger *et al.* 2007). In the case of this FEIS, uncertainty prevents NHTSA from being able to quantify the impacts of the alternatives under consideration on specific tipping-point thresholds.

In the IPCC WG II report, certain thresholds are assumed and then used with analyses of emissions scenarios and stabilization targets to assess how certain impacts might be avoided (Schneider *et al.* 2007). For example, several authors hypothesize that a large-scale climatic event or other impacts (for example, widespread coral-reef bleaching; deglaciation of West Antarctica) would be likely if atmospheric CO_2 concentrations stabilize at levels exceeding 450 ppm, although the location of the tipping points and thresholds is uncertain (O'Neill and Oppenheimer 2002, Lowe *et al.* 2006, and Corfee-Morlot and Höhne 2003, all as cited in Schneider *et al.* 2007).

USCCSP Perspectives on Tipping Points

The USCCSP reaches similar conclusions in its report *Scientific Assessment of the Effects of Global Change on the United States* (National Science and Technology Council 2008). The USCCSP report summarizes scientific studies that suggest that there are several "triggers" of abrupt climate change and that "anthropogenic forcing *could* increase the risk of abrupt climate change;" however, "future abrupt changes cannot be predicted with confidence" because of the insufficiencies of current climate

[10] Paleoclimatology is the study of climate change through the physical evidence left on earth of historical global climate change (prior to the widespread availability of records to temperature, precipitation, and other data). *See generally* http://www.giss.nasa.gov/research/paleo/.

models, which reflect the limits of current understanding.[11] However, the USCCSP report does reiterate the conclusion that if it occurs, an abrupt climate change event would likely transpire over the course of many hundreds of years and that it is *"very unlikely"* that any abrupt climate change will occur "during the 21st century."

The USCCSP analysis considers the susceptibility of the same three systems to abrupt change as IPCC highlighted: the AMOC system that drives Atlantic Ocean circulation, the collapse of the West Antarctic ice sheet, and the loss of the Greenland ice sheet (National Science and Technology Council 2008). The USCCSP analysis also suggests that there are thresholds in non-climate systems influenced by CO_2 emissions, such as ocean acidification, where there could be a threshold beyond which existing coral reef ecosystems cannot survive (CCSP 2008e). The USCCSP report concludes that these impacts, including climate-related thresholds, could occur in groups as thresholds are crossed, but, due to the uncertainty, more research is needed to quantify the impacts of crossing particular thresholds and to determine when these thresholds would be reached (CCSP 2008e). A forthcoming USCCSP report, Synthesis and Assessment Product 3.4, "Abrupt Climate Change," will provide additional information on this topic, focusing on glaciers and ice sheets, hydrological change, the MOC, and methane releases.

Paleoclimate Evidence on Tipping Points

The paleoclimate record cited by IPCC, USCCSP, and others gives an indication of sea-level rise from previous ice-sheet melt, and the corresponding temperature for these periods. For example, geological evidence showing the presence of elevated beaches suggests that global sea level was 4 to 6 meters higher during the most recent interglacial period about 125,000 years ago (Jansen *et al.* 2007). Paleoclimatic reconstructions suggest that global average temperature then was about 1 °C (1.8 °F) warmer than during the present interglacial period (Hansen *et al.* 2007b). Corings from the ice sheets to determine their ages, supplemented by simulations of ice-sheet extent, suggest that large-scale retreat of the southern half of the Greenland ice sheet and other Arctic ice fields likely contributed roughly 2 to 4 meters of sea-level rise during the last interglacial, with most of any remainder likely coming from the Antarctic ice sheet (Jansen *et al.* 2007).

Paleoclimatic reconstructions also indicate occurrences of abrupt changes in the terrestrial, ice, and oceanic climatic records. For example, ice-core records suggest that temperatures atop the Greenland ice sheet warmed by 8 to 16 °C (14 to 29 °F) within a few decades during Dansgaard-Oeschger events,[12] which were likely caused by the North Atlantic Ocean being covered by catastrophic outflows of glacial meltwater from the North American ice sheet that was present during glacial times (Jansen *et al.* 2007). A more recent study (Steffensen *et al.* 2008) provides more detail, indicating that a there was a sharp warming over 1 to 3 years (that is, "abrupt climate change happens in [a] few years"), followed by a more gradual warming over 50 years.

Based on the IPCC estimates of temperature increases of approximately 2 to 4 °C in the next 100 years, MacCracken (2008) notes that paleoclimatic research indicates that corresponding sea-level rise could be 10 to 20 meters or more from the melting of the West Antarctic and Greenland ice sheets. The time required to melt the ice sheets is uncertain, ranging from decades to centuries or longer. MacCracken (2008) suggests that "significant sea level rise [over 1 meter] could happen relatively

[11] *See* U.S. Climate Change Science Program, Synthesis and Assessment Product 3.1 (Climate Models: An Assessment of Strengths and Limitations), Final Report (July 2008), *available at* http://www.climatescience.gov/Library/default.htm#sap.

[12] Dansgaard-Oeschger events are very rapid climate changes—up to 7 °C in some 50 years—during the Quaternary geologic period, and especially during the most recent glacial cycle. (A Dictionary of Geography. Oxford University Press, 1992, 1997, 2004.)

quickly," meaning less than a century. For example, the average rate of rise from 20 kiloannum[13] (ka) to 8 ka was about 1 meter per century, so there have been periods with high rates of rise, although the melting North American ice sheet was an order of magnitude larger than Greenland is today (MacCracken, personal communication, 2008). For the future, Hansen *et al.* (2007b) asserts that positive feedback mechanisms in the climate system have the potential to cause large and rapid shifts in climate and in factors like glacial melt and sea-level rise that are closely dependent on the climate; Rahmstorf (2007) presents a projected sea-level rise in 2100 of 0.5 to 1.4 meters above the 1990 level.

In a study utilizing model runs and paleoclimatic data[14], Hansen *et al.* (2007b) conclude that "…a CO_2 level exceeding about 450 ppm is 'dangerous,'" where "dangerous" is defined by the authors to be global warming of more than 1 ºC (1.8 ºF) above the level in 2000, potentially leading to highly disruptive effects. Although this 450-ppm estimate has limitations and uncertainties, Hansen actually considers this estimate of dangerous CO_2 concentration to be an upper limit because it depends on several simplifying assumptions (Hansen 2008b). He warns that the limit might be lower and that a "safe" level of CO_2 could be 350 ppm – lower than the CO_2-equivalent concentration, including the offsetting effects of aerosols, is today (Hansen 2008b).

The range of views linking past and future sea-level rise is clearly broad, with uncertainty attributable to each view. Therefore, the forthcoming USCCSP report – Synthesis and Assessment Product 3.4, "Abrupt Climate Change" – should provide additional, more complete information on the issue.

Perspectives on Tipping Points from a Critical Review of the Literature and an Expert Elicitation as Presented by Lenton *et al.* (2008)

Building on the IPCC and USCCSP research, during a workshop titled "Tipping Points in the Earth System," experts identified several climate systems that have tipping points and conducted an expert elicitation involving 52 members of the international scientific community, many of whom participated in the IPCC. This study identified nine systems facing separate tipping points due to increased CO_2 and temperature levels that met four scientifically based criteria to be considered "policy-relevant potential future tipping elements in the climate system" (Lenton *et al.* 2008). Additional systems were identified but insufficient information precluded these systems from meeting the definition of policy relevant. The systems at risk that the researchers identified are:

- Arctic sea ice
- Greenland ice sheet
- West Antarctic ice sheet
- Atlantic thermohaline circulation (a component of the AMOC)
- El-Niño-Southern oscillation
- Indian summer monsoon
- Sahara/Sahel and West African monsoon
- Amazon rainforest
- Boreal forest

[13] Kiloannum means 1,000 years ago.

[14] The authors compare the corresponding GHG concentrations and associated temperature increases alongside paleoclimatology research to demonstrate that abrupt changes have occurred in Earth's past, resulting from a similar range in increased temperature as those being predicted, and to argue the existence of a CO_2 concentration equivalent level (in atmospheric GHG concentration) at which the probability of abrupt, irreversible changes in climate-affected systems might occur.

The discussion that follows is drawn primarily from the Lenton *et al.* (2008) study, including the citations therein.

Arctic sea ice. The surface of Arctic sea ice has a higher reflectivity (albedo) than the darker ocean surface. As sea ice melts from higher air and ocean temperatures, more of the ocean is exposed, which allows more radiation to be absorbed, amplifying the sea-ice melt. In summer, Arctic sea-ice loss could lead to the ice cap melting beyond a certain size/thickness, making it unstable and leading to an ice-free Arctic. Recent record ice losses and modeling studies have led some researchers to suggest that the summer Arctic will be ice free within a decade or less, that there is a critical threshold for summer Arctic sea-ice loss, and that this threshold has already been crossed (Borenstein and Joling 2008).

Greenland ice sheet. The Greenland ice sheet is also susceptible to positive feedbacks. Melting at the glacial margins lowers the edge of the ice sheet to elevations that are warmer and where more melting will occur. The IPCC estimated the Greenland ice sheet threshold for negative surface mass at 1.9 to 4.6 °C (3.4 to 8.3 °F) above pre-industrial temperature, well within the predicted temperature range for this century. Dynamic ice-melting processes, regional temperatures, warming surrounding oceans, and recent observations indicating that both Greenland and Antarctica are now losing mass have led researchers to conclude that the timescale for Greenland ice-shelf collapse is conceivably on a scale of hundreds rather than thousands of years.

West Antarctic ice sheet. The West Antarctic ice sheet is grounded below sea level and positive feedbacks could result from the loss of buttressing sea-ice shelves and the ingress of warmer ocean water. While centuries or millennia could to pass before a collapse, the thresholds for ocean and surface atmospheric warming temperature are likely to be crossed this century. A recent study of ice-core records suggests strong links between past West Antarctic climate, and potentially its ice sheet, to large-scale changes in global climate, particularly major El Niño events (Schneider and Steig 2008). It should be noted that ice-sheet loss, even over millennia, could cause the sea level to rise at a rate greater than 1 meter per century – more than five times the rate of rise during the 20th Century. The level reached would be higher than has been the case during at least the past few thousand years when coastal cities were established.

Atlantic thermohaline circulation. The term thermohaline circulation (THC) refers to the physical driving mechanism of ocean circulation, resulting from fluxes of heat and freshwater across the sea surface, subsequent interior mixing of heat and salt, and geothermal heat sources. The MOC, discussed in the IPCC and USCCSP reports, is the observed response in an ocean basin to this type of ocean circulation coupled with wind-driven currents. The Lenton *et al.* (2008) paper refers to risk to the Atlantic THC instead of the AMOC because they are discussing the influence of climate change on the underlying cooling or freshwater forcing of the Atlantic Ocean circulation, even though this in turn dramatically affects the AMOC.

If enough freshwater enters the North Atlantic (such as from melting sea ice or the Greenland ice sheet), the density-driven sinking of North Atlantic waters might be reduced or even stopped, as evidence indicated occurred happened during the last glacial cycle. This would likely reduce the northward flow of energy in the Gulf Stream and result in less heat transport to the North Atlantic. At the same time, reduced formation of very cold water would likely slow the global ocean THC, leading to impacts on global climate and ocean currents. The IPCC review of the results of model simulations suggests that an abrupt transition of the Atlantic Ocean's component of the global THC is *very unlikely* this century. However, more recent modeling that includes increased freshwater inputs suggests there could be initial changes this century, with larger and more intense reductions in the overturning circulation persisting for many centuries (Mikolajewicz *et al*. 2007).

El-Niño-Southern oscillation (ENSO). The changes that might lead to increasingly persistent (and frequent) El Niño (or La Niña) conditions are particularly uncertain. Increases in ocean heat content could have an effect on ENSO conditions, but predictive and paleoclimate modeling studies do not agree on the magnitude, frequency, and direction of these effects. However, ENSO has substantial and large-scale effects on the global climate system.

Indian summer monsoon. The Indian summer monsoon is the result of land-to-ocean pressure gradients and advection of moisture from ocean to land. By warming the land more than the ocean, climate change generally strengthens the monsoon. However, reductions in the amount of solar radiation that is absorbed by the land surface, such as land-use change, generally weaken it. An albedo greater than roughly 50 percent is necessary to simulate the collapse of the Indian summer monsoon in a simple model (Zickfield *et al.* 2005). IPCC projections do not project passing a threshold this century, although paleoclimatic reconstructions do indicate that the monsoon has changed substantially in the past.

West African monsoon. Sahara/Sahel rainfall depends on the West African monsoon circulation, which is affected by sea-surface temperature. By warming the land more than the ocean and therefore causing greater upward movement of the air, GHG forcing is expected to draw more moist oceanic air inland and thereby increase rainfall in the region, which has been shown by some models. Other models, however, project a less productive monsoon. The reasons for this inconsistency are not clear.

Amazon rainforest. The recycling of precipitation in the Amazon rainforest means that deforestation, reductions in precipitation, a longer dry season, and increased summer temperature could cause forest dieback. These conditions are thought to be linked to a more persistent El Niño and an increase of global average temperature by 3 to 4 °C (5.4 to 6.8 °F). Important additional stressors also present include forest fires and human activity (such as land clearing). A critical threshold might exist in canopy cover, which could be reached through changes in land use or regional precipitation, ENSO variability, and global forcing.

Boreal Forest. The dieback of boreal forest could result from a combination of increased heat stress and water stress, leading to decreased reproduction rates, increased disease vulnerability, and subsequent fire. Although highly uncertain, studies suggest a global warming of 3 °C (5.4 °F) could be the threshold for loss of the boreal forest.

Comparative Evaluation

The Lenton *et al.* (2008) group's list differs slightly from that of the IPCC because of differences in definition and criteria, an attempt to be more explicit than the IPCC, and the inclusion of more recent studies. The scientists defined these tipping points as "tipping elements" and attempted to estimate when the tipping element of the various systems might be reached, ranging from about 1 year (rapid) to more than 300 years (slow). As with the IPCC and USCCSP conclusions, this group also concluded that the loss of the Greenland ice sheet, the collapse of the West Antarctic ice sheet, and the disruption of the Atlantic THC systems are not expected to cross their estimated tipping elements in this century (though actions this century could create enough momentum in the climate system to cross the threshold in future centuries[15]). However, this group determined that several other systems could reach a tipping threshold within the century: loss of Arctic sea ice, Indian summer monsoon disruption, Sahara/Sahel and West African monsoon changes, drying of the Amazon rainforest, and warming of the boreal forest.

Another factor that might accelerate climate change at rates faster than those currently observed is the possible shift of soil and vegetation-carbon feedbacks, causing the soil and vegetation to become

[15] *See* Lenton *et al.* (2008), p. 1787.

carbon sources rather than carbon sinks. Currently, soil and vegetation act as sinks, absorbing carbon from the atmosphere as plant material and storing carbon in the soil when the plants die. However, by mid-century (about the time the IPCC predicts the global average temperature reaches 2 ºC (3.6 ºF) above pre-industrial levels), increasing temperatures and precipitation could cause increased rates of transpiration, resulting in soil and vegetation becoming a potential source of carbon emissions (Cox *et al.* 2000 as cited in Meehl *et al.* 2007). Warming could also thaw frozen Arctic soils (permafrost), causing the wet soils to emit more methane, a GHG. There is evidence that this process is already taking place (Walter *et al.* 2007). This additional research clarifies the concept of tipping points by further revealing that several climate systems might have tipping points that could occur within the century, and in some systems changes are currently being observed. However, uncertainties exist, especially for timing estimates, and the uncertainties are at least partly responsible for the broad spectrum of views regarding the tipping point. Exactly where these tipping points exist, and the levels at which they occur, are still a matter in need of further scientific investigation before precise quantitative conclusions can be made.

Where information in this FEIS analysis is incomplete or unavailable, as here due to current climate modeling limitations, NHTSA has relied on CEQ regulations regarding incomplete or unavailable information (40 CFR § 1502.22(b)). CEQ regulations state, in part, that when an agency is evaluating "reasonably foreseeable significant adverse impacts on the human environment and …information relevant to…[the] impacts cannot be obtained because the overall costs of obtaining it are exorbitant or the means to obtain it are not known, the agency shall include within the [EIS]:

1. a statement that such information is incomplete or unavailable;
2. a statement of the relevance of the incomplete or unavailable information to evaluating reasonably foreseeable significant adverse impacts on the human environment;
3. a summary of existing credible scientific evidence which is relevant to evaluating the reasonably foreseeable significant adverse impacts on the human environment; and
4. the agency's evaluation of such impacts based upon theoretical approaches or research methods generally accepted in the scientific community. For the purposes of this section, "reasonably foreseeable" includes impacts which have catastrophic consequences, even if their probability of occurrence is low, provided that the analysis of the impacts is supported by credible scientific evidence, is not based on pure conjecture, and is within the rule of reason." 40 CFR § 1502.22 (b).

This FEIS addresses the requirements of 40 CFR § 1502.22 appropriately. The above survey of the current state of climate science tipping points provides a "summary of existing credible scientific evidence which is relevant to evaluating the…adverse impacts of the CAFE standards." In *Colorado Environmental Coalition v. Dombeck,* the Tenth Circuit found that the ultimate goal of the agency is to ensure that the EIS's "form, content, and preparation foster both informed decision making and informed public participation" (185 F.3d 1162, 1172 [10th Cir. 1999] [quoting *Oregon Envtl. Council v. Kunzman*, 817 F.2d 484, 492 (9th Cir. 1987)]. The Tenth Circuit held that 40 CFR § 1502.22 could not be read as imposing a "data gathering requirement under circumstances where no such data exists." *Id.*

In this case, this FEIS acknowledges that information on tipping points or abrupt climate change is incomplete, and the state of the science does not allow for a characterization of how the CAFE alternatives influence these risks. This action alone, even as analyzed for the most stringent alternative, does not produce sufficient CO_2 emissions reductions to avert levels of abrupt and severe climate change. To the degree that the action in this rulemaking reduces the rate of CO_2 emissions, the rule contributes to the general reduction or delay of reaching these tipping-point thresholds. These conclusions are not meant to be read as expressing NHTSA's view that tipping points in climate-related systems are not areas of concern for policymakers. Under NEPA, the agency is obligated to discuss "the environmental

impact[s] *of the proposed action*" (42 U.S.C. § 4332(2)(C)(i) [emphasis added]). The above discussion fulfills NHTSA's NEPA obligations regarding this issue.

4.4.4 Environmental Consequences

This section describes the consequences of the MY 2011-2015 CAFE standards in relation to GHG emissions and climate effects.

4.4.4.1 Greenhouse Gas Emissions

To estimate the emissions resulting from changes in passenger car and light truck CAFE standards, NHTSA uses the Volpe model (*see* Section 3.1.3 for a description of the model). The change in fuel use projected to result from each alternative CAFE standard determines the resulting impacts on total and petroleum energy use, which in turn affects the amount of CO_2 emissions. These CO_2 emissions estimates also include upstream emissions, which occur from the use of carbon-based energy during crude oil extraction, transportation, and refining, and in the transportation, storage, and distribution of refined fuel. Because CO_2 accounts for such a large fraction of total GHG emitted during fuel production and use – more than 95 percent, even after accounting for the higher global warming potentials (GWPs) of other GHGs – NHTSA's consideration of GHG impacts focuses on reductions in CO_2 emissions resulting from the savings in fuel use that accompany higher fuel economy.[16]

NHTSA considers three measures of the cumulative impact of alternative CAFE standards (for MY 2011-2015 *and* using the assumption of reaching 35 mpg by 2020 to estimate the foreseeable MY 2016-2020) on CO_2 emissions:

- CO_2 emissions from the vehicles they would affect, namely, MY 2011-2020 passenger cars and light trucks;
- CO_2 emissions by the entire U.S. passenger car and light truck fleets that would result during future years (2021-2100) from each alternative increase in CAFE standards; and
- Cumulative emissions reductions over the history of the CAFE Program, including those projected to result from each alternative increase in CAFE standards considered for NHTSA's proposed action. Emissions reductions represent the differences in total annual emissions by all cars or light trucks in use between their estimated future levels under the No Action Alternative (baseline), and with each alternative CAFE standard in effect.

Under NEPA, the assessment of cumulative impacts must include the impact on the environment resulting from "the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions." 40 CFR § 1508.7. Because EISA directs NHTSA to increase CAFE standards to reach a combined fleet average CAFE level of at least 35 mpg by model year 2020, MY 2016-2020 CAFE standards are reasonably foreseeable and must be accounted for when analyzing the cumulative impacts of the MY 2011-2015 CAFE standards. For each alternative, NHTSA assumed that passenger-car and light-truck CAFE standards would continue to increase over MY 2016-2020 at their average annual rate of increase over MY 2011-2015. This assumption results in passenger-car and light-truck CAFE standards under each action alternative that meet or exceed the EISA requirement of a combined fleet average of at least 35 mpg by model year 2020. NHTSA assumed further that the fuel economy

[16] Although this section only includes a discussion of CO_2 emissions, the climate modeling discussion in Section 3.4.4.4 assesses the direct and indirect effects associated with emissions reductions of multiple gases, including CO_2, CH_4, N_2O, SO_2, CO, NO_x, and VOCs.

standards for model year 2020 would remain in effect through the end of the analysis period. Because the CAFE standards apply to new vehicles, this assumption results in emissions reductions and fuel savings that continue to grow as new vehicles meeting the CAFE standards for MY 2020 and beyond are added to the fleet in each subsequent year, reaching their maximum values when all passenger cars and light trucks in the U.S. fleet meet these standards. Thus, NHTSA evaluated the effect of CAFE standards to date, and potential CAFE standards for MY 2016-2020 because they are considered a reasonably foreseeable action.

NHTSA estimates that the cumulative CO_2 reductions from CAFE to date, from 1978-2007, have been 8,911 $MMTCO_2$, according to the Volpe model. Assuming no further increases in fuel economy standards – that is, the standards for MY 2010 vehicles remain in force through 2100 – NHTSA estimates that continuation of the MY 2010 standards would result in further emissions reductions of 135,535 $MMTCO_2$ as compared to the reference case of no CAFE standards.

Emissions reductions resulting from the CAFE standards for MY 2011-2015 and MY 2016-2020 cars and light trucks were estimated from 2010 to 2100. Reductions begin in the year 2010, the first year that MY 2011 vehicles are on the road. For each alternative, all vehicles after MY 2020 were assumed to meet the MY 2020 CAFE standards. Emissions were estimated for all alternatives through 2100, and these emissions were compared against the NPRM baseline (which assumes all vehicles post-MY 2010 meet the MY 2010 standards) to estimate emissions reductions. The Volpe model estimates emissions through the year 2060. Annual emissions reductions from 2061-2100 were held constant at 2060 levels.

Table 4.4-1 lists total emissions reductions from MY 2010-2100 new passenger cars and light trucks for each of the seven alternatives. Projections of emissions reductions over the 2010 to 2100 period due to the MY 2011-2015 CAFE standards and the potential standards for MY 2016-2020 ranged from 24,321 to 49,157 $MMTCO_2$. Compared to global emissions of 4,850,000 $MMTCO_2$ over this period (projected by the A1B-medium scenario), the incremental impact of this rulemaking is expected to reduce global CO_2 emissions by about 0.5 to 1.0 percent.

Table 4.4-1

Reference Case Cumulative Emissions and Emissions Reductions Due to the MY 2011-2015 Standards and Potential MY 2016-2020 Standards Projected for 2010-2100 ($MMTCO_2$)

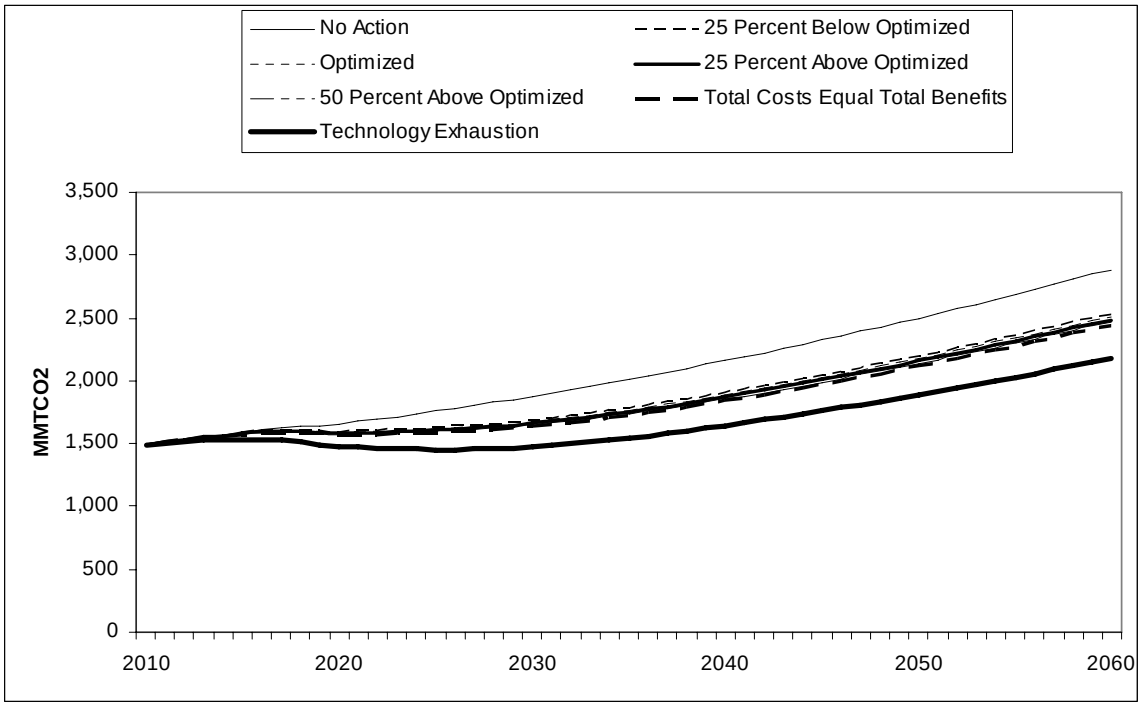
Alternative	Emissions	Emissions Reductions Compared to No Action Alternative
1 No Action	221,258	0
2 25 Percent Below Optimized	196,937	24,321
3 Optimized	195,816	25,442
4 25 Percent Above Optimized	194,057	27,201
5 50 Percent Above Optimized	192,478	28,780
6 Total Costs Equal Total Benefits	191,073	30,185
7 Technology Exhaustion	172,101	49,157

To gain a sense of the relative impact of these reductions, it can be helpful to compare them against emissions projections from the transportation sector, and expected or stated goals from existing programs designed to reduce CO_2 emissions. For ease of comparison, NHTSA focuses on the Optimized Alternative for this discussion.

As mentioned earlier, U.S. cars and light trucks account for 19.2 percent of CO_2 emissions in the United States. Thus, with the action alternatives reducing U.S. car and light truck CO_2 emissions by 11 to 22 percent, this would represent a reduction of 2.1 to 4.3 percent of total U.S. CO_2 emissions (assuming

the relative contribution of cars and light trucks stays the same). Projected annual emissions from cars and light trucks under the MY 2011-2015 and MY 2016-2020 CAFE standards are shown in Figure 4.4-6.

Figure 4.4-6. Reference Case Cumulative Annual Emissions Under the MY 2011-2015 Standards and Potential MY 2016-2020 Standards ($MMTCO_2$)



Emissions of CO_2, the primary gas that drives climate effects, from the U.S. automobile and light truck fleet represented about 2.5 percent of total global emissions of CO_2 in 2000 (EPA 2008a, WRI 2008). Although substantial, this source is a still small percentage of global emissions. The relative contribution of CO_2 emissions from the U.S. light vehicle fleet is expected to decline in the future, due primarily to rapid growth of emissions from developing economies (which are due in part to growth in global transportation sector emissions). In the SRES A1B (medium) scenario (Nakicenovic *et al.* 2000), the share of liquid fuel use, mostly petroleum and biofuels, from OECD countries declines from 60 percent in 2000 to 17 percent in 2100.

In their *Annual Energy Outlook 2007*, the EIA projects U.S. transportation-derived CO_2 emissions will increase from 2,037 $MMTCO_2$ in 2010 to 2,682 $MMTCO_2$ in 2030, with cumulative emissions from transportation over this period reaching 49,287 $MMTCO_2$. Over this same period, the emissions reductions from this rulemaking are projected to be 1,582 to 3,870 $MMTCO_2$, which would yield a 3- to 8-percent reduction in emissions from the transportation sector. The emissions reductions as a result of increasing fuel economy standards would be expected to increase further as new vehicles enter the fleet and older vehicles are retired. For example, in 2030, projected emissions reductions would be 192 to 402 $MMTCO_2$, a 7- to 15-percent decrease from projected U.S. transportation emissions of 2,682 $MMTCO_2$ in 2030. It is important to note that the EIA did not account for the expected effects of this rulemaking in their forecast (EIA 2007), thus allowing a comparison of the impact of this rulemaking to U.S. transportation emissions under the No Action Alternative.

As another measure of the relative environmental impact of this rulemaking, these emissions reductions can be compared to existing programs designed to reduce GHG emissions in the United States. In 2007, Arizona, California, New Mexico, Oregon, and Washington formed the Western Climate

Initiative (WCI) to develop regional strategies to address climate change. WCI has a stated goal of reducing 350 $MMTCO_2$ equivalent over the period from 2009 to 2020 (WCI 2007a). Emissions levels in 2020 would represent a 33-percent reduction from the future baseline, and a 15-percent reduction from the beginning of the action (WCI 2007b). By comparison, this rulemaking is expected to reduce CO_2 emissions by 197 to 755 $MMTCO_2$ over the same time period, with emissions levels in 2020 representing a 4- to 11-percent reduction from the future baseline emissions for cars and light trucks. In the Northeast, nine Northeast and Mid-Atlantic states have formed the Regional Greenhouse Gas Initiative (RGGI) to reduce CO_2 emissions from power plants. Emissions reductions from 2006 to 2024 are estimated at 268 $MMTCO_2$ (RGGI 2006).[17] This represents a 23-percent reduction from the future baseline and a 10-percent reduction from the beginning of the action (RGGI 2006). By comparison, NHTSA forecasts that this rulemaking will reduce CO_2 emissions by 593 to 1,731 $MMTCO_2$ over this timeframe, with emissions levels in 2024 representing a 7- to 16-percent reduction from the future baseline emissions for cars and light trucks.

Two points are important to note. First, emissions from sources addressed in the WCI and RGGI both *decrease* compared to the beginning of the action, while emissions from cars and trucks continue to *increase* under this rulemaking – despite increased fuel efficiency – due to increases in VMT. Second, these projections are only estimates, and the scopes of these climate programs differ from this rulemaking in geography, sector, and purpose. Also, the approach, goals, and methods of reductions vary between NHTSA's action and these initiatives. However, the expected end result – reduction of tons of CO_2 – for all these initiatives is similar.

The Stabilization Wedge Theory described by Pacala and Socolow (2004) for climate change mitigation includes a graphical representation of the contributions of many GHG reduction initiatives and the ability for all of these "wedges," over time, to add up to a climate change solution. The reductions from this rulemaking could be viewed in this context as being one of many needed to reduce U.S. transportation emissions.

Where information in the analysis included in this FEIS is incomplete or unavailable, NHTSA has relied on CEQ regulations regarding incomplete or unavailable information (40 CFR § 1502.22(b)). In this case, the comparison of emissions reductions from the action alternatives to emissions reductions associated with other programs is intended to aid decisionmakers by providing relative benchmarks, rather than absolute metrics for selecting among alternatives. In summary, the alternatives analyzed here deliver GHG emissions reductions that are on the same scale as many of the most progressive and ambitious GHG emissions reduction programs underway in the United States.

4.4.4.2 Direct and Indirect Effects on Climate Change

The approach to estimating the cumulative effects of climate change from the MY 2011-2015 CAFE standards combined with the potential MY2016-2020 CAFE standards mirrors that used to estimate the direct and indirect effects of the MY 2011-2015 CAFE standards. Again, because EISA requires average fuel economy of the passenger cars and light trucks to reach a combined average of at least 35 mpg by 2020, the MY 2016-2020 CAFE standards are a reasonably foreseeable future action and, therefore, must be accounted for when analyzing the cumulative impacts of the MY 2011-2015 CAFE standards. For each alternative, NHTSA assumed that passenger-car and light-truck CAFE standards would continue to increase over MY 2016-2020 at their average annual rate of increase over MY 2011-2015. This assumption results in passenger-car and light-truck CAFE standards under each action alternative that meet or exceed the EISA requirement of a combined fleet average of at least 35 mpg by

[17] Emission reductions were estimated by determining the difference between the RGGI Cap and the Phase III RGGI Reference Case. These estimates do not include offsets.

model year 2020. NHTSA assumed further that the fuel economy standards for model year 2020 would remain in effect through the end of the analysis period. Because the CAFE standards apply to new vehicles, this assumption results in emissions reductions and fuel savings that continue to grow as new vehicles meeting the CAFE standards for MY 2020 and beyond are added to the fleet in each subsequent year, reaching their maximum values when all passenger cars and light trucks in the U.S. fleet meet these standards. Overall, the emissions reductions for the MY 2011-2015 CAFE standards have a small impact on climate change. The emissions reductions and resulting climate impacts for the MY 2011-2015 and MY 2016-2020 CAFE standards are larger, although they are still relatively small in absolute terms.

The direct and indirect effects of the alternatives on climate change are described in the following section in terms of (1) atmospheric CO_2 concentrations, (2) temperature, (3) precipitation, and (4) sea-level rise.

4.4.4.2.1 Atmospheric Carbon Dioxide Concentrations

MAGICC is a simple climate model that is well calibrated to the mean of the multi-model ensemble results for three of the most commonly used emissions scenarios – B1 (low), A1B (medium), and A2 (high) from the IPCC SRES series – as shown in Table 4.4-2.[18] As the table indicates, the model runs developed for this analysis achieve relatively good agreement with IPCC WGI estimates in terms of both CO_2 concentrations and surface temperature.

Table 4.4-2

Comparison of MAGICC Results and Reported IPCC Results (IPCC 2007a)

	CO_2 Concentration (ppm)		Global Mean Increase in Surface Temperature (°C)		Sea-level Rise (cm)	
Scenario	**IPCC WGI (2100)**	**MAGICC (2100)**	**IPCC WGI (2080-2099)**	**MAGICC (2090)**	**IPCC WGI (2090-2099) a/**	**MAGICC (2095)**
B1	550	538.3	1.79	1.81	28	26
A1B	715	717.2	2.65	2.76	35	35
A2	836	866.8	3.13	3.31	37	38

a/ The IPCC values represent the average of the 5- to 95-percent range of the rise of sea level between 1980 to 1989 and 2090 to 2099.

A comparison of the sea-level rise from MAGICC 5.3 and the IPCC Fourth Assessment Report can be found in the release documentation for MAGICC 5.3 (Wigley 2008). In Table 3 of the documentation, Wigley (2008) presents the results for six SRES scenarios that show the comparable value for sea-level rise from MAGICC 5.3 (total sea-level rise minus estimates for contributions from non-melt sources such as warming of the permafrost) within 0.01 centimeter (cm) in 2095.

As discussed earlier in Section 3.4.2, the SRES A1B scenario was used to represent the No Action Alternative (Alternative 1) in the MAGICC runs for this FEIS. Table 4.4-3 and Figures 4.4-7 to 4.4-10 show the mid-range results of MAGICC model simulations for Alternative 1 and the six action alternatives for CO_2 concentrations and increase in global mean surface temperature in 2030, 2060, and 2100. As Figures 4.4-7 and 4.4-8 show, the impact on the growth in CO_2 concentrations and temperature is just a fraction of the total growth in CO_2 concentrations and global mean surface temperature. However, the relative impact of the CAFE alternatives is illustrated by the reduction in growth of both CO_2 concentrations and temperature in the Technology Exhaustion Alternative (Alternative 7).

[18] NHTSA used the default climate sensitivity in MAGICC of 3.0 °C.

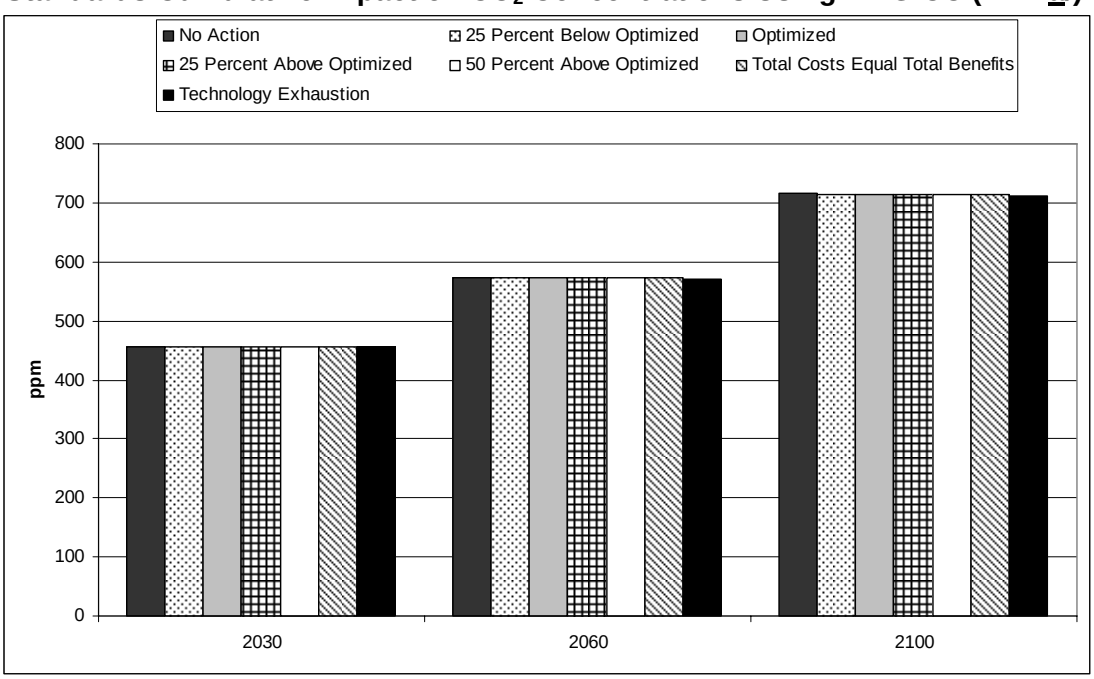
Table 4.4-3

Reference Case MY 2011-2015 Standards and Potential MY 2016-2020 Standards Cumulative Impact on CO_2 Concentrations, Surface Temperature Increase, and Sea-level Rise Using MAGICC (A1B a/)

	CO_2 Concentration (ppm)			Surface Temperature Increase (°C)			Sea-level Rise (cm)		
	2030	2060	2100	2030	2060	2100	2030	2060	2100
Totals by Alternative									
1 No Action (A1B-AIM)	455.5	573.7	717.2	0.874	1.944	2.959	7.99	19.30	37.10
2 25 Percent Below Optimized	455.4	572.7	714.9	0.873	1.940	2.950	7.99	19.27	37.02
3 Optimized	455.4	572.7	714.8	0.873	1.940	2.950	7.99	19.27	37.02
4 25 Percent Above Optimized	455.3	572.6	714.7	0.873	1.940	2.949	7.99	19.27	37.01
5 50 Percent Above Optimized	455.3	572.5	714.5	0.873	1.940	2.948	7.99	19.27	37.01
6 Total Costs Equal Total Benefits	455.3	572.5	714.4	0.873	1.939	2.948	7.99	19.26	37.00
7 Technology Exhaustion	455.1	571.7	712.6	0.871	1.934	2.938	7.99	19.23	36.92
Reduction under CAFE Alternatives									
2 25 Percent Below Optimized	0.1	1.0	2.3	0.001	0.004	0.009	0.00	0.03	0.08
3 Optimized	0.1	1.0	2.4	0.001	0.004	0.009	0.00	0.03	0.08
4 25 Percent Above Optimized	0.2	1.1	2.5	0.001	0.005	0.010	0.00	0.03	0.09
5 50 Percent Above Optimized	0.2	1.2	2.7	0.001	0.005	0.011	0.00	0.03	0.09
6 Total Costs Equal Total Benefits	0.2	1.2	2.8	0.001	0.005	0.011	0.00	0.04	0.10
7 Technology Exhaustion	0.4	2.0	4.6	0.002	0.010	0.020	0.00	0.07	0.18

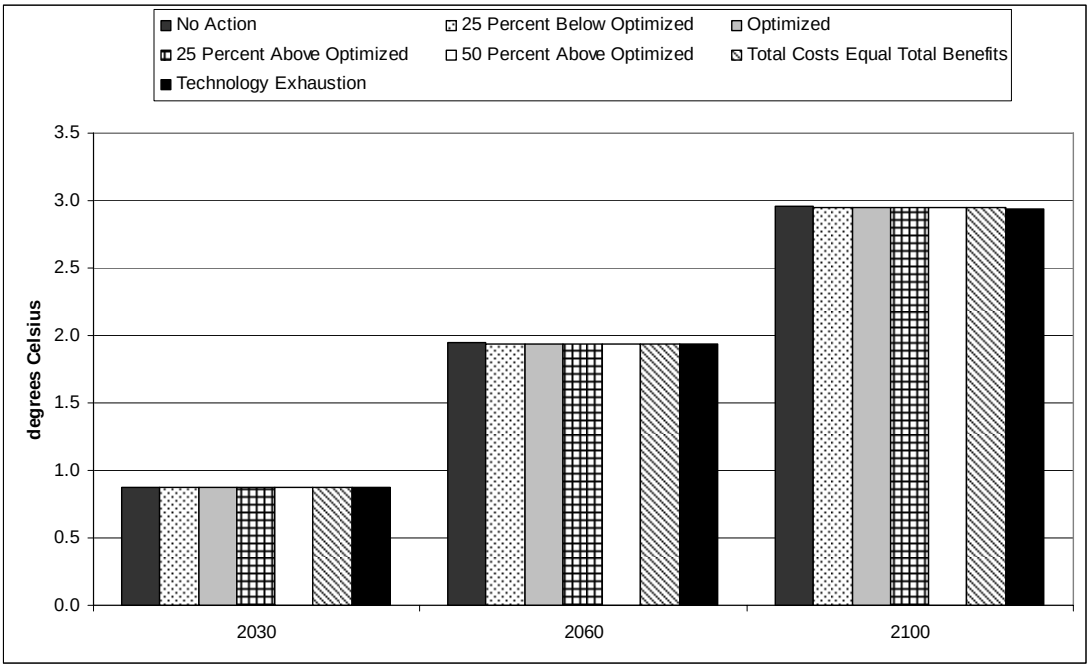
a/ The A1B scenario is the SRES marker scenario used by the IPCC WGI to represent the SRES A1B (medium) storyline.

Figure 4.4-7. Reference Case MY 2011-2015 Standards and Potential MY 2016-2020 Standards Cumulative Impact on CO_2 Concentrations Using MAGICC (A1B a/)



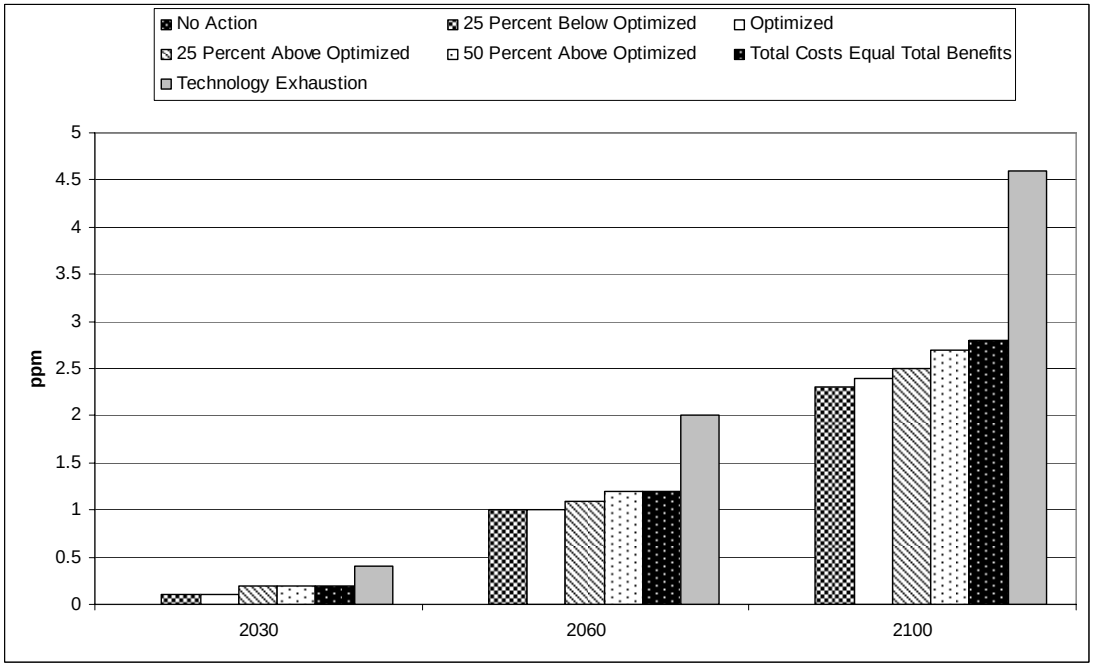
a/ The A1B scenario is the SRES marker scenario used by the IPCC WGI to represent the SRES A1B (medium) storyline.

Figure 4.4-8. Reference Case MY 2011-2015 Standards and Potential MY 2016-2020 Standards Cumulative Impact on the Global Mean Surface Temperature Increase Using MAGICC (A1B a/)



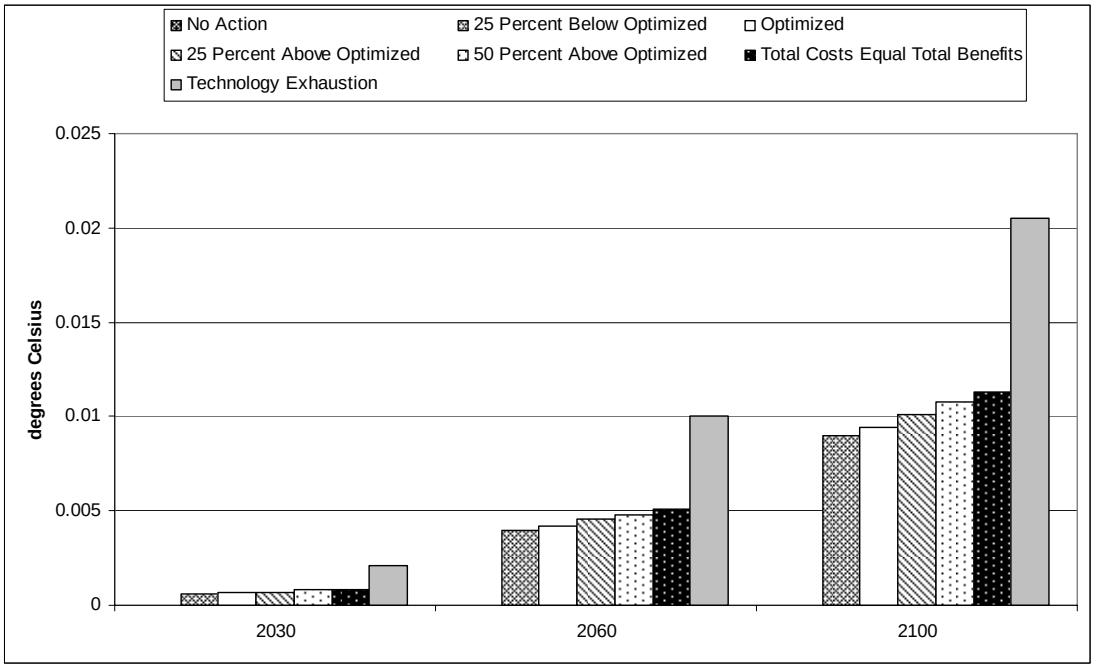
a/ The A1B scenario is the SRES marker scenario used by the IPCC WGI to represent the SRES A1B (medium) storyline.

Figure 4.4-9. Reference Case MY 2011-2015 Standards and Potential MY 2016-2020 Standards Cumulative Impact on the Reduction in the Growth of CO_2 Concentrations Using MAGICC (A1B a/)



a/ The A1B scenario is the SRES marker scenario used by the IPCC WGI to represent the SRES A1B (medium) storyline.

Figure 4.4-10. Reference Case MY 2011-2015 Standards and Potential MY 2016-2020 Standards Cumulative Impact on the Reduction in the Growth of Global Mean Temperature Using MAGICC (A1B a/)



a/ The A1B scenario is the SRES marker scenario used by the IPCC WGI to represent the SRES A1B (medium) storyline.

As shown in Figures 4.4-9 and 4.4-10, the reduction in increase of CO_2 concentrations and the reduction in increase of temperature under the No Action Alternative is nearly twice that of the 25 Percent Below Optimized Alternative (Alternative 2).

As shown in the table and figures, there is a fairly narrow band of estimated CO_2 concentrations as of 2100, from 713 ppm for the Technology Exhaustion Alternative to 717 ppm for the No Action Alternative. For 2030 and 2060, the range is even smaller. Because CO_2 concentrations are the key driver of all other climate effects, this leads to small differences in these effects.

4.4.4.2.2 Temperature

The MAGICC simulations of mean global surface air temperature increases are shown above in Table 4.4-3. For all alternatives, the cumulative global mean surface temperature increase is about 0.87 °C as of 2030, 1.93 to 1.94 °C as of 2060, and 2.94 to 2.96 °C as of 2100 (Table 4.4-3). The differences among alternatives are small. For 2100, the reduction in temperature increase relative to the No Action Alternative ranges from 0.009 °C to 0.02 °C.

Table 4.4-4 summarizes the regional changes to warming and seasonal temperatures from the IPCC Fourth Assessment Report. Quantifying the changes to regional climate from the CAFE alternatives is not possible at this point, but it is expected that the alternatives would reduce the changes relative to the reduction in global mean surface temperature.

Table 4.4-4

Summary of Regional Changes to Warming and Seasonal Temperatures Extracted from the IPCC Fourth Assessment Report (Christensen *et al.* 2007)

Land Area	Sub-region	Mean Warming	Maximum Summer Temperatures
Africa	Mediterranean area and northern Sahara	*Likely* larger than global mean throughout continent and in all seasons	
	Southern Africa and western margins		
	East Africa		
Mediterranean and Europe	Northern Europe	*Likely* to increase more than the global mean with largest warming in winter	
	Southern and Central Europe		Maximum Summer Temperatures *likely* to increase more than average
	Mediterranean area		
Asia	Central Asia	*Likely* to be well above the global mean	
	Tibetan Plateau	*Likely* to be well above the global mean	
	Northern Asia	*Likely* to be well above the global mean	
	Eastern Asia	*Likely* to be above the global mean	*Very likely* that heat waves/hot spells in summer will be of longer duration, more intense and more frequent *Very likely* fewer very cold days
	South Asia	*Likely* to be above the global mean	*Very likely* fewer very cold days
	Southeast Asia	*Likely* to be similar to the global mean	
North America	Northern regions/Northern North America	*Likely* to exceed the global mean	Warming *likely* to be largest in winter Minimum winter temperatures *likely* to increase more than the average
	Southwest		Warming *likely* to be largest in summer Maximum summer temperatures *likely* to increase more than the average
	Northeast USA		
	Southern Canada		
	Canada		
	Northernmost part of Canada		

Table 4.4-4 (cont'd)

Summary of Regional Changes to Warming and Seasonal Temperatures Extracted from the IPCC Fourth Assessment Report (Christensen *et al.* 2007)

Land Area	Sub-region	Mean Warming	Maximum Summer Temperatures
Central and South America	Southern South America	*Likely* to be similar to the global mean	
	Central America	*Likely* to be larger than global mean	
	Southern Andes		
	Tierra del Fuego		
	Southeastern South America		
	Northern South America		
Australia and New Zealand	Southern Australia	*Likely* comparable to the global mean but less than in the rest of Australia	Increased frequency of extreme high daily temperatures and a decrease in the frequency of cold extremes *very likely*
	Southwestern Australia	*Likely* comparable to the global mean	
	Rest of Australia	*Likely* comparable to the global mean	
	New Zealand, South Island	*Likely* less than the global mean	
	Rest of New Zealand	*Likely* comparable to the global mean	
Polar Regions	Arctic	*Very likely* to warm during this century more than the global mean	Warming largest in winter and smallest in summer
	Antarctic	*Likely* to warm	
Small Islands		*Likely* to be smaller than the global annual mean	

MAGICC 5.3 estimates radiative forcing from black carbon, a primary aerosol emitted through the incomplete combustion of fossil fuel and biomass burning. However, emissions trends for black carbon are "hard-wired" in the model to follow emissions of SO_2, which means they cannot be specified separately in the model.[19] The radiative forcing of black carbon is difficult to quantify accurately as it is a function of microphysical properties, the geographic and vertical placement, and lifetime of the aerosol; however, black carbon clearly contributes substantially to global warming (Jacobson 2001). Total global black carbon emissions are estimated to be approximately 8 TgC/yr (Bond *et al.* 2004, as cited in Forster *et al.* 2007), with estimates of fossil fuel contributions ranging from 2.8 TgC/yr (Ito and Penner 2005, as cited in Forster *et al.* 2007) to 8.0 TgC/yr (Haywood and Boucher 2000, as cited in Forster *et al.* 2007). The United States is estimated to contribute 6.1 percent of the global soot emissions, with non-road vehicles, on road vehicles, stack emissions, and fugitive sources comprising major sources (Jacobson Testimony 2007). In summary, the climate modeling does take into account the effects of black carbon on climate variables.

[19] Accurately determining the magnitude of mobile source emissions of black carbon is difficult because the emissions vary with fuel properties and fluctuations in the combustion environment. MOBILE6.2 outputs particulate matter mass that is then incorporated in the Volpe model. This particulate matter is based on tailpipe emissions and thereby includes carbon emissions from the combustion process. Because the carbon emissions are lumped into the particulate matter and not treated independently, the Volpe model does not provide direct results of the impact of the carbon emissions.

4.4.4.2.3 Precipitation

According to the IPCC WGI (Meehl *et al.* 2007), global mean precipitation is expected to increase under all scenarios. Generally, precipitation increases would occur in the tropical regions and high latitudes, with decreases in the sub-tropics. The results from the AOGCMs suggest considerable uncertainty in future precipitation for the five SRES scenarios. Where information in the analysis included in this FEIS is incomplete or unavailable, the agency has relied on CEQ regulations regarding incomplete or unavailable information *(see* 40 CFR § 1502.22(b)). In this case, the IPCC (Meehl *et al.* 2007) summary of precipitation represents the most thoroughly reviewed, credible assessment of this highly uncertain factor. NHTSA expects that the CAFE alternatives would reduce the changes in precipitation in proportion to their effects on temperature.

The global mean change in precipitation provided by the IPCC for the A2 (high), A1B (medium), and B1 (low) scenarios (Meehl *et al.* 2007) is given as the scaled change in precipitation (as a percentage change from 1980-1999 averages) divided by the increase in global mean surface warming for the same period (per °C), as shown in Table 4.4-5 below. IPCC provided scaling factors in the year ranges 2011-2030, 2046-2065, 2080-2099, and 2180-2199. The scaling factors for the A1B (medium) scenario were used in this FEIS analysis because MAGICC does not directly estimate changes in global mean precipitation.

Table 4.4-5

Global Mean Precipitation Change (scaled, % per °C) (Meehl *et al.* 2007)

Scenario	2011-2030	2046-2065	2080-2099	2180-2199
A2	1.38	1.33	1.45	NA
A1B	1.45	1.51	1.63	1.68
B1	1.62	1.65	1.88	1.89

Applying these scaling factors to the reductions in global mean surface warming provides estimates of changes in global mean precipitation. Given that the action alternatives would reduce temperature increases slightly relative to the No Action Alternative, they also would reduce predicted increases in precipitation slightly, as shown in Table 4.4-6 (again, based on the A1B [medium] scenario).

In addition to changes in mean annual precipitation, climate change is anticipated to affect the intensity of precipitation as described below (Meehl *et al.* 2007):

> "Intensity of precipitation events is projected to increase, particularly in tropical and high latitude areas that experience increases in mean precipitation. Even in areas where mean precipitation decreases (most subtropical and mid-latitude regions), precipitation intensity is projected to increase but there would be longer periods between rainfall events. There is a tendency for drying of the mid-continental areas during summer, indicating a greater risk of droughts in those regions. Precipitation extremes increase more than does the mean in most tropical and mid- and high-latitude areas."

Regional variations and changes in the intensity of precipitation events cannot be quantified further. This inability is due primarily to the lack of availability of AOGCMS required to estimate these changes. AOGCMS are typically used to provide results among scenarios having very large changes in emissions such as the SRES B1 (low), A1B (medium), and A2 (high) scenarios; very small changes in emissions profiles produce results that would be difficult to resolve among scenarios having relatively small changes in emissions. Also, the multiple AOGCMs produce results that are regionally consistent in some cases but are inconsistent in others.

Table 4.4-6

Reference Case MY 2011-2015 Standards and Potential MY 2016-2020 Standards Cumulative Impact on Reductions in Global Mean Precipitation based on A1B a/ SRES Scenario (% change), Using Increases in Global Mean Surface Temperature Simulated by the MAGICC Model

Scenario	2020	2055	2090
Global Mean Precipitation Change (scaled, % K-1)			
	1.45	1.51	1.63
Global Temperature above average 1980-1999 levels (°C) for the A1B scenario and CAFE Alternatives, mid-level results			
1. No Action	0.560	1.764	2.765
2. 25 Percent Below Optimized	0.560	1.759	2.753
3. Optimized	0.560	1.758	2.752
4. 25 Percent Above Optimized	0.560	1.758	2.751
5. 50 Percent Above Optimized	0.560	1.757	2.750
6. Total Costs Equal Total Benefits	0.560	1.757	2.750
7. Technology Exhaustion	0.559	1.756	2.749
Reduction in Global Temperature (°K) for CAFE Alternatives, mid-level results (compared to No Action Alternative)			
2. 25 Percent Below Optimized	0.000	0.005	0.011
3. Optimized	0.000	0.006	0.013
4. 25 Percent Above Optimized	0.000	0.006	0.014
5. 50 Percent Above Optimized	0.000	0.007	0.015
6. Total Costs Equal Total Benefits	0.000	0.007	0.015
7. Technology Exhaustion	0.000	0.008	0.016
Mid Level Global Mean Precipitation Change (%)			
1. No Action	0.81%	2.66%	4.51%
2. 25 Percent Below Optimized	0.81%	2.66%	4.49%
3. Optimized	0.81%	2.65%	4.49%
4. 25 Percent Above Optimized	0.81%	2.65%	4.48%
5. 50 Percent Above Optimized	0.81%	2.65%	4.48%
6. Total Costs Equal Total Benefits	0.81%	2.65%	4.48%
7. Technology Exhaustion	0.81%	2.65%	4.48%
Reduction in Global Mean Precipitation Change for CAFE Alternatives (% compared to No Alternative Action)			
2. 25 Percent Below Optimized	0.00%	0.01%	0.02%
3. Optimized	0.00%	0.01%	0.02%
4. 25 Percent Above Optimized	0.00%	0.01%	0.02%
5. 50 Percent Above Optimized	0.00%	0.01%	0.02%
6. Total Costs Equal Total Benefits	0.00%	0.01%	0.02%
7. Technology Exhaustion	0.00%	0.01%	0.03%

a/ The A1B scenario is the SRES marker scenario used by the IPCC WGI to represent the SRES A1B (medium) storyline.

Table 4.4-7 summarizes the regional changes to precipitation from the IPCC Fourth Assessment Report. Quantifying the changes to regional climate from the action alternatives is not possible at this point, but the action alternatives would reduce the changes relative to the reduction in global mean surface temperature.[20]

Table 4.4-7

Summary of Regional Changes to Precipitation Extracted from the IPCC Fourth Assessment (Christensen *et al.* 2007)

Land Area	Sub-region	Precipitation	Snow Season and Snow Depth
Africa	Mediterranean area and northern Sahara	*Very likely* to decrease	
	Southern Africa and western margins	Winter rainfall *likely* to decrease in southern	
	East Africa	*Likely* to be an increase in annual mean precipitation	
Mediterranean and Europe	Northern Europe	*Very likely* to increase and extremes are *likely* to increase	*Likely* to decrease
	Southern and Central Europe		
	Mediterranean area	*Very likely* to decrease and precipitation days *very likely* to decrease	
Asia	Central Asia	Precipitation in summer *likely* to decrease	
	Tibetan Plateau	Precipitation in boreal winter *very likely* to increase	
	Northern Asia	Precipitation in boreal winter *very likely* to increase Precipitation in summer *likely* to increase	
	Eastern Asia	Precipitation in boreal winter *likely* to increase Precipitation in summer *likely* to increase *Very likely* to be an increase in the frequency of intense precipitation Extreme precipitation and winds associated with tropical cyclones *likely* to increase	

[20] *See* 42 U.S.C. § 4332 (requiring federal agencies to "identify and develop methods and procedures … which will insure that presently unquantified environmental amenities and values may be given appropriate consideration"); 40 CFR § 1502.23 (requiring an EIS to discuss the relationship between a cost-benefit analysis and any analyses of unquantified environmental impacts, values, and amenities); CEQ, *Considering Cumulative Effects Under the National Environmental Policy Act* (1984), *available at* http://ceq.hss.doe.gov/nepa/ccenepa/ccenepa.htm (last visited June 20, 2008) (recognizing that agencies are sometimes "limited to qualitative evaluations of effects because cause-and-effect relationships are poorly understood" or cannot be quantified).

Table 4.4-7 (cont'd)

Summary of Regional Changes to Precipitation Extracted from the IPCC Fourth Assessment (Christensen *et al*. 2007)

Land Area	Sub-region	Precipitation	Snow Season and Snow Depth
	South Asia	Precipitation in summer *likely* to increase *Very likely* to be an increase in the frequency of intense precipitation Extreme precipitation and winds associated with tropical cyclones *likely* to increase	
	Southeast Asia	Precipitation in boreal winter *likely* to increase in southern parts Precipitation in summer *likely* to increase in most parts of southeast Asia Extreme precipitation and winds associated with tropical cyclones *likely* to increase	
North America	Northern regions/Northern North America		Snow season length and snow depth *very likely* to decrease
	Southwest	Annual mean precipitation is *likely* to decrease	
	Northeast USA	Annual mean precipitation *very likely* to increase	
	Southern Canada		
	Canada	Annual mean precipitation *very likely* to increase	
	Northernmost part of Canada		Snow season length and snow depth *likely* to increase
Central and South America	Southern South America		
	Central America	Annual precipitation *likely* to decrease	
	Southern Andes	Annual precipitation *likely* to decrease	
	Tierra del Fuego	Winter precipitation *likely* to increase	
	Southeastern South America	Summer precipitation *likely* to increase	
	Northern South America	Uncertain how precipitation will change	
Australia and New Zealand	Southern Australia	Precipitation *likely* to decrease in winter and spring	
	Southwestern Australia	Precipitation *very likely* to decrease in winter	
	Rest of Australia		
	New Zealand, South Island	Precipitation *likely* to increase in the west	
	Rest of New Zealand		

Table 4.4-7 (cont'd)

Summary of Regional Changes to Precipitation Extracted from the IPCC Fourth Assessment (Christensen *et al*. 2007)

Land Area	Sub-region	Precipitation	Snow Season and Snow Depth
Polar Regions	Arctic	Annual precipitation *very likely* to increase; *Very likely* that the relative precipitation increase will be largest in winter and smallest in summer	
	Antarctic	Precipitation *likely* to increase	
Small Islands		Mixed, depending on the region	

4.4.4.2.4 Sea-level Rise

IPCC identifies four primary components to sea-level rise: thermal expansion of ocean water, melting of glaciers and ice caps, loss of land-based ice in Antarctica, and loss of land-based ice in Greenland (IPCC 2007c). Ice sheet discharge is an additional factor that could influence sea level over the long term. MAGICC calculates the oceanic thermal expansion component of global-mean sea-level rise, using a non-linear temperature- and pressure-dependent expansion coefficient (Wigley 2003 to 2008). The model also addresses the other three primary components using ice-melt models for small glaciers and the Greenland and Antarctic ice sheets, and excludes non-melt sources, which the IPCC Fourth Assessment Report also excluded. Neither MAGICC 5.3 nor the Fourth Assessment Report include the more recent information suggesting accelerated ice flow from Greenland and Antarctica, which the Fourth Assessment Report estimates to be between 9 and 17 centimeters by 2100 (Wigley 2008).

The state of the science reflected in the IPCC Fourth Assessment Report projects sea level to rise 18 to 59 centimeters by 2090-2099 (Parry *et al.* 2007, as cited in National Science and Technology Council 2008). This projection does not include all changes in ice sheet flow or the potential for rapid acceleration in ice loss (Alley *et al.* 2005, Gregory and Huybrechts 2006, Hansen 2005, all as cited in Pew 2007). Several recent studies have found that the IPCC projections of potential sea-level rise could underestimate ice loss from the Greenland and Antarctic ice sheets (Shepherd and Wingham 2007, Csatho *et al.* 2008) and ice loss from mountain glaciers (Meier *et al.* 2007). Further, IPCC might underestimate sea-level rise that would be gained through changes in global precipitation (Wentz *et al.* 2007, Zhang *et al.* 2007). Rahmstorf (2007) used a semi-empirical approach to project future sea-level rise. The approach yielded a proportionality coefficient of 3.4 millimeters (mm) per year per °C of warming, and a projected sea-level rise of 0.5 to 1.4 meter (m) above 1990 levels in 2100 when applying IPCC Third Assessment Report warming scenarios. Rahmstorf (2007) concludes that, "A rise over 1 m [meter] by 2100 for strong warming scenarios cannot be ruled out." Section 4.5.5 of this FEIS discusses sea-level rise in more detail.

The impact on sea-level rise from the scenarios is presented in Table 4.4-3, showing sea-level rise in 2100 ranging from 37.10 centimeters for the No Action Alternative to 36.92 centimeters for the Technology Exhaustion Alternative, for a maximum reduction of 0.18 centimeter by 2100 from the CAFE alternatives.

In summary, the impacts of the MY 2011-2015 and MY 2016-2020 standards on global mean surface temperature, sea-level rise, and precipitation are relatively small in the context of the expected changes associated with the emissions trajectories in the SRES scenarios. This is due primarily to the global and multi-sectoral nature of the climate problem.

4.4.4.2.5 SRES and Climate Sensitivity Variants

NHTSA examined the sensitivity of climate effects to key assumptions used in the analysis. This examination included reviewing the impact of the Optimized Alternative (Alternative 3) with various scenarios of global emissions and with various climate sensitivities. The results from the additional sensitivity runs for the action alternatives are presented with the Reference Case results (medium-level CAFE assumptions, 3.0 °C for a doubling of CO_2 climate sensitivity, SRES A1B emissions scenario).

The use of alternative global emissions scenarios can influence the results in several ways. Emissions reductions can lead to larger reductions in the CO_2 concentrations in later years because more of the anthropogenic emissions can be expected to stay in the atmosphere. The use of different climate sensitivities (the equilibrium warming that occurs at a doubling of CO_2 from pre-industrial levels) can affect not only warming but also indirectly affect sea-level rise and CO_2 concentration.

As shown in Table 4.4-8, the sensitivity of the simulated CO_2 emissions in 2030, 2060, and 2100 to assumptions of global emissions and climate sensitivity is low. The Optimized Alternative (Alternative 3) has the greatest impact in the SRES scenarios with the highest CO_2 emissions (A2 and A1FI) and the least impact in the scenarios with the lowest CO_2 emissions (B1). The total range of the impact of the Optimized Alternative on CO_2 concentrations in 2100 is from 2.1 to 2.6 ppm. The Reference Case using A1B and a 3.0 °C climate sensitivity has an impact of 2.4 ppm.

The sensitivity of the simulated global mean surface temperatures for 2030, 2060, and 2100 varies, as shown in Table 4.4-9. In 2030, the impact is low due primarily to the rate at which the global mean surface temperature increases in response to increases in radiative forcing. In 2100, the impact is large due not only to the climate sensitivity but also to the change in emissions. In 2030, the change from the 2.5 °C climate sensitivity to the 4.5 °C climate sensitivity is consistently 0.3 °C, as listed in Table 4.4-9. The impact on global mean surface temperature due to assumptions concerning global emissions of GHG is also important. The scenarios with the higher global emissions of GHGs such as A2 and A1FI have a lower reduction in global mean surface temperature and the scenarios with lower global emissions have a higher reduction. This is in large part due to the non-linear and near-logarithmic relationship between radiative forcing and CO_2 concentrations. At high emissions levels, CO_2 concentrations are high and, as a result, a fixed reduction in emissions yields a lower reduction in radiative forcing and global mean surface temperature.

The sensitivity of the simulated sea-level rise to change in climate sensitivity and global GHG emissions mirrors that of global temperature as shown in Table 4.4-10. Scenarios with lower climate sensitivities have lower increases in sea-level rise; the reduction in the increase in sea-level rise is lower with the Optimized Alternative. Conversely, scenarios with higher climate sensitivities have higher sea-level rise and the reduction in the increase of sea-level rise is less with the Optimized Alternative. Higher global GHG emissions have higher sea-level rise but the impact of the Optimized Alternative is less; conversely, lower global GHG emissions have lower sea-level rise and the reduction in sea-level rise is greater in the Optimized Alternative.

Table 4.4-8

Reference Case MY 2011-2015 Standards and Potential MY 2016-2020 Standards: Cumulative Impact on CO_2 Concentration (ppm) for Varying Climate Sensitivities and SRES Scenarios

SRES Scenario	CAFE Alternative	Climate Sensitivity (°C for 2xCO_2)	2030	2060	2100
A1B	1 No Action	2.5	454.9	570.9	708.8
		3.0	455.5	573.7	717.2
		4.5	457.1	580.5	739.1
	3 Optimized	2.5	454.7	569.9	706.4
		3.0	455.4	572.7	714.8
		4.5	456.9	579.5	736.7
	Reduction compared to No Action	2.5	0.2	1.0	2.4
		3.0	0.1	1.0	2.4
		4.5	0.2	1.0	2.4
A2	1 No Action	2.5	450.1	579.0	856.8
		3.0	450.7	581.6	866.8
		4.5	452.3	588.1	892.4
	3 Optimized	2.5	449.9	578.0	854.4
		3.0	450.5	580.6	864.3
		4.5	452.1	587.1	889.8
	Reduction compared to No Action	2.5	0.2	1.0	2.4
		3.0	0.2	1.0	2.5
		4.5	0.2	1.0	2.6
B1	1 No Action	2.5	436.1	505.4	533.2
		3.0	436.7	507.5	538.3
		4.5	438.3	512.7	551.5
	3 Optimized	2.5	435.9	504.4	531.1
		3.0	436.6	506.5	536.1
		4.5	438.1	511.7	549.3
	Reduction compared to No Action	2.5	0.2	1.0	2.1
		3.0	0.1	1.0	2.2
		4.5	0.2	1.0	2.2
B2	1 No Action	2.5	427.3	499.4	613.3
		3.0	428.0	501.9	619.9
		4.5	429.7	507.8	637.1
	3 Optimized	2.5	427.1	498.5	611.1
		3.0	427.8	500.9	617.7
		4.5	429.5	506.8	634.8
	Reduction compared to No Action	2.5	0.2	0.9	2.2
		3.0	0.2	1.0	2.2
		4.5	0.2	1.0	2.3
A1F1	1 No Action	2.5	455.5	640.1	980.4
		3.0	456.2	643.4	993.5
		4.5	457.8	651.5	1026.9
	3 Optimized	2.5	455.3	639.1	977.9
		3.0	456.0	642.4	990.9
		4.5	457.7	650.5	1024.3
	Reduction compared to No Action	2.5	0.2	1.0	2.5
		3.0	0.2	1.0	2.6
		4.5	0.1	1.0	2.6

Table 4.4-9

Reference Case MY 2011-2015 Standards and Potential MY 2016-2020 Standards: Cumulative Impact on Global Mean Surface Temperature Increase (°C) for Varying Climate Sensitivities and SRES Scenarios

SRES Scenario	CAFE Alternative	Climate Sensitivity (°C for $2xCO_2$)	2030	2060	2100
A1B	1 No Action	2.5	0.777	1.715	2.569
		3.0	0.874	1.944	2.959
		4.5	1.099	2.493	3.937
	3 Optimized	2.5	0.777	1.711	2.560
		3.0	0.873	1.940	2.950
		4.5	1.098	2.488	3.925
	Reduction compared to No Action	2.5	0.001	0.004	0.008
		3.0	0.001	0.004	0.009
		4.5	0.001	0.005	0.012
A2	1 No Action	2.5	0.719	1.685	3.343
		3.0	0.811	1.906	3.812
		4.5	1.027	2.436	4.959
	3 Optimized	2.5	0.719	1.681	3.336
		3.0	0.810	1.902	3.803
		4.5	1.026	2.431	4.948
	Reduction compared to No Action	2.5	0.001	0.004	0.007
		3.0	0.001	0.004	0.008
		4.5	0.001	0.005	0.011
B1	1 No Action	2.5	0.671	1.206	1.615
		3.0	0.759	1.377	1.880
		4.5	0.968	1.796	2.557
	3 Optimized	2.5	0.670	1.202	1.605
		3.0	0.758	1.373	1.868
		4.5	0.967	1.790	2.543
	Reduction compared to No Action	2.5	0.001	0.004	0.010
		3.0	0.001	0.005	0.011
		4.5	0.001	0.006	0.014
B2	1 No Action	2.5	0.756	1.401	2.256
		3.0	0.854	1.598	2.597
		4.5	1.086	2.077	3.456
	3 Optimized	2.5	0.755	1.397	2.247
		3.0	0.853	1.594	2.587
		4.5	1.085	2.071	3.443
	Reduction compared to No Action	2.5	0.001	0.004	0.009
		3.0	0.001	0.005	0.010
		4.5	0.001	0.006	0.013
A1F1	1 No Action	2.5	0.810	2.185	3.864
		3.0	0.911	2.463	4.414
		4.5	1.146	3.118	5.762
	3 Optimized	2.5	0.809	2.182	3.857
		3.0	0.910	2.459	4.406
		4.5	1.145	3.113	5.753
	Reduction compared to No Action	2.5	0.001	0.003	0.007
		3.0	0.001	0.004	0.007
		4.5	0.001	0.005	0.009

Table 4.4-10

Reference Case MY 2011-2015 Standards and Potential MY 2016-2020 Standards: Cumulative Impact on Sea-level Rise (cm) for Varying Climate Sensitivities and SRES Scenarios

SRES Scenario	CAFE Alternative	Climate Sensitivity (°C for 2xCO_2)	2030	2060	2100
A1B	1 No Action	2.5	7.22	17.25	32.76
		3.0	7.99	19.30	37.10
		4.5	9.78	24.11	47.67
	3 Optimized	2.5	7.21	17.23	32.69
		3.0	7.99	19.27	37.02
		4.5	9.78	24.08	47.57
	Reduction compared to No Action	2.5	0.01	0.02	0.07
		3.0	0.00	0.03	0.08
		4.5	0.00	0.03	0.10
A2	1 No Action	2.5	7.08	16.86	36.98
		3.0	7.85	18.83	41.71
		4.5	9.63	23.48	53.11
	3 Optimized	2.5	7.08	16.83	36.91
		3.0	7.85	18.81	41.63
		4.5	9.62	23.45	53.01
	Reduction compared to No Action	2.5	0.00	0.03	0.07
		3.0	0.00	0.02	0.08
		4.5	0.01	0.03	0.10
B1	1 No Action	2.5	6.87	14.15	24.14
		3.0	7.63	15.86	27.40
		4.5	9.38	19.94	35.42
	3 Optimized	2.5	6.86	14.12	24.05
		3.0	7.62	15.83	27.30
		4.5	9.38	19.90	35.30
	Reduction compared to No Action	2.5	0.01	0.03	0.09
		3.0	0.01	0.03	0.10
		4.5	0.00	0.04	0.12
B2	1 No Action	2.5	7.14	15.30	28.84
		3.0	7.94	17.17	32.68
		4.5	9.79	21.63	42.06
	3 Optimized	2.5	7.14	15.27	28.76
		3.0	7.94	17.14	32.59
		4.5	9.79	21.60	41.94
	Reduction compared to No Action	2.5	0.00	0.03	0.08
		3.0	0.00	0.03	0.09
		4.5	0.00	0.03	0.12
A1F1	1 No Action	2.5	7.35	19.40	43.01
		3.0	8.15	21.67	48.59
		4.5	9.99	26.97	62.05
	3 Optimized	2.5	7.35	19.38	42.94
		3.0	8.15	21.64	48.52
		4.5	9.98	26.94	61.96
	Reduction compared to No Action	2.5	0.00	0.02	0.07
		3.0	0.00	0.03	0.07
		4.5	0.01	0.03	0.09

4.4.5 Input Scenarios

In response to public comments, and to test how different economic assumptions might affect estimates of emissions reductions and resulting climate effects, NHTSA modeled three additional scenarios – High, Mid-1, and Mid-2 – and compared the results to the Reference Scenario. Variables that were altered include fuel price, the social cost of carbon, oil import externalities, and the discount rate for other benefits.

For the High Scenario, NHTSA used the AEO 2008 high fuel prices, a social cost of carbon of $33/ton (2007 dollars), and a 3-percent discount rate for other benefits. Tables 4.4-11 and 4.4-12 show the emissions and emissions reductions due to the High Scenario.

Table 4.4-11

High Scenario MY 2011-2015 Standards and Potential MY 2016-2020 Standards Cumulative Emissions and Emissions Reductions for 2010 through 2100 ($MMTCO_2$)

Alternative	Emissions	Emissions Reductions
1 No Action	195,501	0
2 25 Percent Below Optimized	160,903	34,598
3 Optimized	157,088	38,413
4 25 Percent Above Optimized	154,618	40,884
5 50 Percent Above Optimized	151,781	43,721
6 Total Costs Equal Total Benefits	150,919	44,583
7 Technology Exhaustion	152,290	43,211

Table 4.4-12

High Scenario MY 2011-2015 Standards and Potential MY 2016-2020 Standards Cumulative Impact on CO_2 Concentrations, Global Mean Surface Temperature Increase, and Sea-level Rise in 2100 Using MAGICC (A1B a/)

	CO_2 Concentration (ppm)			Global Mean Surface Temperature Increase (°C)			Sea-level Rise (cm)		
Totals by Alternative	**2030**	**2060**	**2100**	**2030**	**2060**	**2100**	**2030**	**2060**	**2100**
1 No Action (A1B-AIM)	455.5	573.7	717.2	0.874	1.944	2.959	7.99	19.30	37.10
2 25 Percent Below Optimized	455.3	572.3	714.0	0.873	1.938	2.946	7.99	19.26	36.99
3 Optimized	455.2	572.1	713.6	0.872	1.937	2.944	7.99	19.25	36.97
4 25 Percent Above Optimized	455.2	572.0	713.4	0.872	1.937	2.943	7.99	19.25	36.96
5 50 Percent Above Optimized	455.2	571.9	713.1	0.872	1.936	2.942	7.99	19.25	36.95
6 Total Costs Equal Total Benefits	455.2	571.9	713.0	0.872	1.936	2.942	7.99	19.24	36.95
7 Technology Exhaustion	455.2	571.9	713.1	0.872	1.935	2.941	7.99	19.24	36.94
Reduction under CAFE Alternatives									
2 25 Percent Below Optimized	0.2	1.4	3.2	0.001	0.006	0.013	0.00	0.04	0.11
3 Optimized	0.3	1.6	3.6	0.001	0.007	0.015	0.00	0.05	0.13
4 25 Percent Above Optimized	0.3	1.7	3.8	0.001	0.007	0.016	0.00	0.05	0.14
5 50 Percent Above Optimized	0.3	1.8	4.1	0.001	0.008	0.017	0.00	0.05	0.15
6 Total Costs Equal Total Benefits	0.3	1.8	4.2	0.002	0.008	0.017	0.00	0.06	0.15
7. Technology Exhaustion	0.3	1.8	4.1	0.002	0.009	0.018	0.00	0.06	0.16

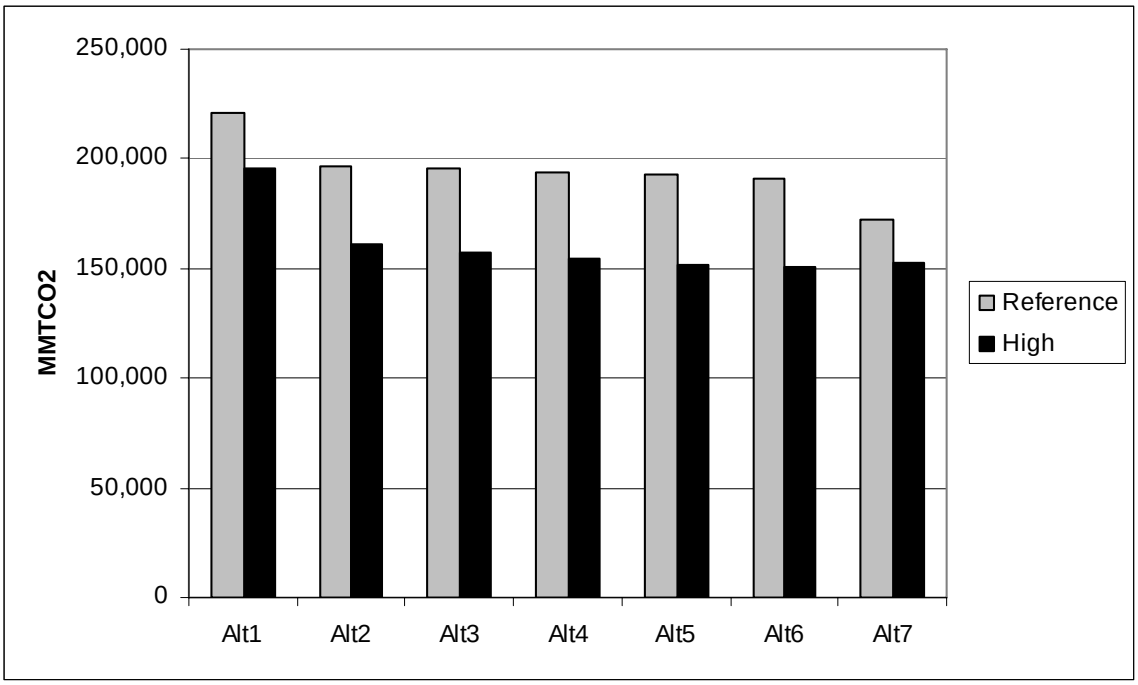
a/ The A1B scenario is the SRES marker scenario used by the IPCC WGI to represent the SRES A1B (medium) storyline.

Compared to the Reference Case, total emissions under the High Scenario were lower for all alternatives (*see* Figure 4.4-11). The primary reason for this difference is the lower VMT forecast under the High Scenario. Emissions reductions for Alternatives 2 through 7 compared to the No Action Alternative were all higher under the High Scenario than under the Reference Case, except for the Technology Exhaustion Alternative (*see* Figure 4.4-12). Emissions reductions were greater under the Technology Exhaustion Alternative for the Reference Case than for the High Scenario.

Table 4.4-12 lists the resulting effects on CO_2 concentration, global mean surface temperature, and sea-level rise. Under the High Scenario, the resulting CO_2 concentration, global mean surface temperature, and sea-level rise were lower than under the Reference Case for all action alternatives except the Technology Exhaustion Alternative. Thus, the differences for the action alternatives compared to the No Action Alternative are greater under the High Scenario than under the Reference Case, except for the Technology Exhaustion Alternative.[21]

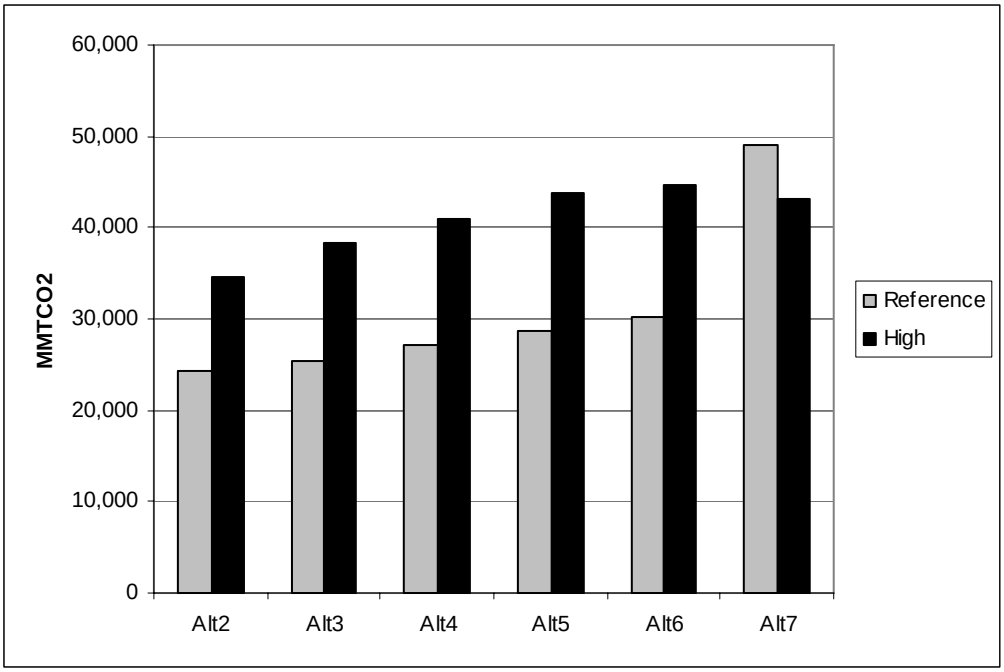
For the Mid-1 Scenario, NHTSA used the AEO 2008 high fuel prices, a social cost of carbon of $33/ton (2007 dollars), and a 7-percent discount rate for other benefits. Compared to the Reference Case, total emissions under the Mid-1 Scenario were lower for all alternatives. Emission reductions for all alternatives compared to the No Action Alternative were higher under the Mid-1 Scenario as compared to the Reference Case, except for the Technology Exhaustion Alternative. The primary reason for this

Figure 4.4-11. Comparison of Cumulative Emissions under the Reference Case and High Scenario Due to the MY 2011-2020 CAFE Standards from 2010-2100 ($MMTCO_2$)



[21] Note that in both the Reference Case and the High Scenario, the No Action Alternative is modeled to have the same emissions, *viz*. emissions set to the A1B scenario. This is the case even though, in absolute terms, U.S. passenger-care and light-truck emissions are lower in the High Scenario than in the Reference Case. In other words, the MAGICC model runs are intended to show relative differences in relation to a no action case; they are not intended to show absolute differences between Volpe model assumptions.

Figure 4.4-12. Comparison of Cumulative Emissions Reductions under the Reference Case and High Scenario Due to the MY 2011-2020 CAFE Standards from 2010-2100 ($MMTCO_2$)



difference is the lower VMT forecast under the Mid-1 Scenario. The resulting CO_2 concentration, global mean surface temperature, and sea-level rise were lower for all alternatives under the Mid-1 Scenario than under the Reference Case, except for the Technology Exhaustion Alternative. Thus, the differences between the action alternatives and the No Action Alternative are greater for the Mid-1 Scenario than for the Reference Case except for the Technology Exhaustion Alternative.

For the Mid-2 Scenario, NHTSA used the AEO 2008 high fuel prices, a social cost of carbon of $2/ton (2007 dollars), and a 7% discount rate for other benefits. Compared to the Reference Case, total emissions under the Mid-1 Scenario were lower for all alternatives. Emissions reductions compared to the No Action alternative were higher for all alternatives under the Mid-2 Scenario as compared to the Reference Case, except for the Technology Exhaustion Alternative. The primary reason for this difference is the lower VMT forecast under the Mid-2 Scenario. The resulting CO_2 concentration, global mean surface temperature, and sea-level rise were lower for all alternatives under the Mid-2 Scenario, except for the Technology Exhaustion Alternative. Thus, the differences between the action alternatives and to the No Action Alternative are greater under the Mid-2 Scenario than under the Reference Scenario, except for the Technology Exhaustion Alternative.

Appendix B presents the results from analysis of the Mid-1 and Mid-2 Scenarios.

4.5 RESOURCE IMPACTS OF CLIMATE CHANGE

4.5.1 Introduction

The effects of the alternative CAFE standards on climate as described in Section 4.4 – CO_2 concentrations, temperature, precipitation, and sea-level rise – can translate into impacts on key natural and human resources, including freshwater resources; terrestrial ecosystems; coastal systems and low-lying areas; managed ecosystems that produce food, fiber, and forest products; industry, settlements, society, and other aspects of the built environment; and human health. This section describes the impacts associated with climate change on each resource.

After a discussion of methodology, Section 4.5 is divided into six sections, one for each resource area. Each section discusses the affected environment, provides an overview of the resource globally and in the United States, and addresses the consequences of climate change on that resource. Observed changes are also reported. In each section, both positive and negative effects of climate change, as they are represented in the literature, are presented. The sections are:

- Freshwater resources
- Terrestrial ecosystems
- Coastal systems and low-lying areas
- Food, fiber, and forests
- Industry, settlements, and society
- Human health

The sections generally follow the organization of topic areas in the climate literature, notably by IPCC, which is a key source for much of the information presented in this section, and by USCCSP. These categories do not follow the classification of resources typically found in an EIS. *See* the chart in Section 4.1 to find where specific NEPA topics are covered.

As shown in Section 4.4, although the alternatives could substantially decrease GHG emissions, they do not prevent climate change from occurring; instead they would only result in small reductions in the anticipated increases in CO_2 concentrations, temperature, precipitation, and sea level. As discussed below, NHTSA's assumption is that these reductions in climate effects would be reflected in reduced impacts on affected resources. However, the magnitude of the changes in climate effects that the alternatives produce – a few ppm of CO_2, a hundredth of a °C difference in temperature, a small percentage change in the rate of precipitation increase, and 1 or 2 mm of sea-level rise – are too small to address quantitatively in terms of their impacts on resources. Given the enormous resource values at stake, these distinctions could be important – very small percentages of huge numbers can still yield substantial results – but they are too small for current quantitative techniques to resolve. Consequently, the discussion of resource impacts does not distinguish among the CAFE alternatives, but rather provides a qualitative review of the benefits of reducing GHG emissions and the magnitude of the risks involved in climate change.

4.5.2 Methodology

NHTSA reviewed various reports to assess the cumulative impacts of the proposed action. The key reports consulted for material include the IPCC Fourth Assessment Report by Working Group II (WGII) entitled *Climate Change 2007 – Impacts, Adaptation, and Vulnerability* (IPCC 2007b), and the

USCCSP SAP Reports. NHTSA reviewed the National Science and Technology Council's *Scientific Assessment of the Effects of Global Climate Change on the United States*, and SAP Reports, as follows:

- SAP 4.1, Coastal Elevations and Sensitivity to Sea Level Rise
- SAP 4.2, Thresholds of Change in Ecosystems
- SAP 4.3, The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity
- SAP 4.4, Preliminary Review of Adaptation Options for Climate-Sensitive Ecosystems and Resources
- SAP 4.5, Effects of Climate Change on Energy Production and Use in the United States
- SAP 4.6, Analyses of the Effects of Global Change on Human Health and Welfare and Human Systems
- SAP 4.7, Impacts of Climate Variability and Change on Transportation Systems and Infrastructure — Gulf Coast Study

Not all of the SAP Reports are final; although publicly available and generally in later stages of review and revision, some were still in draft form at the time NHTSA prepared this FEIS. More information on the SAP Reports can be found at www.climatescience.gov/Library/sap. Researchers also referenced additional studies published since the release of the IPCC and SAP reports.

NHTSA compiled research was compiled on freshwater resources; ecosystems and biodiversity; coastal and low-lying areas; industry, settlement and society; food, fiber, and forest products; and human health. Each section provides an introduction and addresses the impacts and adaptations anticipated for both the United States and the global environment. To assess the impacts of climate change on the United States, NHTSA first consulted the SAP Reports and then examined more recent materials of relevance, such as the Natural Resources Defense Council (NRDC) *Cost of Climate Change* (NRDC 2008), the Union of Concerned Scientists (UCS) *Confronting Climate Change in the U.S. Northeast* (Frumhoff *et al.* 2007), and the University of Maryland's (UMD) *The US Economic Impacts of Climate Change and the Costs of Inaction* (CIER 2007). The global impacts sections focus on the IPCC Fourth Assessment Report because it is the most recent, comprehensive, and peer-reviewed material on this topic. Articles and studies cited within the IPCC Report also were consulted for additional information on various topics.

To accurately reflect the likelihood of climate change impacts for each sector, NHTSA referenced the IPCC uncertainty guidelines. This approach provided a consistent methodology to define confidence levels and percent probability of a predicted outcome or impact. More information on the uncertainty guidelines is provided in the *Treatment of Uncertainties in the IPCC's Working Group II Assessment* in Solomon *et al.* (2007).

4.5.2.1 Cumulative Climate Impacts of Alternative CAFE Standards

As described in Chapter 3, the alternative CAFE standards being considered result in different periods of CO_2 emissions associated with the operation of U.S. vehicles. These emissions, in combination with U.S. GHG emissions from other sources (such as power plants, natural gas use, and agricultural production) and with emissions of all GHGs globally, would alter atmospheric concentrations of GHGs. As the modeling results presented in Section 4.4 show, different atmospheric concentrations of GHGs will be associated with long-term changes in global climate variables, including global average temperature, precipitation, and rising sea level. In turn, these climate changes would result in changes to

a range of natural and human resources and systems, including water supplies, human health, the built environment, and a host of others.

The most common approach to assessing the impacts of climate change is to construct future scenarios that represent combinations of changes in levels, and sometimes patterns or variability, of temperature, precipitation, sea-level rise, and other relevant climatic and related variables (IPCC 2007b). In some cases these scenarios will represent the results of specific climate modeling (the output of General Circulation Models [GCMs]), often downscaled to provide results at a finer level of geographic resolution. In other cases, scenarios might be designed to be representative of the *types* and *ranges* of effects that are expected to occur under climate change, and not the results of specific models (Parsons *et al.* 2007). Impacts associated with these scenarios are then estimated using a variety of techniques, including models of individual systems (specific ecosystems or geographic areas, such as a park) and examination of performance under similar historical conditions.

The impacts literature suggests that some regions and sectors will experience positive effects of future climate change, particularly at lower levels of temperature change (less than 1 to 3 °C above 1990 levels), while others will experience negative effects (IPCC 2007b). The IPCC WGII for the Fourth Assessment Report found that, at higher levels of temperature, on balance the net global effects are expected to be negative: "while developing countries are expected to experience larger percentage losses, global mean losses could be 1 to 5 percent gross domestic product (GDP) for 4 °C of warming" (IPCC 2007b). To put these numbers in context, the IPCC has projected longer term warming (associated with a doubling of CO_2 concentrations) in the range of 2 to 4.5 °C (IPCC 2007a). The modeling results presented in Section 4.4 suggest that, for the CAFE alternatives, the cumulative climate effects in terms of temperature rise under a moderate emissions scenario lie in the range of 2.7 to 2.8 °C as of 2100.

NHTSA's presumption, consistent with the general literature cited above and reviewed for Section 4.5, is that reducing emissions and concomitant climate effects will reduce the net negative long-term effects that have been projected for climate change. NHTSA has not, however, conducted a quantitative comparison of the climate impacts of the alternative CAFE standards, for several reasons.

First, as indicated above, analyses of impacts often focus on discrete climate scenarios, rather than a continuum of climate outcomes; the information to analyze small changes in climate variables is not, therefore, generally available in the literature. Moreover, as the global climate changes, so will regional and local climates. Changes in global climate variables will be reflected in regional and local changes in average climate variables, and in the variability and patterns of climate, such as seasonal and annual variations, the frequency and intensity of extreme events, and other physical changes, such as the timing and amount of snowmelt. Impacts assessments often rely on highly localized data for both climate and other conditions and circumstances (CCSP 2008f). Thus, changes in impacts due to changes in global average climate, as projected in this analysis, likely will not be adequately represented by a simple scaling of results. Where information in the analysis included in the FEIS is incomplete or unavailable, the agency has relied on CEQ regulations regarding incomplete or unavailable information (*see* 40 CFR § 1502.22(b)). Information on the effect of very small changes in temperature, precipitation, and sea-level rise (at the scale of the distinctions among the alternative CAFE standards) is not currently available. Nevertheless, NHTSA's qualitative characterization – that the greater the reductions in GHG emissions, the lower the environmental impact – is consistent with theoretical approaches and research methods generally accepted in the scientific community.

Second, there is considerable debate about the likely shape of a global climate impacts damage function; although many believe the function to be upwardly sloped (so that marginal net damages increase with increasing levels of climate change), fewer agree on its shape, that is, how *rapidly* net climate damages increase as temperature and other variables increase (IPCC 2007b). There is also the

important question of whether thresholds exist, that is, stress points at which ecosystems collapse or the negative impacts rapidly accelerate – a topic important enough to warrant attention in an SAP Report on which the U.S. Geological Survey (USGS) is the lead agency. Finally, much of the work on impacts – both global and more localized – is, in and of itself, qualitative and so does not lend itself to further quantification.

NHTSA assumes that reductions in climate effects due to the alternative CAFE standards would be reflected in reduced impacts on affected resources. However, the magnitudes of the changes in these climate effects that the alternatives might produce – a few ppm of CO_2, a hundredth of a °C difference in temperature, a small percentage change in the rate of precipitation increase, and 1 or 2 mm of sea level – are too small to address quantitatively in terms of their impacts on resources. Consequently, the discussion of resource impacts does not distinguish among the alternative CAFE standards, but rather provides an overview of climate impacts and therefore a qualitative review of the benefits of reducing GHG emissions and the magnitude of the risks involved in climate change.

NHTSA assumes that reductions in emissions and, therefore, climate effects would be reflected in reduced impacts on affected resources. However, the magnitudes of the changes in the climate effects that the alternative CAFE standards might produce are too small to address quantitatively in terms of their impacts on resources. Consequently, as discussed further in Section 4.5.2, the discussion of resource impacts does not distinguish among the CAFE alternatives. Where information in the analysis included in this FEIS is incomplete or unavailable, the agency has relied on CEQ regulations related to incomplete or unavailable information (40 CFR § 1502.22(b)). Information on the effects of very small changes in temperature, precipitation, and sea-level rise (at the scale of the distinctions among the CAFE alternatives) is not currently available. Nevertheless, NHTSA's qualitative characterization - that the greater the reductions in GHG emissions, the lower the environmental impact - is consistent with theoretical approaches and research methods generally accepted in the scientific community.

4.5.2.2 Treatment of Uncertainties in the Working Group I Assessment

Uncertainties can be classified in several different ways. "Value uncertainties" and "structural uncertainties" are two primary types of uncertainties. When data are inaccurate or do not fully represent the phenomenon of interest, value uncertainties arise. These types of uncertainties are typically estimated with statistical techniques, and then expressed probabilistically. An incomplete understanding of the process that controls particular values or results generates structural uncertainties. These types of uncertainties are described by presenting the authors' collective judgment of their confidence in the correctness of a result. As stated in the WGI Assessment, a "careful distinction between levels of confidence in scientific understanding and the likelihoods of specific results" are drawn in the uncertainty guidance provided for the Fourth Assessment Report.

The standard terms used to define levels of confidence are:

Confidence Terminology	Degree of Confidence in Being Correct
Very high confidence	At least 9 out of 10 chance
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than 1 out of 10 chance

The standard terms used to define the likelihood of an outcome or result where the outcome or result can be estimated probabilistically are:

Likelihood Terminology	Likelihood of the Occurrence/Outcome
Virtually certain	Greater than 99% probability
Extremely likely	Greater than 95% probability
Very likely	Greater than 90% probability
Likely	Greater than 66% probability
More likely than not	Greater than 50% probability
About as likely as not	33 to 66% probability
Unlikely	Less than 33% probability
Very unlikely	Less than 10% probability
Extremely unlikely	Less than 5% probability
Exceptionally unlikely	Less than 1% probability

4.5.3 Freshwater Resources

This section addresses climate-related impacts on freshwater resources. Water is necessary to support life, societal welfare, and economic activity. "Given water's importance, plant, animal, and human communities are all sensitive to variations in the availability, storage, fluxes, and quality of surface and groundwater. These, in turn, are sensitive to climate change" (National Science and Technology Council 2008).

4.5.3.1 Affected Environment

This affected environment section for freshwater resources is based on information contained in *World Water Resources at the Beginning of the 21st Century* (Shiklomanov and Rodda 2003), the United Nations Educational, Scientific and Cultural Organization – World Water Assessment Program (UNESCO-WWAP) *World Water Development Report 2* (UNESCO and WWAP 2006), and *Pilot Analysis of Global Ecosystems: Freshwater Systems* (Revenga *et al.* 2000).

Water supports all life on Earth. About 70 percent of Earth's surface is covered by water, and most (97.5 percent) is contained in the oceans. Freshwater refers to the 2.5 percent of Earth's hydrosphere that is not saline. The freshwater resource is divided among glaciers (68.7 percent), groundwater (30.1 percent), permafrost (0.8 percent), and surface and atmospheric water (0.4 percent). The 0.4 percent occurs as freshwater lakes (67.4 percent) and wetlands (8.5 percent), rivers (1.6 percent), soil moisture (12.2 percent), water in the atmosphere (9.5 percent), and water in living organisms (0.8 percent) (Shiklomanov and Rodda 2003, as cited in UNESCO and WWAP 2006).

The largest volume of freshwater is frozen in glaciers and ice sheets, most of which occur in Antarctica (almost 90 percent), with the remainder found in Greenland (almost 10 percent) and in mountain glaciers. Permafrost extends over northeastern Europe and the northern and northeastern parts of Asia, including the Arctic islands, northern Canada, the fringes of Greenland and Antarctica, and the high-altitude areas of South America.

Groundwater is the second largest source of freshwater. Groundwater occurs in the pores of soils and fractures of rocks and is the largest source of unfrozen freshwater. Groundwater feeds springs, streams, and lakes; supports wetlands; and is a critical source of water for human consumption. Groundwater also includes aquifers, underground strata of water-bearing permeable rock or

unconsolidated materials (sand, gravel, and some silts and clays) from which water can be extracted using well systems.

Lakes, which can be broadly defined as bodies of water collected in depressions in Earth's surface, are widespread and numerous (there are around 15 million) and store the largest volume of fresh surface waters. Reservoirs, which could be considered lakes, are enclosed areas constructed for the storage of water, and are typically created by damming a river channel in a valley.

Wetlands, such as marshes, swamps, bogs, and estuaries, are transitional zones between land and water environments where the soil is frequently or permanently waterlogged. Wetlands of various types exist all over the world. During the 20th Century, half of them are estimated to have been lost as land was converted to agriculture and urban use or filled to combat disease.

Rivers are bodies of flowing water that drain surface runoff from land to the seas and oceans. They begin in higher elevations such as mountains and hills where rainwater and snowmelt collect, forming small tributary streams that flow into larger streams and rivers.

Soil moisture is water that drains into the soil, mainly the top 2 meters, and becomes part of the soil water store, where it is used by plants.

Water exists in the atmosphere in the form of water vapor, water drops, and ice crystals, and falls as precipitation, which occurs as rain, snow, sleet, hail, frost, or dew. Biological water is the water contained in living organisms such as plants and animals.

Much of the discussion that follows below is drawn from the following studies and their citations: the IPCC *Freshwater Resources and their Management* (Kundzewicz *et al.* 2007), the National Science and Technology Council *Scientific Assessment of the Effects of Global Change on the United States* (National Science and Technology Council 2008), *World Water Resources at the Beginning of the 21st Century* (Shiklomanov and Rodda 2003), *Pilot Analysis of Global Ecosystems: Freshwater Systems* (Revenga *et al.* 2000), and *Threats to the World's Freshwater Resources* (Glick *et al.* 2001).

4.5.3.2 Non-climate Threats to Freshwater Resources

Pressure on global freshwater resources during recent decades is a result of non-climatic as well as climatic drivers. The non-climate threats include changes in population, economy, and technology. Population growth and economic development create increasing demands from the industrial, municipal, and agricultural sectors. For example, irrigated agriculture to support the demand for food accounts for nearly 70 percent of global freshwater withdrawals and for more than 90 percent of global consumptive use (Shiklomanov and Rodda 2003, as cited in Kundzewicz *et al.* 2007). The extent of irrigated areas, which is expected to expand in areas that are already water-stressed, will determine the effect that this use will have on global water use in the future.

The driving threats to the world's supply of freshwater resources are consistently reported in the literature: population growth and increased demand; infrastructure development (dams, dikes, levees, and river diversions); poor land use (urbanization, conversion to crop or grazing lands, wetland removal or reduction, deforestation); overexploitation (groundwater aquifer depletion and reduced water levels in lakes, rivers, and wetlands); water pollution from industrial, municipal, and agricultural sources (phosphorus and nitrogen from fertilizers, pesticides, pathogens and microbial contaminants, heavy metals, toxic organic compounds and micro-organic pollutants); silt and suspended particles (from soil erosion); acidification (from air pollution); and thermal pollution (from industrial discharges and slow flows caused by dams and reservoirs).

Shiklomanov and Rodda (2003) state that "Every year human influences grow and cause more and more changes to natural processes…These changes bring about alterations to the water balance and to water resources and their availability. The rapid growth of population, the development of industrial production and the rise of agriculture have resulted in the increased use of water…Human activities have also changed the character of groundwater…more often the water table has been lowered to provide water for drinking…The construction of reservoirs has led to the slowing down of the movement of river waters. Slowing the movement of water can influence its quality particularly by the accumulation of pollutants."

The freshwater resources in the United States are affected by the same non-climate threats discussed above. The National Science and Technology Council (2008) found that "most water quality changes observed so far across the continental United States are likely attributable to causes other than climate change." EPA cites siltation, nutrients, and metals (*e.g.*, mercury) as the main sources of pollution in U.S. waters, primarily as a result of nonpoint source pollution from urban and agricultural lands (EPA 2000b, EPA 2002b).

Ecosystem integrity, as defined by Glick *et al.* (2001), is the interaction between the biological processes and chemical processes that support the functioning of an ecosystem and the health of the species it supports. Water withdrawal and consumption by humans is directly connected to the integrity of freshwater ecosystems, because these uses compete with natural systems for water and lead to pollution, disrupting natural ecosystem processes. As a result, the health of habitats, and the species that live in them, is affected. Revenga *et al.* (2000) found that between 1900 and 1995, world water withdrawals increased six-fold, more than twice the rate of population growth. As water withdrawals increase, more stress will be put on freshwater ecosystems.

4.5.3.3 Environmental Consequences

Much of the discussion that follows is drawn from the following studies including the citations therein: the IPCC *Freshwater Resources and their Management* (Kundzewicz *et al.* 2007), *Scientific Assessment of the Effects of Global Change on the United States* (National Science and Technology Council 2008), and *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States* (Lettenmaier *et al.* 2008). Additional recent studies from peer-reviewed literature are also cited.

Non-climate-related impacts on freshwater resources have received more attention than climate-related impacts to date. However, "climate change is expected to result in increasing effects in the future" (National Science and Technology Council 2008). Climate change effects are especially relevant to freshwater resource management for the future. Freshwater resource infrastructure has been designed to accommodate the variability in water supply based on the historical record. This assumption – that, on average, the future will be the same as the past – is referred to as the "stationarity assumption" (Lettenmaier *et al.* 2008, as cited in National Science and Technology Council 2008). However, this assumption is now challenged by the demonstrated occurrence of climate change (Arnell 2002, Lettenmaier 2003, and Milly *et al.* 2008, all as cited in National Science and Technology Council 2008). As a result, "the global population is highly vulnerable to climate change impacts on freshwater resources" (National Science and Technology Council 2008).

Global warming resulting from the enhanced greenhouse effect causes changes in temperature, precipitation, ice melt, and other climate change effects. Evaporation, transpiration, and the water-holding capacity of the atmosphere all increase at higher temperatures. Increased atmospheric water content favors increased climate variability – more intense droughts and more intense precipitation (Trenberth *et al.* 2003, as cited in Kundzewicz *et al.* 2007).

"While temperatures are expected to increase everywhere over land and during all seasons of the year, although by different increments, precipitation is expected to increase globally and in many river basins, but to decrease in many others" (Kundzewicz *et al.* 2007). Precipitation might also increase in one season and decrease in another (Meehl *et al.* 2007, Section 10.3.2.3, as cited in Kundzewicz *et al.* 2007). Changes in temperature and precipitation are the main climatic drivers observed to affect freshwater availability, quality, and water use. A recent study by Allan and Soden (2008) using satellite observations and model simulations showed a link between rainfall extremes and temperature. The observed amplification of rainfall extremes was larger than other model predictions, leading the authors to infer that "projections of future changes in rainfall extremes due to anthropogenic global warming may be underestimated."

4.5.3.3.1 Globally Observed Climate Effects

General climate change impacts on hydrology and freshwater resources identified to date include the following (Arnell *et al.* 2001, as cited in Kundzewicz *et al.* 2007):

- Changes in streamflow volume – increases and decreases
- Variation in streamflow and groundwater recharge – largely following precipitation
- Shifts in peak streamflow timing – earlier snowmelt
- Lower streamflow in summer and autumn
- Glacier retreat and disappearance of small glaciers
- Water quality degradation – higher water temperatures
- Increases in flood magnitude and frequency

Climate-related trends have already been observed in various inputs, throughputs, and outputs to the freshwater system, including the following (Kundzewicz *et al.* 2007):

- Precipitation – increasing over northern (30°N) latitudes; decreasing over middle latitudes (10°S to 30°N); increasing in intensity

- Snow cover – decreasing in most regions

- Glaciers – decreasing almost everywhere

- Permafrost – thawing between 0.08 inch per year (Alaska) and 1.8 inches per year (Tibetan plateau)

- Streamflow – increasing in Eurasian Arctic, measurable increases or decreases in some river basins; earlier spring peak flows and increased winter-based flows in North America and Eurasia

- Evapotranspiration – increased actual evapotranspiration in some areas

- Lakes – warming, substantial increases and decreases in some lake levels, and reduction in ice cover

For other anticipated changes in the freshwater system, data are insufficient to observe a climate trend, especially when compared to the non-climatic pressures mentioned previously. The absence of an observed trend does not indicate that freshwater resources will not be sensitive to future climate trends. As described in the section on impacts below, changes are also anticipated for groundwater levels, floods,

droughts, water quality, erosion and sediment transport, and irrigation water demand (Kundzewicz *et al.* 2007).

4.5.3.3.2 Observed and Projected Impacts of Climate Change on Freshwater Resources in the United States

Most of the freshwater resource analyses are keyed either to climate scenarios (what happens if temperature increases by 6 °F, and precipitation declines by 10 percent) or to global climate model outputs pegged to IPCC-reported emission scenarios. The projected impacts resulting from such analyses, current sensitivities, and potential vulnerabilities (including extreme events) are summarized in this section for the United States and in the next section for the globe.

The climate change impacts on freshwater resources in the United States are described by National Science and Technology Council (2008), Lettenmaier *et al.* (2008), and Field *et al.* (2007).

"In regards to the hydrologic observing systems on which these sections are based, Lettenmaier *et al.* (2008) found that the current hydrologic observing system was not designed specifically for the purpose of detecting the effects of climate change on water resources. In many cases, the resulting data are unable to meet the predictive challenges of a rapidly changing climate" (National Science and Technology Council 2008).

Several recent state and regional studies have examined specific climate change impacts on freshwater resources. For example, many impacts on freshwater resources described above have been predicted for New Mexico (D'Antonio 2006), New Jersey (EPA 1997b), and the West (Saunders *et al.* 2008).

"Projections for the western mountains of the United States suggest that warming, and changes in the form, timing, and amount of precipitation will *very likely* lead to earlier melting and significant reductions in snowpack by the middle of the 21st century" (*high confidence*). "In mountainous snowmelt-dominated watersheds, projections suggest advances in the timing of snowmelt runoff, increases in winter and early spring flows (raising flooding potential), and substantially decreased summer flows. Heavily utilized water systems of the western United States that rely on capturing snowmelt runoff, such as the Columbia River system, will be especially vulnerable" (Field *et al.* 2007, as cited in National Science and Technology Council 2008). Trends in declining snowpack are perhaps best illustrated from studies conducted for California. Reduced snowpack has been identified as a major concern for the State (California Energy Commission 2006, as cited in National Science and Technology Council 2008). Several authors anticipate a coming crisis in water supply for the western United States (Barnett *et al.* 2008), and have projected that Lake Mead (on the Colorado River system) might go dry (Barnett and Pierce 2008). While these studies focus on issues already identified in the literature, their findings suggest that freshwater resources might be more sensitive to climate change than previously projected. A recent article by Rauscher *et al.* (2008) used a high-resolution nested climate model to investigate future changes in snowmelt-driven runoff over the western United States; and modeled increases in seasonal temperature of approximately 3 to 5 °C by 2100, which could cause snowmelt-driven runoff to occur as much as two months earlier than present – twice as early as other predictions – affecting reservoir water storage and hydroelectric generation, and impacting land use, agriculture, and water management.

4.5.3.3.3 Precipitation

Precipitation is the primary driver of the land surface hydrological system. Precipitation variability, and subsequent surface water availability varies regionally across the United States depending on a catchment's (watershed) physical, hydrological, and geological characteristics (National Science and

Technology Council 2008). In general, conditions become increasingly dry from east to west. Upslope areas in the Cascade and coastal mountain ranges are more humid with relatively low precipitation variability. The Intermountain West and Southwest are driest, and the greatest precipitation variability is in the arid and semi-arid West (Lettenmaier *et al.* 2008, as cited in National Science and Technology Council 2008). Stream gauge data (Mauget 2003, as cited in Lettenmaier *et al.* 2008) showed increases in streamflow from 1939 through 1998 in the eastern United States and a more or less reverse pattern in the western United States (National Science and Technology Council 2008).

4.5.3.3.4 Surface Water

The observed impacts on surface water (Field *et al.* 2007, as cited in National Science and Technology Council 2008) include the following:

- Streamflow in the eastern United States has increased 25 percent in the past 60 years (Groisman *et al.* 2004), but over the past century has decreased by about 2 percent per decade in the central Rocky Mountain region (Rood *et al.* 2005).

- Since 1950, stream discharge in both the Colorado and Columbia River Basins has decreased, while over the same time period annual evapotranspiration from the conterminous United States increased by 2.2 inches (Walter *et al.* 2004).

- In regions with winter snow, warming has shifted the magnitude and timing of hydrologic events (Mote *et al.* 2005, Regonda *et al.* 2005, Stewart *et al.* 2005). From 1949 to 2004, the fraction of annual precipitation falling as rain (rather than snow) increased at 74 percent of the weather stations studied in the western mountains of the United States (Knowles *et al.* 2006).

- Spring and summer snow cover has decreased in the western United States (Groisman *et al.* 2004). April snow water equivalent has declined 15 to 30 percent since 1950 in the western mountains of North America, particularly at lower elevations and primarily due to warming rather than changes in precipitation (Mote *et al.* 2003, 2005, Lemke *et al.* 2007, as cited in National Science and Technology Council).

- Streamflow peaks in the snowmelt-dominated western mountains of the United States occurred 1 to 4 weeks earlier in 2002 than in 1948 (Stewart *et al.* 2005).

Lettenmaier *et al.* (2008) assessed the following potential impacts on surface water in the United States (National Science and Technology Council 2008):

- There is a trend toward reduced mountain snowpack and earlier spring snowmelt runoff peaks across much of the western United States. Evidence suggests this trend is *very likely* attributable, at least in part, to long-term warming, although decadal-scale variability, including a shift in Pacific decadal oscillation in the 1970s, might have played some part. Where shifts to earlier snowmelt peaks and reduced summer and fall low flows have already been detected, continuing shifts in this direction are expected and could have substantial impacts on the performance of reservoir systems.

- Recent climate model simulations reported in the IPCC Fourth Assessment Report project increased runoff over the eastern United States, gradually transitioning to little change in the Missouri and lower Mississippi, to substantial decreases in annual runoff in the interior of the West (Colorado and Great Basin). The projected drying in the interior of the West is quite

consistent among models. These changes are, very roughly, consistent with observed trends in the second half of the 20th Century, which show increased streamflow over much of the United States, but sporadic decreases in the West.

- Snowpack in the mountainous headwater regions of the western United States generally declined over the second half of the 20th Century, especially at lower elevations and in locations where average winter temperatures are close to or above 0 °C. These trends toward reduced winter snow accumulation and earlier spring melt are also reflected in a tendency toward earlier runoff peaks in the spring, a shift that has not occurred in rainfall-dominated watersheds in the same region.

- Climate model projections of increased temperatures and slight precipitation increases indicate that modest streamflow increases are expected in the East, but that larger (in absolute value) declines are expected in the West, where the balance between precipitation and evaporative demand will shift toward increased evaporative demand. However, because of the uncertainty in climate model projections of precipitation change, future projections of streamflow are highly uncertain across most of the United States. One exception is watersheds that are dominated by spring and summer snowmelt, most of which are in the western United States. In these cases, where shifts to earlier snowmelt peaks and reduced summer and fall low flows have already begun to be detected, continuing shifts in this direction are generally expected and could have substantial impacts on the performance of reservoir systems.

4.5.3.3.5 Groundwater

The effects of climate on groundwater – especially groundwater recharge – is a topic that requires further research to determine effects resulting from climate change. The available literature (Vaccaro 1992, Loaiciga *et al.* 2000, Hanson and Dettinger 2005, Scibek and Allen 2006, Gurdak *et al.* 2007, all as cited in Lettenmaier *et al.* 2008) implies that groundwater systems generally respond more slowly to climate change than surface water systems do. Groundwater levels correlate most strongly with precipitation. Temperature is a more important factor for shallow aquifers during warm periods (National Science and Technology Council 2008).

Groundwater and surface water might also be affected by sea-level rise. Saltwater intrusion into aquifers might occur in coastal areas, and increased salinity of ground and estuary water might reduce freshwater availability.

4.5.3.3.6 Water Quality

Chemical and microbial inputs, biogeochemical processes, water temperature, and water levels control water quality. Water temperature and water quantity are sensitive to climate change. However, pollution from land use – especially agricultural runoff, urban runoff, and thermal pollution from energy production – have caused most of the observed changes in water quality (National Science and Technology Council 2008).

Rising water temperatures negatively affect aquatic biota, especially certain fish species such as salmon (Bartholow 2005, Crozier and Zabel 2006, both as cited in Lettenmaier *et al.* 2008). Rising temperatures also affect dissolved oxygen, oxidation/reduction potentials, lake stratification, and mixing rates. However, the direction of climate change effects associated with water quantity on water quality is not as evident. Increased streamflow can dilute pollutant concentrations or transport additional pollutants

into surface water sources. Extreme events – floods and droughts – generally exacerbate water quality problems.

Region-specific studies conducted for the United States were reviewed by IPCC (Field *et al.* 2007, Kundzewicz *et al.* 2007). Projected impacts on water quality include the following (National Science and Technology Council 2008):

- Changes in precipitation could increase nitrogen loads from rivers in the Chesapeake and Delaware Bay regions by up to 50 percent by 2030 (Kundzewicz *et al.* 2007).
- Decreases in snow cover and increases in winter rain on bare soil will *likely* lengthen the erosion season and enhance erosion intensity. This will increase the potential for sediment-related water quality impacts in agricultural areas (Field *et al.* 2007).
- Increased precipitation amounts and intensities will lead to greater rates of erosion in the United States and in other regions unless protection measures are taken (Kundzewicz *et al.* 2007). Soil management practices (crop residue, no-till) in some regions (*e.g.*, the Corn Belt) might not provide sufficient erosion protection against future intense precipitation and associated runoff (Field *et al.* 2007).
- For the Midwest, in simulated low flows used to develop pollutant discharge limits (Total Maximum Daily Loads) flows decrease more than 60 percent with a 25-percent decrease in mean precipitation, declining by 100 percent with the incorporation of irrigation demands (Eheart *et al.* 1999).
- Restoration of beneficial uses (to address habitat loss, eutrophication, beach closures) under the Great Lakes Water Quality Agreement will *likely* be vulnerable to declines in water levels, warmer water temperatures, and more intense precipitation (Mortsch *et al.* 2003).
- Based on simulations, phosphorus remediation targets for the Bay of Quinte (Lake Ontario) and the surrounding watershed could be compromised as 5.4- to 7.2-°F warmer water temperatures contribute to 77 to 98 percent increases in summer phosphorus concentrations in the Bay (Nicholls 1999), and as changes in precipitation, streamflow, and erosion lead to increases in average phosphorus concentrations in streams of 25 to 35 percent (Walker 2001, as cited in Field *et al.* 2007).

Kundzewicz *et al.* (2007) also concluded (*high confidence*) that climate change is *likely* to make achieving existing water quality goals for North America more difficult (National Science and Technology Council 2008).

4.5.3.3.7 Extreme Events—Floods and Drought

Extreme events such as floods and drought affect freshwater resources. Climatic phenomena – intense/long-lasting precipitation, snowmelt, ice jams – and non-climatic phenomena – dam failure, landslides – can exacerbate floods and drought.

As previously mentioned, research to date has not provided clear evidence for a climate-related trend in floods during past decades. However, evidence suggests that the observed increase in precipitation intensity and other observed climate changes could have affected floods (National Science and Technology Council 2008).

Because the intensity and mean amount of precipitation will increase across the United States at middle and high latitudes, the risk of flash flooding and urban flooding will increase in these areas (Kundzewicz *et al.* 2007, as cited in National Science and Technology Council 2008). At the same time, greater temporal variability in precipitation increases the risk of drought (Christensen *et al.* 2007, as cited in National Science and Technology Council 2008).

There is some evidence of long-term drying and increase in drought severity and duration in the West and Southwest (National Science and Technology Council 2008) that is probably a result of decadal-scale climate variability and long-term change (Lettenmaier *et al.* 2008, as cited in National Science and Technology Council 2008).

Over-allocation and continuing competition for freshwater resources for agriculture, cities, and industry increases vulnerability to extended drought in North America (Field *et al.* 2007), despite the fact that per capita water consumption has declined over the past two decades in the United States (Lettenmaier *et al.* 2008). Reducing water consumption will mitigate the impacts of climate change on freshwater resources.

4.5.3.4 Projected Impacts of Climate Change on Global Fresh Water Resources

The IPCC report is the most recent, comprehensive, and peer-reviewed summary of impacts on global freshwater resources available. Kundzewicz *et al.* (2007) summarized the conclusions from the freshwater resources and management chapter as follows:

- The impacts of climate change on freshwater systems and their management are mainly due to the observed and projected increases in temperature, sea level, and precipitation variability (*very high confidence*).
- More than one-sixth of the world's population lives in glacier- or snowmelt-fed river basins and will be affected by the seasonal shift in streamflow, an increase in the ratio of winter to annual flows, and possibly the reduction in low flows caused by decreased glacier extent or snow water storage (*high confidence*).
- Sea-level rise will extend areas of salinization of groundwater and estuaries, resulting in a decrease in freshwater availability for humans and ecosystems in coastal areas (*very high confidence*).
- Increased precipitation intensity and variability is projected to increase the risks of flooding and drought in many areas (*high confidence*).
- Semi-arid and arid areas are particularly exposed to the impacts of climate change on freshwater (*high confidence*).
- Many of these areas (Mediterranean basin, western United States, southern Africa, and northeastern Brazil) will suffer a decrease in water resources due to climate change (*very high confidence*).
- Efforts to offset declining surface water availability due to increasing precipitation variability will be hampered by the fact that groundwater recharge will decrease considerably in some already water-stressed regions (*high confidence*), where vulnerability is often exacerbated by the rapid increase in population and water demand (*very high confidence*).

- Higher water temperatures, increased precipitation intensity, and longer periods of low flows exacerbate many forms of water pollution, with impacts on ecosystems, human health, water system reliability, and operating costs (*high confidence*).

- These pollutants include sediments, nutrients, dissolved organic carbon, pathogens, pesticides, salt, and thermal pollution.

- Climate change affects the function and operation of existing water infrastructure as well as water management practices (*very high confidence*).

- Adverse effects of climate on freshwater systems aggravate the impacts of other stresses, such as population growth, changing economic activity, land use change, and urbanization (*very high confidence*).

- Globally, water demand will grow in the coming decades, primarily due to population growth and increased affluence; regionally, large changes in irrigation water demand as a result of climate change are *likely* (*high confidence*).

- Current water management practices are very likely to be inadequate to reduce the negative impacts of climate change on water supply reliability, flood risk, health, energy, and aquatic ecosystems (*very high confidence*).

- Improved incorporation of current climate variability into water-related management would make adaptation to future climate change easier (*very high confidence*).

- Adaptation procedures and risk management practices for the water sector are being developed in some countries and regions (the Caribbean, Canada, Australia, Netherlands, United Kingdom, United States, and Germany) that have recognized projected hydrological changes with related uncertainties (*very high confidence*).

- Since the IPCC Third Assessment, uncertainties have been evaluated, their interpretation has improved, and new methods (*e.g.*, ensemble-based approaches) are being developed for their characterization (*very high confidence*).

- Nevertheless, quantitative projections of changes in precipitation, river flows, and water levels at the river-basin scale remain uncertain (*very high confidence*).

- The negative impacts of climate change on freshwater systems outweigh its benefits (*high confidence*).

- All IPCC regions (*see* Chapters 3 through16 of the IPCC report) show an overall net negative impact of climate change on water resources and freshwater ecosystems (*high confidence*).

- Areas in which runoff is projected to decline are *likely* to face a reduction in the value of the services provided by water resources (*very high confidence*).

- The beneficial impacts of increased annual runoff in other areas will be tempered by the negative effects of increased precipitation variability and seasonal runoff shifts on water supply, water quality, and flood risks (*high confidence*).

Observed global climate-related trends affecting freshwater resources were identified previously. The following discussion identifies key projected impacts on surface waters, groundwater, extreme events, and water quality.

4.5.3.4.1 Surface Water

Data from 24 climate model runs generated by 12 different general circulation models (Milly *et al.* 2005, as cited in Kundzewicz *et al.* 2007) generally agreed that by 2050:

- Annual average river runoff and water availability will increase by 10 to 40 percent at high latitudes (North America, Eurasia) and in some wet tropical areas.
- Annual average river runoff and water availability will decrease by 10 to 30 percent over some dry regions at mid-latitudes and in the dry tropics, some of which are presently water-stressed areas (Mediterranean, southern Africa, and western United States/northern Mexico).

Hydrological impact studies have shown that warming leads to changes in the seasonality of river flows where much winter precipitation currently falls as snow, including the European Alps, the Himalayas, western North America, central North America, eastern North America, the Russian territory, Scandinavia, and Baltic regions. Winter flows will increase, summer flows will decrease, and peak flow will occur at least one month earlier in many cases (Kundzewicz *et al.* 2007).

Higher temperatures increase glacier melt. Glacier melt sustains many rivers during the summer in the Hindu Kush Himalaya and the South American Andes (Singh and Kumar 1997, Mark and Seltzer 2003, Singh 2003, Barnett *et al.* 2005, all as cited in Kundzewicz *et al.* 2007). The mass of some northern hemisphere glaciers is projected to decrease up to 60 percent by 2050 (Schneeberger *et al.* 2003, as cited in Kundzewicz *et al.* 2007).

Predictions for rain-fed basins describe higher flows in peak-flow season with either lower flows in low-flow season or extended dry periods (Kundzewicz *et al.* 2007).

Lake levels are determined by river and rain water inputs and evaporation outputs. By the end of the 21st Century, water levels are predicted to change between −4.5 feet and +1.15 feet in the Great Lakes (Lofgren *et al.* 2002, Schwartz *et al.* 2004b, both as cited in Kundzewicz *et al.* 2007) and to drop about 29.5 feet in the Caspian Sea (Elguindi and Giorgi 2006, as cited in Kundzewicz *et al.* 2007).

From 2010 to 2015, the ice cover on Siberian rivers is expected to melt 15 to 27 days sooner than it did from 1950 to 1979. The maximum ice cover is also expected to be 20 to 40 percent thinner (Vuglinsky and Gronskaya 2005, as cited in Kundzewicz *et al.* 2007).

A combination of land-use changes and climate change could affect annual runoff. Land-use changes are predicted by model studies to have a small effect compared to climate change in the Rhine basin, southeastern Michigan, Pennsylvania, and central Ethiopia. In southeastern Australia and southern India, predictions are comparable, with climate change having the potential to exacerbate reductions in runoff caused by afforestation (Kundzewicz *et al.* 2007).

Evapotranspiration – water loss from plant leaves – responds to increases in carbon dioxide in two distinct ways. First, higher CO_2 concentrations cause leaf stomata to close, reducing evapotranspiration. Second, CO_2 fertilization encourages plant growth, increasing total leaf area and subsequent evapotranspiration. Considering these vegetation effects, global mean runoff has been predicted to increase by 5 percent for a doubling of CO_2 concentration (Betts *et al.* 2007, Leipprand and

Gerten 2006, both as cited in Kundzewicz *et al.* 2007) compared to a 5 to 17 percent increase under climate change alone (Kundzewicz *et al.* 2007).

4.5.3.4.2 Groundwater

Climate change will mainly affect groundwater recharge rates, although very little research has been done on the issue. Groundwater levels could change as a result of thawing permafrost, vegetation changes, changes in river level (where hydraulic connection is adequate), and changes in floods. Global hydrological models predict that globally averaged groundwater recharge will increase less (2 percent) than total runoff (9 percent) in the 2050s compared to recharge and runoff rates from 1961 to 1990. In northeastern Brazil, southwestern Africa, and the southern Mediterranean coast, groundwater recharge is predicted to decrease by more than 70 percent. In contrast, recharge is predicted to increase by more than 30 percent in the Sahel, Near East, northern China, Siberia, and the western United States (Döll and Flörke 2005, as cited in Kundzewicz *et al.* 2007). Projected impacts on individual aquifers return very site-specific results.

Any decrease in groundwater recharge will exacerbate the effect of saltwater intrusion. Saltwater intrusion has been projected for a sea-level rise of 0.33 feet on two coral islands off the Indian coast – the thickness of the freshwater lens decreasing from 82 feet to 32 feet and from 118 feet to 92 feet (Bobba *et al.* 2000, as cited in Kundzewicz *et al.* 2007). Saltwater intrusion from sea-level rise might also affect groundwater/aquifer water supplies on similar small islands.

4.5.3.4.3 Extreme Events—Floods and Droughts

As discussed earlier, increased climate variability increases the risks of both floods and droughts depending on climatic and non-climatic variables. Extreme floods and extreme droughts are predicted to become more frequent in the future under various climate models (Kundzewicz *et al.* 2007). However, climate change impacts on flood magnitude and frequency can be both positive and negative depending on the global climate model used, snowmelt contributions, catchment characteristics, and location (Reynard *et al.* 2004, as cited in Kundzewicz *et al.* 2007).

By the 2090s, the proportion of the total land surface in extreme drought is predicted to increase from the current rate of 1 to 3 percent to 30 percent; extreme drought events per 100 years are predicted to double; and mean drought duration is predicted to increase by a factor of six (Burke *et al.* 2006, as cited in Kundzewicz *et al.* 2007).

More floods are predicted for northern and northeastern Europe, while more drought is predicted for southern and southeastern Europe (Lehner *et al.* 2005, as cited in Kundzewicz *et al.* 2007).

The area flooded in Bangladesh is projected to increase by 23 to 29 percent for a global temperature rise of 3.6 °F (Mirza 2003, as cited in Kundzewicz *et al.* 2007). Up to 20 percent of the world's population lives in river basins at risk from increased flooding (Kleinen and Petschel-Held 2007, as cited in Kundzewicz *et al.* 2007).

4.5.3.4.4 Water Quality

Higher water temperatures and runoff variations are *likely* to affect water quality negatively (Patz 2001, Lehman 2002, O'Reilly *et al.* 2003, Hurd *et al.* 2004, all as cited in Kundzewicz *et al.* 2007). Negative impacts on water quality from changes in water quantity include resuspension of bottom sediments, increased turbidity (suspended solids), pollutant introduction, and reduced dilution. Negative impacts from water temperature include algal blooms, increased microbial concentrations, and out-

gassing of volatile and semi-volatile compounds like ammonia, mercury, dioxins, and pesticides (Kundzewicz *et al.* 2007).

Acidic atmospheric deposition is projected to increase acidification in rivers and lakes (Ferrier and Edwards 2002, Gilvear *et al.* 2002, Soulsby *et al.* 2002, all as cited in Kundzewicz *et al.* 2007).

Salt concentration is expected to increase in estuaries and inland reaches under decreasing streamflows. For example, salinity is projected to increase in the tributary rivers above irrigation areas in Australia's Murray-Darling Basin by 13 to 19 percent by 2050 and by 21 to 72 percent by 2100 (Kundzewicz *et al.* 2007).

No quantitative studies projecting the impact of climate change on microbiological water quality for developing countries are cited by the IPCC. However, climate change will be an additional stressor affecting water quality and public health. Potential impacts include increased waterborne disease with increases in extreme rainfall, and great incidence of diarrheal and water-related diseases in regions with increased drought (Kundzewicz *et al.* 2007). A brief overview of the effects of climate change on the availability and quality of drinking water is provided by Anderson *et al.* (2005).

Developed countries are also experiencing water quality issues in their water and wastewater treatment plants. Increased filtration is required in drinking water plants to address micro-organism outbreaks following intense rain, thus increasing some operating costs by 20 to 30 percent (AWWA 2006, as cited in Kundzewicz *et al.* 2007). Other stressors on water quality include the following (Kundzewicz *et al.* 2007):

- More water impoundments for hydropower (Kennish 2002, Environment Canada 2004).
- Stormwater drainage operation and sewage disposal disturbances in coastal areas resulting from sea-level rise (Haines *et al.* 2000).
- Increasing water withdrawals from low-quality sources.
- Greater pollutant loads resulting from increased infiltration rates to aquifers or higher runoff to surface waters (resulting from high precipitation).
- Water infrastructure malfunctioning during floods (GEO-LAC 2003, DFID 2004).
- Overloading the capacity of water and wastewater treatment plants during extreme rainfall (Environment Canada 2001).
- Increased amounts of polluted storm water.

In many regions, there is no alternative supply even as water quality declines, and reusing wastewater (*e.g.*, to irrigate crops) can introduce other public health problems.

Global adaptation to freshwater resource stressors will require the availability of relevant information, more water resource options (*e.g.*, storage), and proactive responses in the face of climatic changes. These responses will include effluent disposal strategies accounting for reduced biodegradation; water and wastewater treatment plant design accounting for extreme climate conditions; and reducing, reusing, and recycling water (Luketina and Bender 2002, Environment Canada 2004, Patrinos and Bamzai 2005, all as cited in Kundzewicz *et al.* 2007).

4.5.4 Terrestrial Ecosystems

This section addresses climate-related impacts on terrestrial ecosystems. An ecosystem is defined as a complex of biological communities (plants, animals, and microorganisms) and their non-living environments, which act together as a unit (MA 2005e and Reid *et al.* 2005, as cited in Fischlin *et al.* 2007). By definition, relationships within an ecosystem are strong while relationships with components outside the ecosystem boundaries are weak (Reid *et al.* 2005, Part 2, as cited in Fischlin *et al.* 2007).

4.5.4.1 Affected Environment

Earth's biosphere is an interconnected network of individuals, populations, and interacting natural systems, referred to as ecosystems. Ecosystems are critical, in part, because they supply humans with services that sustain life and are beneficial to the functioning of society (Fischlin *et al.* 2007). Ecosystems include:

- Terrestrial communities, such as forests, grasslands, shrublands, savanna, and tundra
- Aquatic communities, such as rivers, coral reefs, lakes, and estuaries
- Wetlands, such as marshes, swamps, and bogs (Peterson *et al.* 2008)

The focus of this section is on terrestrial ecosystems.

4.5.4.1.1 Global Terrestrial Ecosystems

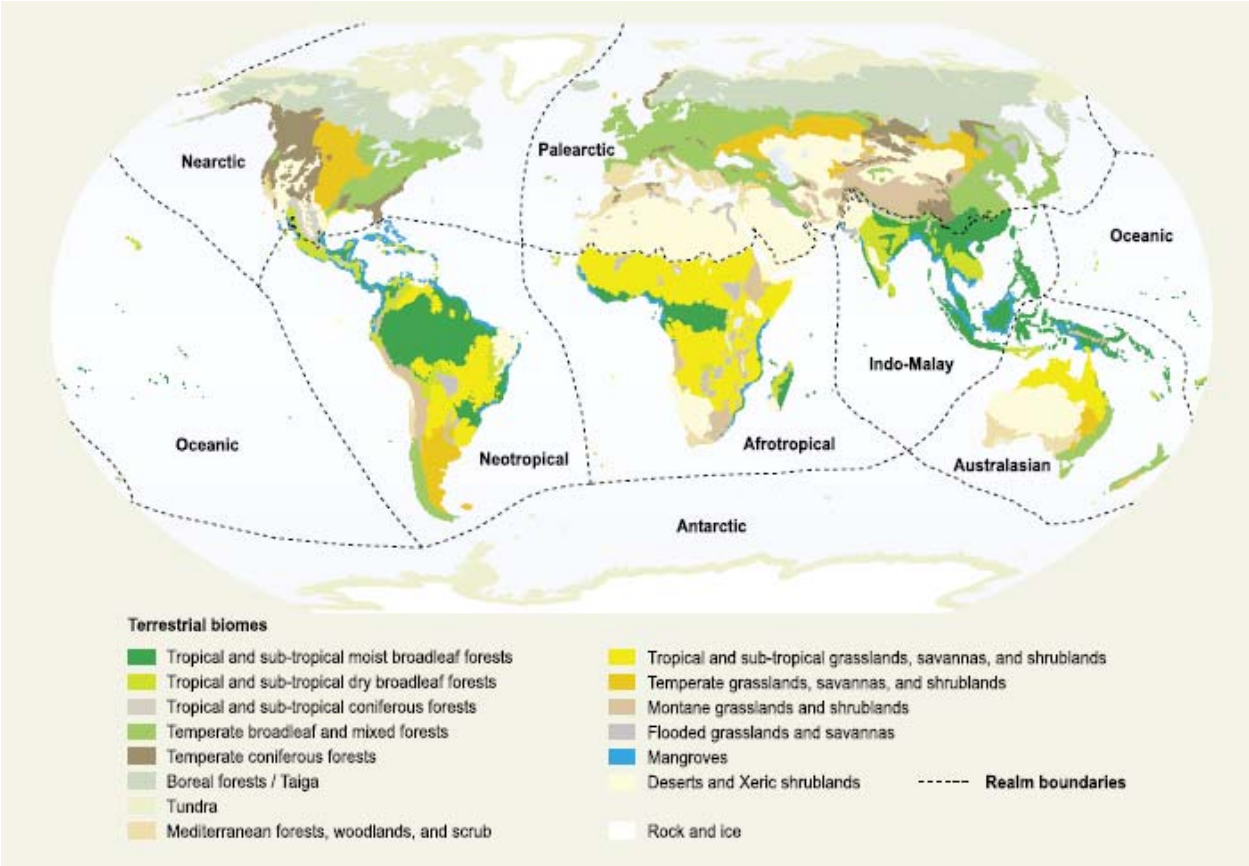
The World Wildlife Fund (WWF) has developed a widely accepted global ecosystem classification that consists of what are referred to as ecozones, biomes, and ecoregions. Similar to the classification of Miklos Udvary's (1975) biogeographical realm, the ecozone is the biogeographic division of Earth's surface at the largest scale. Terrestrial ecozones follow the floral and faunal boundaries that separate the world's major plant and animal communities. The WWF has identified eight ecozones, as indicated in Figure 4.5-1.

Biomes are climatically and geographically defined areas of ecologically similar communities of plants, animals, and microorganisms. These habitat types are defined by factors such as plant structures, leaf types, plant spacing, and climate. The land classification system developed by WWF identifies 14 major terrestrial habitat types, which can be further divided into 825 smaller, more distinct terrestrial ecoregions (WWF 2008a). The 14 primary terrestrial habitats recognized by WWF are as follows.

Tundra is a treeless polar desert found at high latitudes in the polar regions, primarily in Alaska, Canada, Russia, Greenland, Iceland, and Scandinavia, and sub-Antarctic islands. These regions are characterized by long, dry winters, months of total darkness, and extremely frigid temperatures. The vegetation is composed of dwarf shrubs, sedges and grasses, mosses, and lichens. A wide variety of animals thrive in the tundra, including herbivorous and carnivorous mammals and migratory birds.

Boreal Forests and Taiga are forests found at northerly latitudes in inland Alaska, Canada, Sweden, Finland, Norway, and Russia, and parts of the extreme northern continental United States, northern Kazakhstan, and Japan. Annual temperatures are low and precipitation ranges from 15 to 40 inches per year and can fall mainly as snow. Vegetation includes coniferous and deciduous trees, lichens, and mosses. Herbivorous mammals and small rodents are the predominant animal species; however, predatory birds and mammals also occupy this habitat type.

Figure 4.5-1. Ecozones and Biomes of the World a/



a/ Source: MA 2005f

Temperate coniferous forests are found predominantly in areas with warm summers and cool winters. Plant life varies greatly across temperate coniferous forests. In some forests, needleleaf trees dominate, while others consist of broadleaf evergreen trees or a mix of both tree types. Typically, there are two vegetation layers in a temperate coniferous forest: an understory dominated by grasses and shrubs and an overstory of large tree species.

Temperate broadleaf and mixed forests experience a wide range of variability in temperature and precipitation. In regions where rainfall is distributed throughout the year, deciduous trees are mixed with evergreens. Species such as oak, beech, birch, and maple typify the tree composition of this habitat type. Diversity is high for plants, invertebrates, and small vertebrates.

Mediterranean forests, woodlands, and shrub ecoregions are characterized by hot and dry summers, while winters tend to be cool and moist. Most precipitation arrives during winter. Only five regions in the world experience these conditions: the Mediterranean, south-central and southwestern Australia, the fynbos of southern Africa, the Chilean matorral, and the Mediterranean ecoregions of California. These regions support a tremendous diversity of habitats and species.

Tropical and subtropical coniferous forests are found predominantly in North and Central America and experience low levels of precipitation and moderate variability in temperature. These forests are characterized by diverse species of conifers, whose needles are adapted to deal with the variable climate conditions. These forests are wintering ground for a variety of migratory birds and butterflies.

Tropical and subtropical moist broadleaf forests are generally found in large, discontinuous patches centered on the equatorial belt and between the Tropics of Cancer and Capricorn. They are characterized by low variability in annual temperature and high levels of rainfall. Forest composition is dominated by semi-evergreen and evergreen deciduous tree species. These forests are home to more species than any other terrestrial ecosystem. A square kilometer can support more than 1,000 tree species. Invertebrate diversity is extremely high, and dominant vertebrates include primates, snakes, large cats, amphibians, and deer.

Tropical and subtropical dry broadleaf forests are found in southern Mexico, southeastern Africa, the Lesser Sundas, central India, Indochina, Madagascar, New Caledonia, eastern Bolivia, central Brazil, the Caribbean, valleys of the northern Andes, and along the coasts of Ecuador and Peru. Deciduous trees predominate in most of these forests and they are home to a wide variety of wildlife, including monkeys, large cats, parrots, various rodents, and ground-dwelling birds.

Temperate grasslands, savannas, and shrublands are known as prairies in North America, pampas in South America, veld in southern Africa, and steppe in Asia. They differ from tropical grasslands in species composition and the annual temperature regime under which they thrive. These regions are devoid of trees, except for riparian or gallery forests associated with streams and rivers. Biodiversity in these habitats includes a number of large grazing mammals and associated predators, burrowing mammals, numerous bird species, and a diversity of insects.

Tropical and subtropical grasslands, savannas, and shrublands are found in the large expanses of land in the tropics that do not receive enough rainfall to support extensive tree cover. However, there could be great variability in soil moisture throughout the year. Grasses dominate the species composition of these ecoregions, although scattered trees can be common. Large mammals that have evolved to take advantage of the ample forage typify the biodiversity associated with these habitats.

Montane grasslands and shrublands include high-elevation grasslands and shrublands, such as the puna and paramo in South America, subalpine heath in New Guinea and East Africa, steppes of the Tibetan plateaus, and other similar subalpine habitats around the world. Montane grasslands and shrublands are tropical, subtropical, and temperate. Mountain ecosystem services such as water purification and climate regulation extend beyond the geographical boundaries of the grasslands and shrublands and affect all continental mainlands (Woodwell 2004). Characteristic plants of these habitats display features such as rosette structures, waxy surfaces, and abundant pilosity (WWF 2008b).

Deserts and xeric shrublands across the world vary greatly with respect to precipitation and temperature. Generally, rainfall is less than 10 inches annually and evaporation exceeds precipitation. Temperature variability is also extremely diverse in these remarkable lands. Many deserts, such as the Sahara, are hot year-round, but others, such as Asia's Gobi, become quite cold in winter. Woody-stemmed shrubs and plants evolved to minimize water loss characterize vegetation in these regions. Animal species are equally well-adapted to the dry conditions, and species are quite diverse.

Mangroves occur in the waterlogged, salty soils of sheltered tropical and subtropical shores, where they stretch from the intertidal zone to the high tide mark. Associated with these tree species is a whole host of aquatic and salt-tolerant plants. Mangroves provide important nursery habitats for a vast array of aquatic animal species.

Flooded grasslands and savannas are common to four continents. These vast areas support numerous plants and animals adapted to the unique hydrologic regimes and soil conditions. Large congregations of migratory and resident water birds can be found in these regions. Ecosystem services

include breeding habitat and the buffering of inland areas from the effects of wave action and storms (MA 2005e).

4.5.4.1.2 Terrestrial Ecosystems in the United States

Published in 1976, *Ecoregions of the United States* was one of the first attempts to divide the Nation into ecosystem regions systematically. Subsequently, Bailey (1980) provided, for each region, a brief description of the dominant physical and biological characteristics based on land-surface form, climate, vegetation, soils, and fauna. Bailey defined four major domains, 12 divisions, and 30 provinces. Since then, the ecoregions of North America have been further refined by the international working group of the Commission of Environmental Cooperation (CEC 1997). Their system divides the continent into 15 broad level I ecoregions, 52 level II ecoregions, and approximately 200 level III ecoregions. The level I ecoregions present in the United States include tundra, taiga, northern forests, northwestern forested mountains, marine west coast forests, eastern temperate forests, great plains, North American deserts, Mediterranean California, southern semi-arid highlands, temperate sierras, and tropical humid forests (*see* Figure 4.5-2).

Ecosystems are dynamic and can change naturally over time as a result of drivers such as climate change (natural or anthropogenic), geological processes (volcanic eruptions, earthquakes, landslides), fire, disease or pest outbreaks, and evolution. All organisms modify their environment to some extent; however, in the past century and especially in the past 50 years, human population growth and technological innovations have affected ecosystems drastically (Vitousek *et al.* 1997). In fact, the structure of the world's ecosystems have changed more rapidly in the second half of the 20th Century than in any time in recorded human history (MA 2005e). It is expected that during the course of this century, the resilience of many ecosystems is likely to be exceeded by anthropogenic pressures (Fischlin *et al.* 2007).

4.5.4.1.3 Non-climate Threats to Global Terrestrial Ecosystems

The Millennium Ecosystems Assessment (MA), a United Nations research project, focuses on identifying the current inventory and conditions of 10 categories of global ecosystems (including 5 categories of natural terrestrial ecosystems) and projecting changes and trends into the future.

In 2005, the MA released five technical volumes and six synthesis reports, providing a scientific appraisal of the condition and trends in the world's ecosystems and the services they provide. From 2001 to 2005, the MA involved the work of more than 1,360 experts worldwide. The MA included the following conclusions regarding the current state of global ecosystems (MA 2005e):

- Cultivated systems now cover one quarter of Earth's terrestrial surface. More than two thirds of the area of 2 of the world's 14 major terrestrial biomes and more than half of the area of 4 other biomes had been converted by 1990, primarily to agriculture.

- Across a range of taxonomic groups, for most species, either the population size or range or both is currently declining.

- The distribution of species on Earth is becoming more homogenous; in other words, the set of species in any one region of the world is becoming more similar to the set in other regions primarily as a result of introductions of species, both intentionally and inadvertently in association with increased travel and shipping.

Figure 4.5-2. Level I Ecoregions in the North America a/

a/ Source: CEC 1997

- The number of species on the planet is declining. Over the past few hundred years, humans have increased the species extinction rate by as much as 1,000 times over background rates typical over Earth's history. Some 10 to 30 percent of mammal, bird, and amphibian species are currently threatened with extinction.

- Only 4 of the 24 ecosystem services examined in this assessment have been enhanced, while 15 have been degraded (Hassan *et al.* 2005).

The MA concluded that biodiversity changes due to human activities were more rapid in the past 50 years than at any time in human history. Moreover, the forces causing biodiversity loss and leading to changes in ecosystem services are either steady, show no evidence of declining over time, or are increasing in intensity. The MA examined four plausible future scenarios and projected that the rates of biodiversity change will continue or accelerate (MA 2005e).

The changes in ecosystems identified in the MA can have impacts on ecological processes, species composition, and genetic diversity. Ecological processes, which include water, nitrogen, carbon, and phosphorous cycling, have all changed more rapidly in the second half of the 20th Century than at any

time in recorded human history (MA 2005e). Human actions have not only changed the structure of ecosystems, but also the processes as functions of the ecosystems.

A change in ecosystem structure also affects the species within the system and vice versa. Historically, the natural processes of evolution and the combination of natural barriers to species migration and local adaptation resulted in substantial phenotypic differences in plant and animal species of different ecosystems. These regional differences are now becoming rare.

Some ecosystem changes have been the inadvertent result of activities unrelated to the use of ecosystem services, such as the construction of roads, ports, and cities and the discharge of pollutants. But most ecosystem changes were the direct or indirect result of changes made to meet growing demands for food, water, timber, fiber, and fuel (MA 2005e). Ecosystems change can be affected by a variety of human and natural drivers, including climate change, land use, land degradation, urbanization, pollution, natural climate change, geological processes, and invasive species. These drivers can act independently or in concert with each other (Lepers *et al.* 2004), and are summarized below.

Land Use Change

Land use change represents the anthropogenic replacement of one land use type by another, such as forest converted to cultivated land (or the reverse), and subtle changes of management practices within a given land use type, such as intensification of agricultural practices. Both forms of land use change are affecting 40 percent of the terrestrial surface (Foley *et al.* 2005). Land use change can lead to habitat loss and fragmentation and is an important driver in ecosystem change (Heywood and Watson 1995, Fahrig 2003). Overall, land transformation represents the primary driving force in the loss of biological diversity (Vitousek *et al.* 1997). In 9 of the 14 terrestrial biomes studied by the MA, over half the area has been transformed, largely by agricultural cultivation (Hassan *et al.* 2005). Only the biomes that are less suitable for agriculture, such as deserts, boreal forests, and tundra, have remained largely untransformed by human activity.

Virtually all of Earth's ecosystems have now been substantially transformed through human actions (MA 2005e). Roughly 70 percent of original temperate grasslands and forests and Mediterranean forests were lost by 1950, chiefly from conversion to agricultural lands. More land was converted to cropland in the 30 years after 1950 than in the 150 years between 1700 and 1850 (MA 2005a, Hassan *et al.* 2005).

Historically, terrestrial ecosystems that have been most substantially altered by human activity include temperate broadleaf forests, temperate grasslands, Mediterranean forests, and tropical dry forests (Hassan *et al.* 2005). Of these, more than two thirds of the temperate grasslands and Mediterranean forests, and more than half of tropical dry forests, temperate broadleaf forests, and tropical grasslands have been converted to agriculture (Hassan *et al.* 2005). Forest systems in general have been reduced by half over the past three centuries, and have effectively disappeared in 25 countries. Another 29 countries have lost 90 percent or more of their forest cover (Hassan *et al.* 2005).

Globally, the rate of ecosystem conversion has begun to decelerate, mainly because the rate of expansion of cultivated land has declined. Ecosystems are beginning to return to conditions and species compositions similar to their pre-conversion states. However, rates of ecosystem conversion remain high or are increasing for specific ecosystems and ecoregions (MA 2005f). Land use changes and land degradation are important drivers of ecosystem change globally and in the United States. For example, "between 1982 and 1997, 11 million acres of nonfederal grasslands and shrublands were converted to other uses" (The H. John Heinz III Center for Science 2002).

The increase in cultivated land, especially for the purpose of grazing, has led to an increase in desertification. Desertification involves the expansion of deserts into semi-arid and subhumid regions, and the loss of productivity in arid zones. Desertification is characterized by loss of groundcover and soils, replacement of palatable, mesophytic grasses by unpalatable xerophytic shrubs, or both (Ryan *et al.* 2008). Desertification affects the livelihoods of millions of people, including a large portion of the poor residents of drylands (Hassan *et al.* 2005). While desertification can certainly be exacerbated by changes in climate, there has been long-standing controversy over the relative contributions of climatic and anthropogenic factors as drivers of desertification (National Science and Technology Council 2008).

Fire

Fire influences ecosystem structure by promoting species that tolerate fire or even enhance fire spread, resulting in a relationship between the relative flammability of a species and its relative abundance in a particular community (Bond and Keeley 2005). Intensified and increasing wildfire occurrences appear to be changing vegetation structure and composition in some ecoregions. In the forest-tundra transition in eastern Canada, this transition is observed in a shift from *Picea*- to *Pinus*-dominated communities and 75 to 95 percent reductions in tree densities (Lavoie and Sirois 1998). Across the boreal forests of North America, total burned areas increased by a factor of 2.5 between the 1960s and the 1990s (Kasischke and Turetsky 2006).

Insect Outbreaks

Invasive alien species represent a major threat to endemic or native biodiversity in terrestrial and aquatic systems. Alien species invasions also interact with other drivers, sometimes resulting in unexpected outcomes. The impact of insect damage is substantial and can exceed the impacts of fire in some ecosystems, but especially in boreal forests (Logan *et al.* 2003). For example, spruce budworm defoliated more than 20 times the area burned in eastern Ontario between 1941 and 1996 (Fleming *et al.* 2002). Fires tended to occur 3 to 9 years after a spruce budworm outbreak (Fleming *et al.* 2002), suggesting that insect outbreaks can be a driver of increased fire events. Forest impacts by the forest tent caterpillar have also increased in western Canada over the past 25 years (Timoney 2003).

Species Decline and Extinction

Although extinction is a natural part of Earth's history, observed modern rates of extinction are not part of natural cycles. Over the past few hundred years, humans have increased the extinction rate by as much as 1,000 times over the rate expected based on natural history (Hassan *et al.* 2005). A decrease in global genetic diversity is linked to extinction. The loss of unique populations has resulted in the loss of genetic diversity. The loss of genetic diversity has also declined among cultivated species as farmers have shifted from locally adapted crop populations to more widely adapted varieties produced through formal breeding practices. Currently, for most species across a wide range of taxonomic groups, either the population size, population range, or both is in decline (MA 2005e).

Pollution

Pollution is another substantial threat to terrestrial ecosystems. Over the past four decades, excessive nutrient loading has emerged as one of the most important direct drivers of ecosystem change in terrestrial, freshwater, and marine systems. A known cause is the use of increasing amounts of synthetic nitrogen and phosphorous fertilizers, which can be lost to the environment after application. Consumption of nitrogen fertilizer grew nearly 800 percent between 1960 and 2003 (MA 2005f). In terrestrial ecosystems, excessive nitrogen flows contribute to acidification. Nitrogen also plays a role in ground-level ozone, which can lead to a loss of forest productivity (MA 2005f).

4.5.4.2 Environmental Consequences

This section discusses current climate change impacts that have already been observed and projected impacts (including the potential for adaptation to climate changes). Climate change impacts are discussed generally, and with specific attention to impacts in the United States. The IPCC WGI Fourth Assessment Report (Fischlin *et al.* 2007) was released in 2007, and in 2008 the USCCSP report on climate sensitive ecosystems was released (CCSP 2008a). The 2007 IPCC report is the most comprehensive, recent summary of projected impacts of global climate change. Many of the impacts discussed in this section were gathered from the 2007 IPCC report, which provides an analysis and discussion on a global scale. Information about impacts specific to ecosystems in the United States was obtained primarily from the 2008 USCCSP report. The projected impacts reported below were forecast with varying degrees of certainty. The level of certainty, as defined by IPCC, is noted in this report where relevant.

4.5.4.2.1 Observed Climate Change Impacts

Because terrestrial ecosystems are defined by the interactions of biotic factors (plants, animals, and microorganisms) and abiotic factors (geology, hydrology, weather), climate is a key factor in determining the different characteristics and distributions of natural systems.

Observed Impacts on Terrestrial Ecosystems Globally

Studies have noted the response of biological and chemical characteristics of ecosystems to climate conditions, especially temperature change. Substantial research has examined the effects of climate change on vegetation and wildlife, leading to the conclusion that the changing climate is already having a real and demonstrable effect on a variety of ecosystem types (CCSP 2008b). As noted in the IPCC report, plants and animals can reproduce, grow, and survive only within specific ranges of climate and environmental conditions (Fischlin *et al.* 2008). Changes in climate can affect terrestrial ecosystems in any of the following ways (Rosenzweig *et al.* 2007):

- Shifting the timing of life cycle events such as blooming or migration
- Shifting range boundaries or densities of individuals within their ranges
- Changing species morphology (body size, egg size), reproduction, or genetics
- Causing extirpation or extinction.

These changes are a result of many factors. Phenology – the timing of seasonal activities of animals and plants – is perhaps the simplest process by which to track changes in the ecology of species in response to climate change (Rosenzweig *et al.* 2007). Observed phenological events include leaf unfolding, flowering, fruit ripening, leaf coloring, leaf fall of plants, bird migration, chorusing of amphibians, and appearance or emergence of butterflies. Global daily satellite data, available since 1981, indicate an earlier onset of spring by 10 to 14 days over 19 years, particularly across temperate latitudes of the northern hemisphere (Zhou *et al.* 2001, Lucht *et al.* 2002). Leaf unfolding and flowering in spring and summer have, on average, advanced by 1 to 3 days per decade in Europe, North America, and Japan over the last 30 to 50 years (Fischlin *et al.* 2007). The seasonal timing of bird migration and egg laying has also changed, associated with the increase of temperature in breeding grounds and migration routes. According to IPCC (Rosenzweig *et al.* 2007), "Many small mammals have been observed to come out of hibernation and to breed earlier in the spring than they did a decade ago (Inouye *et al.* 2000, Franken and Hik 2004) and even larger mammals such as reindeer are showing phenological changes (Post and Forchhammer 2002), as are butterflies, crickets, aphids, and hoverflies (Forister and Shapiro 2003, Stefanescu *et al.* 2003, Hickling *et al.* 2005, and Newman 2005). Increasing regional temperatures are

also associated with earlier calling and mating and shorter time to maturity of amphibians (Gibbs and Breisch 2001, Reading 2003, and Tryjanowski *et al.* 2003)."

Rapid global warming can directly affect the size of a species' range, the density of individuals within the range, and the abundance of preferred habitat within the range. Climate changes have affected the location of suitable habitat for several species of plants and animals. Changes in the distribution of species have occurred across a wide range of taxonomic groups and geographical locations (Rosenzweig *et al.* 2007). Several different bird species no longer migrate out of Europe in the winter as the temperature continues to warm (Rosenzweig *et al.* 2007). Over the past decades, a poleward extension of various species has been observed, which is probably attributable to increases in temperature (Parmesan and Yohe 2003, as cited in Rosensweig *et al.* 2007). Many Arctic and tundra communities are affected and have been replaced by trees and dwarf shrubs (Kullman 2002 and ACIA 2005, both as cited in Rosensweig *et al.* 2007). In some mountainous areas of the northern hemisphere, including in Alaska, tree lines have shifted to higher altitudes over the past century (Sturm *et al.* 2001, as cited in Rosensweig *et al.* 2007).

Decreases in the size of a species' range, the density of individuals within the range, and the abundance of its preferred habitat factors can lower species population size (Wilson *et al.* 2004, as cited in Rosensweig *et al.* 2007) and can increase the risk of extinction. Examples of declines in populations and subsequent extinction or extirpation are found in amphibians around the world (Alexander and Eischeid 2001, Middleton *et al.* 2001, Ron *et al.* 2003, and Burrowes *et al.* 2004, all as cited in Rosensweig *et al.* 2007).

Changes in morphology and reproduction rates have been attributed to climate change. For example, the egg sizes of many bird species are changing with increasing regional temperatures (Jarvinen 1996 and Tryjanowski *et al.* 2004). Several studies conducted in Asia and Europe found that some birds and mammals are experiencing increases in body size as temperatures increase, on a regional scale, most likely due to the increasing availability of food (Nowakowski 2002, Yom-Tov 2003, Kanuscak *et al.* 2004, and Yom-Tov and Yom-Tov 2004, as cited in Rosenzweig *et al.* 2007). Many northern insects have a 2-year life cycle, and warmer winter temperatures allow a larger fraction of overwintering larvae to survive. The mountain pine beetle has expanded its range in British Columbia into areas previously considered too cold (Carroll *et al.* 2003).

Observed Changes on Terrestrial Ecosystems in the United States

Changes and impacts on ecosystems in the United States are similar to those occurring globally. During the 20th Century, the United States already had begun to experience the effects of climate change. Precipitation over the contiguous United States increased 6.1 percent over long-term averages (CCSP 2008a), while a sea-level rise of 0.06 to 0.12 inch per year has occurred at most of the country's coastlines; the Gulf coast has experienced an even greater rise in sea level at a rate of 0.2 to 0.4 inch per year (CCSP 2008a).

Examples of observed changes to terrestrial ecosystems in the United States attributable to anthropogenic climate change include the following:

- Many plant species are expanding leaves or flowering earlier, for example: earlier flowering in lilac,1.8 days per decade (Schwartz and Reiter 2000) and honeysuckle, 3.8 days per decade (Cayan *et al.* 2001); earlier leaf expansion in apple and grape, 2 days per decade (Wolfe *et al.* 2005) and trembling aspen, 2.6 days per decade (Wolfe *et al.* 2005).

- Warmer springs have led to earlier nesting for 28 migrating bird species on the east coast of the United States (Butler 2003) and to earlier egg laying for Mexican jays (Brown *et al.* 1999) and tree swallows (Dunn and Winkler 1999).

- Several frog species now initiate breeding calls 10 to 13 days earlier than a century ago (Gibbs and Breisch 2001).

- In lowland California, 70 percent of 23 butterfly species advanced the date of first spring flights by an average of 24 days over 31 years (Forister and Shapiro 2003).

- Many North American plant and animal species have shifted their ranges, typically to the north or to higher elevations (Parmesan and Yohe 2003).

- Edith's checkerspot butterfly has become locally extinct in the southern, low-elevation portion of its western North American range but has extended its range 56 miles north and 394 feet higher in elevation (Parmesan 1996, Crozier 2003, and Parmesan and Galbraith 2004). Edith's checkerspot butterfly is important to the survival of its grassland and rocky outcrop habitat, and also provides essential ecosystem services because the adult butterflies pollinate various flowers (Scott 1986, as cited in Kayanickupuram 2002).

- The frequency of large forest fires and the length of the fire season in the western United States have increased substantially since 1985. These phenomena are related to the advances in the timing of spring snowmelt and increases in spring and summer air temperatures (Westerling *et al.* 2006).

- In the Great Basin region, the onset of snow runoff is currently 10 to 15 days earlier than it was 50 years ago (Cayan *et al.* 2001).

- The vegetation growing season has increased on average by about 2 days per decade since 1948, with the largest increase happening in the West (Easterling 2002; Feng and Hu 2004).

- Recently, spruce budworm in Alaska has completed its lifecycle in 1 year, rather than the 2 years previously (Volney and Fleming 2000). This allows many more individuals to survive the overwintering period with impacts on the boreal forests of North America.

- Over the past 3 to 5 decades, all the major continental mountain chains exhibited upward shifts in the height of the freezing level (Diaz *et al.* 2003).

- Populations of the American pika, a mountain-dwelling relative of the rabbit, are in decline (Beever *et al.* 2003). The pika might be the first North American mammal to become extinct as a result of anthropogenic climate change.

- Reproductive success in polar bears has declined as a result of melting Arctic Sea ice. Without ice, polar bears cannot hunt seals, their preferred prey (Derocher *et al.* 2004). On May 15, 2008, the U.S. Fish and Wildlife Service listed the polar bear as a threatened species, reflecting the loss of sea ice habitat that once encompassed more than 90 percent of the polar bear's habitat range (*FR* 73, 28212-28303, May 15, 2008).

4.5.4.2.2 Projected Impacts of Climate Change in the United States

The United States is projected to experience changes in average temperature and precipitation over the 21st Century of an even greater magnitude than those experienced in the 20th Century. Although the entire country is projected to experience some degree of change, particular regions of the United States could experience changes of a greater-than-average magnitude. For example, the greatest changes in temperature are projected for Alaska and the western continental United States (CCSP 2008a). In northern Alaska, the average temperatures are projected to increase 5 °C by the end of the 21st Century. Areas near coasts are projected to witness an increase of approximately 2 °C over the same period; summer temperatures nationwide could increase 3 to 5 °C; and winter temperatures are projected to increase 7 to 10 °C (CCSP 2008a).

Additional expected changes in United States climate include:

- More frequent hot days and hot nights (CCSP 2008a)
- Heavier precipitation events, primarily in the form of rain rather than snow (CCSP 2008a). Annual precipitation in the northeastern United States is projected to increase while precipitation in the Southwest is expected to decrease (Christensen *et al.* 2007)
- A decline in spring snow cover, leading to decreased availability of water in reservoirs (CCSP 2008a)

Ecosystems across the United States are projected to experience both positive and negative impacts from climate change over the next century. The degree of impacts will vary by region. Wildlife species have already responded to climate change and its effects on migration patterns, reproduction, and geographic ranges (Field *et al.* 2007, as cited in National Science and Technology Council 2008). Future, more substantial changes in climate are projected to affect many ecosystem services negatively (CCSP 2008a). The IPCC WGII has projected, with a high level of confidence, "that recent regional changes in temperature have had discernible impacts on many physical and biological systems" (National Science and Technology Council 2008).

The IPCC has determined that areas of the United States that experience temperature increases of 1.5 to 2.5 °C are at highest risk for modifications to ecosystem structure and composition (IPCC 2007b, as cited in CCSP 2008a). Over the next century, it is projected that species could move northward and to higher elevations (Field *et al.* 2007, as cited in National Science and Technology Council, 2008). In one example of possible future threats to ecosystem vegetation, the upward move in elevation of species as the snow and tree line advances suggests that alpine ecosystems could be endangered by the introduction of invasive species (National Science and Technology Council 2008).

Rather than experiencing impacts of climate change directly, most animals could experience the effects of climate change indirectly through changes to their habitat, food sources, and predators (Schneider and Root 1996, as cited in National Science and Technology Council 2008). A changing climate facilitates migration of certain species into non-native habitats, potentially affecting current goods and services (CCSP 2008a).

Animals in ecosystems in the United States are projected to experience a variety of climate change impacts. For example:

- Changes in hydrology as a result of changes in precipitation patterns could interrupt the breeding cycles of amphibians, which depend on the ability to migrate to breeding ponds.

The production of their eggs is also highly dependent on temperature and moisture availability (Fischlin *et al.* 2007, as cited in National Science and Technology Council 2008).

- Changes in climate that occur over at least several years are likely to affect the reproductive success of migratory birds and their ability to survive. A mismatch in timing between the migration and reproduction periods and peak food availability is the potential pathway for such impacts (Stenseth and Mysterud 2002, Visser *et al.* 2004, 2006, Visser and Both 2005, all as cited in National Science and Technology Council, 2008).

- The migration of butterflies is highly dependent on spring temperatures, and anthropogenic climate change is likely to lead to earlier spring arrivals. As with migratory birds, an earlier butterfly migration could result in a mismatch with food supply, thus threatening reproduction and survival (Forister and Shapiro 2003, as cited in National Science and Technology Council, 2008).

- Shifts in migration ranges could result in disease entering new areas, for example, avian malaria in Hawaii could move upslope as climate changes (CCSP 2008a).

In one prominent example of mammals experiencing the effects of a warming climate, the polar bear is specifically adapted to conditions in a narrow ecological slot (an environment with cold temperatures and access to snow, ice, and open water) and spends much of its time on the frozen sea (Gunderson 2007). As the climate warms and sea ice melts, the polar bear loses much of its natural habitat. If current trends in sea ice loss continue, the polar bear could become extirpated from most of their range within 100 years (IUCN 2008). Polar bears were listed as threatened under the Endangered Species Act on May 15, 2008 due to the ongoing and projected loss of their sea-ice habitat from global warming (*FR* 73, p 28212-28303, May 15, 2008).

The vegetation of terrestrial ecosystems in the United States is projected to experience a variety of direct impacts from climate change. For example, national forests, which harbor much of the Nation's biodiversity, and national grasslands are expected to experience an exacerbation of pre-existing stressors, such as wildfires, invasive species, extreme weather events, and air pollution (CCSP 2008a).

Warmer, drier climates weaken resistance of trees to insect infestation, as they are more likely to be wilted and weakened under those conditions. In a healthy state, trees can typically fight off beetle infestation by drowning them with resin as they bore through the bark. Drought reduces the flow of resin and beetles that are able to penetrate the bark introduce decay-causing fungus. This problem has already been documented. Since 1994, winter mortality of beetle larvae in Wyoming has been cut due to mild winters (from 80 percent to less than 10 percent mortality). As a result, the beetles have been able to strip 4 million acres of forests (Egan 2002, as cited in Center for Health & the Global Environment 2005). In the southwestern United States, high temperatures, drought, and the piñon ips bark beetle have had the cumulative effect of causing a mass die-back of piñon trees. From 2002 to 2003 alone, piñon mortality in Mesa Verde National Park in Colorado and Bandelier National Monument in New Mexico exceeded 90 percent. Researchers determined that climate factors drove the die-off (Saunders *et al.* 2008). The United States Forest Service indicates that, by 2012, almost all of the mature lodgepole trees in northern Colorado and southern Wyoming will have been killed by bark beetles. This will affect watersheds, timber production, and wildlife habitats, along with other human activities (USFS 2008).

Additional impacts on vegetation in ecosystems in the United States could include the following:

- Water management in the West would be complicated by increases in temperatures and changes in precipitation patterns, which lead to reduced snow pack, earlier snowmelt, and modified hydrology (CCSP 2008a).

- High latitudes would experience increased vegetation productivity. Regions in the mid-latitudes would experience either increased or decreased productivity, depending on whether the primary impact is more precipitation or higher temperatures (increasing evaporation and dryness) (Bachelet *et al.* 2001, Berthelot *et al.* 2002, Gerber *et al.* 2004, Woodward and Lomas 2004, all as cited in National Science and Technology Council 2008).

- Ecosystems in the East would be statistically "likely to become carbon sources, while those in the west would be likely to remain carbon sinks" (Bachelet *et al.* 2004, as cited in National Science and Technology Council 2008).

- The jet stream would move northward with increasing atmospheric temperatures. The consequence of this shift is a drying of the Southeast. Closed-canopy forest ecosystems could be converted to savanna ecosystems, woodlands, or grasslands, measurably increasing the threat of fire occurrence (CCSP 2008a).

- Growing seasons would lengthen, according to several predictive models; this would beneficially act to sustain carbon sinks (Cox *et al.* 2000, Berthelot *et al.* 2002, Fung *et al.* 2005, all as cited in National Science and Technology Council 2008).

- In the Olympic Range, a temperature increase of 2 °C would move tree species upwards 0.20 to 0.38 miles. Temperate species would replace subalpine species over 300 to 500 years (Zolbrod and Peterson 1999).

Adaptation to Climate Change by Terrestrial Ecosystems

The ability or inability of ecosystems to adapt to change is referred to as adaptive capacity. There could be notable regional differences in the adaptive capacity of ecosystems, and adaptive capacity is moderated by anthropogenic influences and capabilities. The ultimate impact of climate change on ecosystems depends on the speed and extent to which these systems can adapt to a changing climate. Adaptation occurs naturally in a biological system to varying degrees, but it can also be a planned human response to anticipated challenges (CCSP 2008a). Ecosystem managers could "proactively alter the context in which ecosystems develop… they can improve the resilience, *i.e.*, the coping capacity, of ecosystems. Such ecosystem management involves anticipatory adaptation options" (Fischlin *et al.* 2007). A strategy proposed for mitigating some of the loss of ecosystem biodiversity calls for moving species out of their native ranges into less threatened zones. Although this strategy could be viewed with suspicion due to the problems posed by some invasive species, the "assisted colonization" would likely be proposed only in situations and for species that are deemed low risk (Hoegh-Guldberg *et al.* 2007).

Because the effectiveness of specific adaptation strategies is uncertain, a "no regrets" path, consisting of practical adaptation options that account for current, known stressors along with the more uncertain future stressors (CCSP 2008a), is typically sought by ecosystem managers. For example, invasive species pose a known threat to many ecosystems. Future climate change is likely to exacerbate this stressor, so an adaptation strategy to tackle current invasive species problems could also address projected impacts of more serious, future invasive species challenges (CCSP 2008a). Another example of dual-purpose adaptation strategies lies with the construction of riparian buffer strips. These not only

reduce agricultural runoff into freshwater systems, but also establish protective barriers against potential increases in both pollution and sediment loadings due to climate change in the future (CCSP 2008a).

4.5.4.2.3 Projected Impacts of Climate Change on Global Terrestrial Ecosystems

The IPCC concludes (*very high confidence*) that anthropogenic temperature rises have visibly altered ecosystems (Parry *et al.* 2007). The exact impacts of climate changes are difficult to discern, however, as they are mediated by other stressors and the capabilities of natural systems to adapt to changing climates to some degree (Parry *et al.* 2007).

Some regions of the world are more vulnerable to changes in climate than others. Regions of snow, ice, and tundra have been visibly altered by changes in global temperature. Observations of frozen regions already show larger glacial lakes and the destabilization of glacial debris that dam these lakes; changes in ecosystems at both poles; and increased melting of ice sheets, glaciers, and ice caps (Parry *et al.* 2007).

Ecosystems in all regions of the world are expected to respond to climate-change impacts with poleward and upward shifts of plants and animals; earlier onset of migration of terrestrial species such as birds and butterflies; and localized disappearance of particular species (Parry *et al.* 2007).

Additional factors, such as projected growth in human populations, are expected to exacerbate the effects of climate change. For example, river basin ecosystems that are already experiencing high levels of stress are projected, with *medium confidence*, to witness growth in human populations from approximately 1.4 to 1.6 billion in 1995 to roughly 4.3 to 6.9 billion by 2050 (Parry *et al.* 2007). River basins experience the stress of increasing human populations as manifested in increasing demands for water (CCSP 2008b) and more inputs of pollutants. A warmer, drier climate could increase these stressors and reduce access to other water sources (CCSP 2008b).

Other projected global impacts of climate change include the following:

- The hardiness of the world's ecosystems is expected (*high confidence*) to be challenged over the 21st Century with "an unprecedented combination of climate change, associated disturbances (*e.g.*, flooding, drought, wildfire, insects, and ocean acidification), and other global change drivers (especially land use, pollution, and over-exploitation of resources) (Fischlin *et al.* 2007).

- CO_2 levels are projected to be much higher than any in the past 650,000 years, and temperatures are projected to be as high as any in the past 740,000 years. Both increases are very likely to impact ecosystems (*very likely*) (Fischlin *et al.* 2007).

- Global average temperature increases in excess of 1.5 to 2.5 °C are statistically likely to threaten 20 to 30 percent of plant and animal species with extinction (Fischlin *et al.* 2007, as cited in National Science and Technology Council 2008).

- Carbon uptake by ecosystems such as forests and grasslands is statistically likely to peak during the 21st Century and might ultimately even reverse (forests and grasslands would emit carbon, rather than taking it in), which would amplify climate change due to increased atmospheric CO_2 (Fischlin *et al.* 2007, as cited in National Science and Technology Council 2008).

In addition to other anthropogenic stressors, "such as extractive use of goods, and increasing fragmentation and degradation of natural habitats" (Bush *et al.* 2004, as cited in Fischlin *et al.* 2007), climate change poses a threat to the wellbeing of ecosystems. Although many ecosystems have been resilient to historical changes in climate, it is not clear whether their resilience is enough to withstand the more rapid and profound changes that are projected given the buildup of GHGs in the atmosphere (Chapin *et al.* 2004, Jump and Peñuelas 2005, as cited in Fischlin *et al.* 2007). Predicted climate change and other anthropogenic stressors are "virtually certain to be unprecedented" (Forster *et al.* 2007, as cited in Fischlin *et al.* 2007). While some of the impacts expected with climate change serve to exacerbate existing stressors on ecosystems, other expected impacts could be altogether new. For example, increasing temperatures could cause some current sinks for GHGs, such as forest vegetation, to actually become sources for these gases (including CO_2 and methane) (Fischlin *et al.* 2007).

Effects of anthropogenic climate change on ecosystems are anticipated at different levels of severity and over varying time scales (decades to centuries) (Lischke *et al.* 2002, as cited in Fischlin *et al.* 2007). Some of the broad impacts on ecosystems associated with climate change are expected to include species extinctions, loss of habitat due to more severe tropical storms (Wiley and Wunderle 1994, as cited in Fischlin *et al.* 2007), changes in the types and abundance of vegetation present in an ecosystem (Schröter *et al.* 2005, Metzger *et al.* 2006, both as cited in Fischlin *et al.* 2007), and increased susceptibility of land to desertification (Burke *et al.* 2006, as cited in Fischlin *et al.* 2007).

Foreseeable pathways of climate change-induced impacts on ecosystems include the following:

- CO_2 fertilization effects on vegetation (Baker *et al.* 2004, Lewis *et al.* 2004, Malhi and Phillips 2004, all as cited in Fischlin *et al.* 2007).
- Higher atmospheric temperatures that could lead to more frequent insect and disease outbreaks (National Science and Technology Council 2008).
- Increased radiation due to a projected decrease in tropical cloud cover (Nemani *et al.* 2003, as cited in Fischlin *et al.* 2007). This is linked to warming, which can directly affect ecosystems and increase the frequency and severity of storms originating in the tropics.

4.5.5 Coastal Systems and Low-lying Areas

This section addresses climate-related impacts on coastal ecosystems. Coastal zones are unique environments where land and water meet. There is no single definition for coastal zones, but what is certain is that all coastal zones include an area of land and an area that is covered by saltwater. Burke *et al.* (2001) defines coastal zones as the "intertidal and subtidal areas on and above the continental shelf (to a depth of about 650 feet) – areas routinely inundated by saltwater – and immediately adjacent lands."

4.5.5.1 Affected Environment

Important ecosystems found in coastal zones can include estuaries, coral reefs, coastal lagoons, mangroves, seagrass meadows, upwelling areas, salt marshes, beaches, bays, deltas, kelp forests, and barrier islands. A variety of terminology exists for describing coastal zone ecosystems. Table 4.5-1 lists some of the more commonly described ecosystems found in coastal zones.

Table 4.5-1

Common Coastal Ecosystem

Coastal Ecosystem	Description
Coastal Wetlands	The broadest definition of wetlands occurring along coastal zones. They include a number of natural communities that share the unique combination of aquatic, semi-aquatic, and terrestrial habitats that results from periodic flooding by tidal waters, rainfall, or runoff. a/
Sandy Shorelines	Sandy areas along coastlines where high-energy wave actions deposit and move around sand and sediment.
Barrier Islands	Long narrow islands running parallel to the mainland that provide protection to the coast.
Tidal Wetlands	A type of coastal wetland that is affected by both tides and freshwater runoff.
Estuaries	Bodies of water and their surrounding coastal habitats typically found where rivers meet the ocean.
Mangroves	Coastal wetlands found in tropical and subtropical regions typically characterized by shrubs and trees with an affinity to saline tidal waters.
Tidal Salt Marshes	A type of coastal wetland frequently or continually inundated with water, characterized by soft-stemmed vegetation adapted to saturated soil conditions. b/
Coral Reefs	A large underwater calcium carbonate formation that includes a diverse collection of biological communities.
Coastal Deltas	Typically a triangular deposit of silt and sand deposited at the mouth of a river along a coast.

a/ California Environmental Resources Evaluation Systems (2000)
b/ EPA (2006b)

The world's coastal length is estimated to be 1,015,756 miles, with North America having the longest coastal length of all continents (Pruett and Cimino 2000, as cited in Burke *et al.* 2001). Canada has the longest coastal length of any country in the world and the United States has the second longest, at 164,988 miles and 82,836 miles, respectively (Pruett and Cimino 2000, as cited in Burke *et al.* 2001).

Coastal zones are areas of substantial biological productivity that provide food, shelter, spawning grounds, and nurseries for fish, shellfish, birds, and other wildlife. The interaction between aquatic and terrestrial components of coastal ecosystems creates a unique environment that is critical to the life cycles of many plant and animal species. In the United States, 85 percent of commercially harvested fish depend on estuaries and coastal waters at some stage in their life cycle (Summers *et al.* 2004), while as much as 95 percent of the world's marine fish harvest is caught or reared in coastal waters (Sherman 1993, as cited in Burke *et al.* 2001). Most historical information available on coastal ecosystems focuses on data related to fisheries. As more research is conducted on other increasingly important coastal ecosystems, new data and information are becoming available. For example, coral reefs alone, while representing only 0.2 percent of the total area of oceans, harbor more than 25 percent of all known marine fish (Bryant *et al.* 1998). In addition, the species in some coral reefs can reach densities of 1,000 per square meter (Tibbets 2004). In the United States, 85 percent of the country's essential nesting, feeding, and breeding habitat for waterfowl and migratory birds is found in coastal ecosystems (Summers *et al.* 2004). Coastal zones have also been found to support a much higher percentage of the world's threatened and endangered species.

Because a disproportionate percentage of the world's population lives in coastal zones, the activities of humans have created environmental pressures that threaten the very resources that make the coastal zones desirable (Summers *et al.* 2004). The impact of these activities varies from place to place and depends on the types and sensitivity of coastal ecosystems involved. A wide range of pressures has been identified as causing adverse changes in coastal ecosystems, but the leading causes of coastal

ecosystem degradation include physical alteration, habitat degradation and destruction, water withdrawal, overexploitation, pollution, and the introduction of non-native species (UNESCO and WWAP 2006). In addition, climate change might compound these pressures through the effects of higher sea levels, warmer seawater, altered ocean circulation patterns, increased and extreme storm events, and increased carbon dioxide concentrations (UNESCO and WWAP 2006, Burke *et al.* 2001).

4.5.5.1.1 Coastal Conditions Globally and in the United States

The conditions of coastal ecosystems vary from place to place and depend on many factors. Attempts have been made to assess the global extent and distribution of aquatic habitats, but estimates vary considerably depending on the type and source of data (UNESCO and WWAP 2006). While inventories of coastal zones exist, no high-quality data sets or indicators are available at the global level that track changes in condition over time (UNESCO and WWAP 2006). Despite the lack of high-quality data, it is safe to assume that coastal zones with substantial human populations are vulnerable to a range of human activities that can increase pressure and cause adverse changes to coastal ecosystems. As mentioned above, typical coastal ecosystem degradation would include physical alteration, habitat degradation and destruction, water withdrawal, overexploitation, pollution, and the introduction of non-native species. The effects of sea-level rise from climate change could compound these potential impacts.

EPA considers the current overall coastal condition of the United States to be fair (Summers *et al.* 2004). Six geographic coastal regions (Great Lakes Coastal Area, Northeast Coastal Area, Southeast Coastal Area, Gulf Coast Coastal Area, West Coastal Area and Alaska, Hawaii, and Island Territories) were evaluated by EPA using five ecological health indicators to assess estuarine coastal conditions as good, fair, or poor. The five indicators are water quality, sediment quality, benthic, coastal habitat, and fish tissue contaminants. Of the five indicators, only the coastal habitat index received an overall poor rating. The benthic and sediment quality indices rated fair to poor, while the water quality and fish tissue contaminants indices received fair ratings. Of the six coastal regions, the Southeast Coastal Area ranked highest with all indicators rating fair to good. The region with the worst coastal condition was the Northeast Coastal Area, with four of the five indicators rating poor or fair to poor. In terms of human and aquatic life use, 21 percent of the assessed coastal resources of the country are considered unimpaired (good condition), whereas 35 percent are impaired (poor condition) and 44 percent threatened (fair condition).

4.5.5.1.2 Observed Trends in Coastal Zones Conditions

Impacts to coastal ecosystems are expected to continue as coastal populations increase and demand more coastal space and resources. Many coastal ecosystems around the globe have been substantially degraded, and many have been lost altogether. Quantifying the changes in coastal ecosystems is difficult because historical data describing the previous extent of coastal ecosystems are very limited. More and higher-quality data characterizing the world's coastal zones are needed. Burke *et al.* (2001) found the following trends in the conditions of coastal ecosystems:

- Many coastal habitats are disappearing at a fast pace, with extensive losses occurring in the past 50 years.
- Although some industrial countries have improved coastal water quality, chemical pollutant discharges are increasing overall as agriculture intensifies and new synthetic compounds are developed.
- Pollution filtering capacities are lost as coastal ecosystems are lost.

- Nutrient inputs to coastal waters appear to be increasing because of population increase and agricultural intensification.
- The frequency of harmful algal blooms resulting in mass mortality of marine organisms has increased substantially over the past few decades.
- Increased occurrences of hypoxia (shortage of oxygen in water) have been reported.
- More than 25 different coral reef diseases have been recorded since 1970, and reports of coral bleaching have increased measurably in recent years.
- Many commercial fish species and other marine wildlife have become threatened.
- Large-scale marine oil spills have been declining, but oil discharges from land-based sources are believed to be increasing.
- An increased number of invasive species is being reported throughout the world coastal ecosystems.
- The number of protected marine and coastal areas has increased, indicating greater awareness of the need to protect these environments.
- Global marine fish production has increased six-fold since 1950.
- The capacity of coastal ecosystems to produce fish for human harvest has been highly degraded by overfishing, destructive trawling techniques, and loss of coastal nursery areas.
- Notable ecosystem changes have occurred over the last half-century in some fishery areas, such as the North Atlantic and Northeast Pacific.

A number of marine wildlife species have been or could be adversely affected by environmental changes in temperature, availability of water and nutrients, runoff from land, wind patterns, and storminess that are associated with climate change (Kennedy *et al.* 2002). Marshes and mangroves are particularly susceptible to sea-level rise affecting the feeding or nesting grounds of black rail, clapper rail, some terns, and plovers (Kennedy *et al.* 2002). Over the short term, however, shrimp, menhaden, dabbling ducks, and some shorebirds would benefit from the release of nutrients from the breakup of marshes (Kennedy *et al.* 2002). The southern sea otter, a keystone species, is listed as threatened by the Endangered Species Act where the population has declined as a result of the increased contaminants associated with high runoff produced by El Niño Southern Oscillation-induced Pacific Ocean storms (Environmental and Energy Study Institute 2001). Marine turtles are affected by unusual changes in high/low temperatures, pollutants, infectious agents, and marine biotoxins, and have become threatened by an epidemic of fibropapillomatosis linked to polluted coastal areas, agricultural runoff, and biotoxins from algae (Environmental and Energy Study Institute 2001). The full effect of marine birds and species inhaling or ingesting biotoxins produced by algal blooms is of concern and not fully understood (Environmental and Energy Study Institute 2001).

There is strong evidence that temperature increases caused a rise in the global sea level during the 20th Century (Parry *et al.* 2007). Because each coastal area has its own unique geographic and environmental characteristics, consequences from adaptations to climate change are expected to differ for each community. Areas of critical sensitivity on the global scale include Tokyo, Shanghai, and London, and Thailand, India, and Vietnam (Nicholls *et al.* 2007, as cited in National Science and Technology

Council 2008). These areas share the characteristics of coastal location, low elevation, large population, and currently stressed resources. Because of their proximity to the water's edge and the high level of infrastructure typical of many coastal communities, these urban centers are sensitive to changes in sea-level rise (National Science and Technology Council 2008).

Recent data suggest that the rise in global sea level has had an effect on some coastal zones of the United States. Sea level data have shown a rise of 0.8 to 1.2 inches per decade since the beginning of the 20th Century along most of the Atlantic and Gulf Coasts in the United States (National Science and Technology Council 2008). Most of the Atlantic Ocean demonstrated a sea-level rise over the past decade at a rate greater than 0.1 inch per year in an east-northeast band from the United States east coast (National Science and Technology 2008). Coastal wetland loss is occurring where these ecosystems are squeezed between natural and artificial landward boundaries and rising sea levels (Field *et al.* 2007, as cited in National Science and Technology 2008). Rise in sea level could be contributing to coastal erosion across the eastern United States (Zhang *et al.* 2004, as cited in Rosenzweig *et al.* 2007). Sea-level rise in the Chesapeake Bay has accelerated erosion rates resulting in wetland destruction (National Science and Technology Council 2008). In Mississippi and Texas, more than half of the shorelines have eroded at average rates of 8.5 to 10.2 feet per year since the 1970s, while 90 percent of the Louisiana shoreline has eroded at a rate of 39.4 feet per year (Nicholls *et al.* 2007, as cited in National Science and Technology Council 2008). Areas in Louisiana are experiencing barrier island erosion resulting in an increased height of waves (Nicholls *et al.* 2007, as cited in National Science and Technology Council 2008). Furthermore, regional sea-level rise has contributed to increased storm surge impacts along the North American eastern coast (National Science and Technology Council 2008). Particularly becuase subsidence is occurring in parts of this area, areas such as the Louisiana and Gulf coasts are considered at high risk from erosion and storm surges, and any area along the coast with low elevation, large populations, and currently stressed resources could be expected to be at risk from any future sea-level rise.

4.5.5.2 Environmental Consequences

This section describes the potential cumulative effects of climate change on coastal zones, both in the United States and globally.

4.5.5.2.1 Projected Impacts of Climate Change for the United States

According to the National Science and Technology Council's Scientific Assessment, 50 percent of Americans live in coastal communities (National Science and Technology Council 2008). Coastal urban centers are expected to experience a surge in population growth of an additional 25 million people over the next 25 years. This change in population is expected to compound the anticipated adverse effects of climate change on coastal communities, placing heavier demand on already stressed resources (National Science and Technology Council 2008). Data have confirmed an average rise in sea level of 0.8 to 1.2 inches per decade since the beginning of the 20th Century along most coasts in the United States, with the Gulf Coast experiencing a rise of a few inches per decade (primarily due to land subsidence) and Alaskan coasts experiencing *decreases* in sea level of a few inches per decade (National Science and Technology Council 2008). In one example, the Union of Concerned Scientists' report (Frumhoff *et al.* 2007) discusses the impacts of surging waters during a coastal storm in December 1992, when strong winds and rising water levels disrupted the New York City public transit system and required the evacuation of communities in New Jersey and Long Island. Sea-level rise in the Chesapeake Bay has accelerated erosion rates, resulting in wetland destruction (National Science and Technology Council 2008). Sea-level rise in the 21st Century is expected to exceed that of past years, causing great alarm for coastal communities and the infrastructures they support.

Although a range of adverse effects from climate change is expected in the United States, one of the most damaging is expected to be that of sea-level rise. The IPCC predicts a sea-level rise of 7 to 23 inches by 2090-2099 (Parry 2007, as cited in National Science and Technology Council 2008). These figures do not include the anticipated sea-level rise from melting ice sheets and glaciers in Greenland and Antarctica where scientists have already noted a decrease in the thickness and depth of sea ice (National Science and Technology Council 2008) or the potential for rapid acceleration in ice loss (Alley *et al.* 2005, Gregory and Huybrechts 2006, Hansen 2005, all as cited in Pew Center on Climate Change 2007). Recent studies have found the IPCC's estimates of ice loss from the Greenland and Antarctic ice sheets and from mountain glaciers might be underestimated (Shepherd and Wingham 2007, Csatho *et al.* 2008, Meier *et al.* 2007). Further, IPCC might underestimate sea-level rise that would be gained through changes in global precipitation (Wentz *et al.* 2007, Zhang *et al.* 2007). Rahmstorf (2007) used a semi-empirical approach to project future sea-level rise. The approach yielded a proportionality coefficient of 3.4 mm per year per °C of warming, and a projected sea-level rise of 0.5 to 1.4 meters above 1990 levels in 2100 when applying IPCC Third Assessment Report warming scenarios. Rahmstorf (2007) concludes that "[a] rise over 1 meter by 2100 for strong warming scenarios cannot be ruled out."

Some general effects associated with rising sea levels include:

- Loss of land area due to submergence and erosion of lands in the coastal zone
- Changes to coastal environments
- More flooding due to storm surges
- Salinization of estuaries and groundwater (National Science and Technology Council 2008)

For islands such as those located in Hawaii and other U.S. territories in the Pacific, outcomes could include a reduction in island size and the abandonment of inundated areas (National Science and Technology Council 2008). Approximately one-sixth of U.S. land that is close to sea level is located in the mid-Atlantic region and, consequently, much of the reporting on effects focuses on this region (National Science and Technology Council 2008).

Over the past century, the highest rate of sea-level rise has been observed in the mid-Atlantic region, in part resulting from subsidence of the land surface (Gutierrez *et al.* 2007). For example, Virginia has observed sea-level rise at 4.4 mm per year compared to 1.8 mm per year in Maine (Zervas 2001, as cited in Gutierrez *et al.* 2007). New Jersey, with 60 percent of its population living along the 127 miles of coastline, has experienced coastline subsidence and beach erosion threatening communities and coastal wetlands (Union of Concerned Scientists 2007, Aucott and Caldarelli 2006, Metro East Coast Regional Assessment 2000).

The effects of sea-level rise on some coastal communities could be devastating with increased erosion and flooding. Extensive erosion has already been documented across the East Coast, as have notable decreases in the coastal wetlands of Louisiana, the mid-Atlantic region, New England, and New York (Rosenzweig *et al.* 2007, as cited in National Science and Technology Council 2008). Erosion is expected to be worse in sandy environments along the mid-Atlantic coast, Mississippi, and Texas (National Science and Technology Council 2008; Nicholls *et al.* 2007, as cited in National Science and Technology Council 2008). The IPCC notes that sandy shorelines are already retreating. Furthermore, areas in Louisiana are experiencing barrier island erosion, resulting in increases in the height of waves that make it to shore (Nicholls *et al.* 2007, as cited in National Science and Technology Council 2008). A large storm can affect the shoreline position for weeks to a decade or longer (Morton 1994, Zhang *et al.* 2004, List *et al.* 2006, Riggs and Ames 2003, all as cited in Gutierrez *et al.* 2007). Tidal wetlands, estuarine beaches, marshes, and deltas are expected to be inundated with water in areas such as the Mississippi River, Louisiana Delta, and the Blackwater River marshes in Maryland (Titus *et al.* 2008, as cited in National Science and Technology Council 2008). The "coastal squeeze" phenomenon, where

wetlands are trapped between natural and human-made land boundaries, is causing wetland loss and habitat destruction (Field *et al.* 2007, as cited in National Science and Technology Council 2008). Freshwater resources are also at risk given the *likely* intrusion of saltwater into groundwater supplies, adversely affecting water quality and salinization rates (Kundzewicz *et al.* 2007, as cited in National Science and Technology Council 2008).

The height of storm surges will increase if sea level rises, regardless of storm frequency and intensity increases; thus, a storm of similar behavior will cause greater damage with rising sea level (Fisher *et al.* 2000). One study suggests the 100-year flood might actually occur every 25 to 30 years (Najjar *et al.* 1999, as cited in Fisher *et al.* 2000). By mid-century, Boston and Atlantic City could experience a 100-year flood event every 2 to 4 years and annually by the end of the century (Frumhoff *et al.* 2007).

Cayan *et al.* (2006) projected future sea-level rise and its implications for California. The study projected sea-level rise, relative to 2000, to range from 11 to 54 centimeters (4.3 to 21 inches); 14 to 61 centimeters (5.5 to 24 inches); and 17 to 72 centimeters (6.7 to 28 inches) by 2070 to 2099 for B1, A2, and A1 GHG modeling scenarios, respectively. The mean sea-level rise from a survey of several climate models was also determined to range from approximately 10 to 80 centimeters (3.9 to 3.15 inches) between 2000 and 2100. The historic rate of sea-level rise observed at San Francisco and San Diego during the past 100 years was 15 to 20 centimeters (5.9 to 7.9 inches). Parts of the California coast are at risk for flood damage, which could further jeopardize levees in the City of Santa Cruz (California Environmental Protection Agency 2006). Santa Cruz is 20 feet above sea level with levees built to contain the 100-year flood. If sea levels were to increase above 12 inches as predicted for the medium warming range of temperatures, a flood associated with a storm surge event at the 100-year level might happen once every 10 years (California Energy Commission 2006). The ENSO events of 1982-1983 and 1997-1998 corresponded to high sea level episodes (Flick 1998, as cited in Cayan *et al.* 2006). These high-sea-level episodes could intensify in future ENSO events if sea-level rise increases.

The frequency and intensity of storms are expected to become more prevalent at the same time as sea levels rise and sea surface temperatures increase. Some societal effects include the following:

- Infrastructure such as bulkheads, dams, and levees could be damaged by flooding and strong storms (Nicholls *et al.* 2007, as cited in National Science and Technology Council 2008).
- Coastal ports, roads, railways, and airports are at risk of disruption due to power outages, flooded routes, and poor travel conditions (Nicholls *et al.* 2007, as cited in National Science and Technology Council 2008).
- Industries reliant on coastal stability, such as travel and recreation, fishing and hunting, and trade, are expected to become increasingly sensitive to these temperature and precipitation changes in the coming decades (Nicholls *et al.* 2007, as cited in National Science and Technology Council 2008).
- The most at-risk state in the United States is expected to be Alaska because the indigenous communities depend on wildlife for hunting and fishing practices, reside within floodplains, and currently face water shortages (Field *et al.* 2007, as cited in National Science and Technology Council 2008).

Loss of coastal wetlands due to intense storms has been documented on many occasions. A prominent recent example is the loss of coastal lands as a result of Hurricane Katrina in 2005. In Louisiana alone, the loss of land during Hurricane Katrina was approximately 217 square miles. The

Chandeleur Islands, which New Orleans relied on as a tropical storm buffer, lost 85 percent of their surface area (CCSP 2008b).

Increases in storm frequency and severity, and sea-level rise itself, have detrimental effects on coastal areas with sandy beaches. Many species rely on the wellbeing of, and accessibility to, beaches. Examples include the following:

- Diamondback terrapins and horseshoe crabs rely on beach sands to bury their eggs. The eggs not only act to propagate the species, but some shorebirds, such as the piping plover, rely on these eggs as a food source (USFWS 1988, as cited in Titus *et al.* 2008).

- Horseshoe crabs rarely spawn unless sand is deep enough to nearly cover their bodies, about 10 centimeters (4 inches) (Weber 2001). Shoreline protection structures designed to slow beach loss can also block horseshoe crab access to beaches and can trap or strand spawning crabs when wave energy is high (Doctor and Wazniak 2005). So, in this case, the loss of beach, as well as the adaptation strategy selected by the community, can result in harm to local species.

- A rare firefly, *Photuris bethaniensis*, is found only in areas between dunes on Delaware's barrier beaches. Its habitat is at risk due to beach stabilization and hardening of shorelines; this limits migration of dunes and the formation of the swales between dunes where the firefly is found (Titus *et al.* 2008).

4.5.5.2.2 Adaptation to Climate Change

There are uncertainties regarding which effects of climate change could affect individual coastal and low-lying areas. However, because these areas are particularly sensitive to climate and hazardous weather events, adaptation to projected climate change remains a potentially attractive option. Adaptations can be preventative, taken before the arrival of an anticipated impact, or reactive, taken in response to the actual changes. Many of the adaptations for coastal and low-lying areas can overlap between these two categories and might differ only by the timing in which they are implemented. The CCSP (2008a, as cited in National Science and Technology Council 2008) outlines seven approaches to adaptation:

- Protecting key ecosystem features
- Reducing anthropogenic stresses
- Representation (maintaining species diversity)
- Replication of ecosystems to maintain species diversity and habitable lands
- Restoration of disturbed ecosystems
- Refugia (using less affected areas to "seed" new areas)
- Relocation

Some examples of possible adaptation strategies in the United States include shifting populations and infrastructure from coastal communities along the East and Gulf Coasts and mid-Atlantic region further inland (Nicholls *et al.* 2007, as cited in National Science and Technology Council 2008). Other possible strategies include elevating infrastructure, introducing barriers such as levees and dams to hold off storm surges; reducing fertilizer and pesticide use in nearshore coastal communities (Epstein *et al.* 2006); preserving contiguous interconnected water systems (including mangrove stands, spawning lagoons, upland forest and watershed systems, coastal wetlands) (Epstein *et al.* 2006); and constructing watertight containment for essential equipment (NY City DEP 2008). Although the options for adaptation in coastal and low-lying areas are many, the key is to consider the period during which these

adaptations are proposed and implemented to best prepare communities. The IPCC in their 2007 Technical Summary has predicted that the costs of adaptation are *virtually certain* to be less than those of inaction (Parry *et al.* 2007).

Current government programs are in effect that assist in subsidizing protection for coastline development, including shoreline protection and beach replenishment, federal disaster assistance, and the National Flood Insurance Program (Fisher *et al.* 2000). In 2006, Maine developed and implemented shoreline regulations to address projected sea-level rise due to climate change (Frumhoff *et al.* 2007). Maine is currently the only state in the Nation with such a program.

4.5.5.2.3 Projected Global Impacts of Climate Change

Globally, coastal systems and low-lying areas are experiencing adverse effects related to climate change and sea-level rise, such as coastal inundation, erosion, ecosystem loss, coral bleaching and mortality at low latitudes, thawing of permafrost, and associated coastal retreat at high latitudes (*very high confidence*) (Nicholls *et al.* 2007). To further exacerbate the stressors, human settlement and encroachment on coastal systems and low-lying areas have been increasing with an estimated 23 percent of the world's population living within about 60 to 65 miles of the coast and no more than about 330 feet above sea level (Small and Nicholls 2003).

Although non-uniform around the world, global sea level is estimated to have risen by 0.07 plus or minus 0.02 inch per year over the past century with western Pacific and eastern Indian Ocean experiencing the greatest rise (Nicholls *et al.* 2007). Sea level is anticipated to continue to increase 0.7 to 2.0 feet or more by the end of the 21st Century (Nicholls *et al.* 2007). This sea-level rise coupled with both projected sea surface temperatures increasing 1 to 3 °C and intensified cyclonic activity could lead to larger waves and storms surges impacting coastal systems and low-lying areas across the globe (Nicholls *et al.* 2007). The loss or degradation of coastal ecosystems has a direct impact on societies that depend on coastal-related goods and services such as freshwater and fisheries with the potential to impact hundreds of millions of people (Parry *et al.* 2007).

There is variability in the projected effects from climate change and sea-level rise on an international scale. For instance, if the global mean annual temperature increases above 1980 to 1999 levels, coastal systems and low-lying areas are anticipated to sustain increased damage due to floods and storms; an additional increase of 2 °C would lead to an increase of millions of people that could experience coastal flooding each year; and an increase of 3 °C is estimated to cause a loss of 30 percent of the global coastal wetlands (*high confidence*; IPCC 2007c, Figure SPM.2). Coastal wetland ecosystems are at substantial risk from sea-level rise if they are sediment-starved or prevented from migrating inland. As sea water temperatures increase, it is *likely* that coral bleaching and mortality will rise unless corals demonstrate thermal adaptation (Nicholls et al 2007). These adverse impacts are expected to increase in severity as the global mean annual temperature increases.

Tide gauges have measured the average rate of sea-level rise to be 0.07 plus or minus 0.02 inch per year from 1961 to 2003 and 0.07 plus or minus 0.02 inches per year (National Science and Technology Council 2008) over the past century. These changes are attributed to thermal expansion associated with rising global temperature, thawing of permafrost, and loss of sea ice (Nicholls *et al.* 2007). The global ocean temperature averaged from the surface to a depth of approximately 2,300 feet has increased by 0.10 °C over the period from 1961 to 2003, contributing to an average increase in sea level of 0.02 plus or minus 0.004 inch per year (National Science and Technology Council 2008). This contribution has increased for the period 1993 to 2003 with a rate of sea-level rise of 0.06 plus or minus 0.02 inch per year. Melting of mountain glaciers, ice caps, and land ice have also contributed to the measured sea-level rise. From 1961 to 2003, the melting of land ice has contributed approximately 0.03

plus or minus 0.02 inch per year to sea-level rise with an accelerated rate of 0.05 ± plus or minus 0.02 inch per year between 1993 and 2003 (Lemke *et al.* 2007, as cited in National Science and Technology Council 2008).

Sea-level rise is non-uniform around the world. In some regions, rates of rise have been as much as several times the global mean, while other regions have experienced falling sea level. This might be the result of variations in thermal expansion and exchanges of water between oceans and other reservoirs, ocean and atmospheric circulation, and geologic processes (Bindoff *et al.* 2007, as cited in National Science Technology Council 2008). Satellite measurements provide unambiguous evidence of regional variability of sea level change for the period 1993 to 2003 with the largest sea-level rise occurring in the western Pacific and eastern Indian oceans (National Science and Technology Council 2008).

Sea level is projected to increase from 0.7 to 2.0 feet or more by the end of the 21st Century (Nicholls *et al.* 2007) with the possibility of additional sea-level rise occurring as a result of the breakdown of West Antarctic and Greenland ice sheets. A temperature increase of 1.1 to 3.8 °C would trigger the breakdown of the Greenland ice sheet, and is *likely* to occur by 2100 (Parry *et al.* 2007). An additional sea-level rise of about 21 to 24 feet would result in the complete disappearance of the Greenland ice sheet (IPCC 2007a, Table 4.1, Epstein *et al.* 2006). This scenario raises concern regarding the viability of coastal communities, salt marshes, corals, and mangroves. A sea-level rise of about 14 inches from 2000 to 2080 is projected to reduce coastal wetlands by 33 percent with the largest impact on the Atlantic and Gulf of Mexico coasts of the Americas, the Mediterranean, the Baltic, and small-islands (Nicholls *et al.* 2007).

IPCC SRES estimated that the coastal population could grow from 1.2 billion people in 1990 to between 1.8 billion and 5.2 billion people by the 2080s with this range dependent on coastal migration. Although the impact of sea-level rise on a specific region can be difficult to quantify given regional and local variations (Parry *et al.* 2007), the IPCC describes the following coastal regions as the most vulnerable to the impact of climate change: South Asia, Southeast Asia, East Asia, Africa, and small islands (Nicholls *et al.* 2007).

Many of the coastal cities that are most vulnerable to adverse impacts of climate change are at further risk due to human activities such as agriculture, aquaculture, silviculture, industrial uses, and residential uses that have degraded the natural protective qualities of the coastal systems (Nicholls *et al.* 2007). Coastal countries at risk for shoreline retreat and flooding due to degradation associated with human activity include Thailand (Durongdej, 2001, Saito 2001, both as cited in National Science and Technology Council 2008); India (Mohanti 2000, as cited in National Science and Technology Council 2008); Vietnam (Thanh *et al.* 2004, as cited in National Science and Technology Council 2008); and the United States (Scavia *et al.* 2002, as cited in National Science and Technology Council 2008), with emphasis on the seven Asian megadeltas that have a combined population greater than 200 million (Nicholls *et al.* 2007). Of particular concern are those highly coastal populated regions within countries with limited financial resources to protect or relocate its populations (Nicholls *et al.* 2007).

Small islands are particularly vulnerable to climate change and sea-level rise, especially those islands prone to subsidence (Parry *et al.* 2007). Beach erosion is projected to increase as sea level rises and sea water temperature increases. Arctic islands could experience increased erosion and volume loss as permafrost and ground ice warms in response to rising global temperatures (Mimura *et al.* 2007).

Positive impacts anticipated to be experienced in high latitudes include a longer tourist season and better navigability (Mimura *et al.* 2007). Without adaptation, IPCC model results suggest more than 100 million people could endure coastal flooding due to sea-level rise every year by 2080 (Nicholls *et al.* 2007).

4.5.5.2.4 Adaptation to Climate Change

In some circumstances, the potential effects from climate change and sea-level rise on coastal systems and low-lying areas can be reduced through widespread adaptation (Nicholls *et al.* 2007). The IPCC modeled results of flood risk associated with rising sea level and storm surges projected to 2080 found substantial benefit associated with upgrading coastline defenses (Nicholls *et al.* 2007). In addition, curtailing the current degradation in coastal systems by anthropogenic activities such as deforestation, fertilizer use, sewage dredging, sand mining, fish harvesting, and sea wall construction would provide a more robust coastal system resistant to extreme water levels during storms.

Small islands in the Indian Pacific Oceans and the Caribbean have much of their infrastructure in coastal locations (Parry *et al.* 2007). Under projected levels of sea-level rise, some infrastructure is *likely* to be at risk from inundation and flooding (Mimura *et al.* 2007). Small islands have limited choices in adaptation to sea-level rise and climate change impact on coastal sections.

4.5.6 Food, Fiber, and Forest Products

This section defines these food, fiber, and product resources and the existing conditions and potential vulnerability of each to climate change impacts. The primary source of information presented in this section is the IPCC Fourth Assessment Report (Easterling *et al.* 2007), specifically, Chapter 5 for food, fiber, and forest products.

The food, fiber, and forest sector is a substantial source of livelihood and food for large numbers of the world's population and a major land cover type at a global level. Cropland, pasture, or natural forests account for approximately 70 percent of the world's land cover. The United Nations Food and Agriculture Organization (FAO) estimates that approximately 450 million of the world's poorest people depend entirely on this sector for their livelihood (Easterling *et al.* 2007).

According to IPCC, this sector includes agriculture, forestry, and fisheries. It also includes subsistence and smallholder agriculture, defined as rural producers who farm or fish primarily with family labor and for whom this activity provides the primary source of income (Easterling *et al.* 2007).

4.5.6.1 Affected Environment

An estimated 40 percent of Earth's land surface is used for cropland and pasture (Foley *et al.* 2005, as cited in Easterling *et al.* 2007). The FAO estimates that natural forests cover another 30 percent of the land surface, and that 5 percent of that natural forest area generates 35 percent of global timber production (FAO 2000, as cited in Easterling *et al.* 2007). Nearly 70 percent of people in lower income countries around the world live in rural areas where agriculture is the primary source of livelihood. Growth in agricultural incomes in developing countries fuels the demand for non-basic goods and services fundamental to human development. The FAO estimates that the livelihoods of roughly 450 million of the world's poorest people depend entirely on managed ecosystem services. Fish provide more than 2.6 billion people with at least 20 percent of their average per-capita animal protein intake, but 75 percent of global fisheries are currently fully exploited, overexploited, or depleted (FAO 2004, as cited in Easterling *et al.* 2007).

4.5.6.1.1 Terrestrial Systems

The distribution of crop, pasture, and forest species between the polar and equatorial latitudes is a function of current climatic and atmospheric conditions, as well as photoperiod. Agricultural, pastoral, and forestry systems depend on total seasonal precipitation and its pattern of variability, as well as wind

and humidity. Crops exhibit threshold responses to their climatic environment, which affect their growth, development, and yield (Porter and Semenov 2005, as cited in Easterling *et al.* 2007). Short-term natural extremes, such as storms and floods, interannual and decadal climate variations, and large-scale circulation changes, such as ENSO, all have important effects on crop, pasture, and forest production (Tubiello 2005, as cited in Easterling *et al.* 2007).

For example, Europe experienced a particularly extreme climate event during the summer of 2003, with temperatures up to 6 °C above long-term means, and precipitation deficits up to 12 inches (Trenberth *et al.* 2007, as cited in Easterling *et al.* 2007). Associated with this extreme climate event was a decline in corn yield of 36 percent in the Po River valley in Italy and 30 percent in France. In addition, French fruit harvests declined by 25 percent, winter wheat yields declined by 21 percent, and hay and other forage production declined on average by 30 percent (Ciais *et al.* 2005, as cited in Easterling *et al.* 2007). Moreover, African droughts between 1981 and 1999 caused livestock mortality from 20 percent to more than 60 percent in countries such as Botswana, Niger, Ethiopia, and Kenya (Easterling *et al.* 2007).

Overall, climate change might benefit crop and pasture yields in mid- to high-latitude regions, while decreasing yields in dry and low-latitude regions. Total forest productivity might rise modestly, with considerable global variation. Local extinctions of fish species are expected, particularly at the edges of habitat ranges (Easterling *et al.* 2007).

Agricultural and forest lands are experiencing multiple stresses that increase their vulnerability to climate change impacts. Examples include soil erosion, salinization of irrigated areas, overgrazing, over-extraction of groundwater, loss of biodiversity, and erosion of the genetic resource base in agricultural, forest, and pasture areas. Overfishing, loss of biodiversity, and water pollution in aquatic areas are stresses that increase vulnerability to climate change to fishery resources (Easterling *et al.* 2007).

The vulnerability of these resources depends on both the exposure to climate conditions and capacity to cope with changing conditions. Exposure to conditions highly depends on local geography and environment. Adaptive capacity is dynamic and depends on wealth, human capital, information and technology, material resources and infrastructure, and institutions and entitlements (Easterling *et al.* 2007).

Sub-Saharan Africa offers one example of a region that is currently highly vulnerable to food insecurity (Vogel 2005, as cited in Easterling *et al.* 2007). Drought conditions, flooding, and pest outbreaks are some of the current stressors on food security that could be influenced by future climate change. Options for addressing food insecurity in this region (and overall development initiatives related to agriculture, fisheries, and forestry) could be constrained by health status, lack of information, and ineffective institutional structures. These constraints could limit future adaptations to periods of heightened climate stress (Reid and Vogel 2006, as cited in Easterling *et al.* 2007).

4.5.6.1.2 Aquatic Systems

Spatial adaptation of marine ecosystems to climate change is in some ways less geographically constrained than for terrestrial systems. The rates at which planktonic ecosystems have shifted their distribution have been very rapid over the past three decades, which can be regarded as natural adaptation to a changing physical environment (Beaugrand *et al.* 2002, as cited in Easterling *et al.* 2007). Most fishing communities use stocks that fluctuate due to interannual and decadal climate variability, and consequently have developed considerable coping capacity (King 2005, as cited in Easterling *et al.* 2007).

Research on the relationship between water temperature and the health of freshwater fishes indicates different impacts in summer and winter. Although temperature increases might cause seasonal

increases in growth in the winter, mortality risks to fish populations occur at the upper end of their thermal tolerance zone in the summer.

World capture production of finfish and shellfish in 2004 was more than twice that of aquaculture, but since 1997 capture production decreased by 1 percent, whereas aquaculture increased by 59 percent (Easterling *et al.* 2007). The increasingly important aquaculture sector allows for the application of similar types of management adaptations to climate change suggested for crop, livestock, and forestry sectors. This is not the case, however, for marine capture fisheries, which are shared resources subject to varying degrees of effective governance. Adaptation options for marine capture fisheries include altering catch size and effort. Three-quarters of world marine fish stocks are currently exploited at levels close to or above their productive capacity (Bruinsma 2003, as cited in Easterling *et al.* 2007). Reductions in the level of effort and harvest are required to sustain yields. Such a course of action might also benefit fish stocks that are sensitive to climate variability when their population age-structure and geographic sub-structure are reduced (Brander 2005, as cited in Easterling *et al.* 2007).

4.5.6.2 Environmental Consequences

Earth's land surface is composed mostly of managed cropland and pasture (40 percent) and natural forests (30 percent) (Foley *et al.* 2005, as cited in Easterling *et al.* 2007). These sectors provide important commodities that are produced in a variety of geographic and climatic regions (CCSP 2008c). The continued growth and productivity of the world's agriculture and forests is necessary to sustain human economic and social development.

The discussion below is focused on impacts on food and industrial crops, fisheries, agricultural pastures, commercial forestry, and subsistence farming (Easterling *et al.* 2007). The key drivers for climate impacts in this sector are higher temperatures, changed precipitation and transpiration dynamics, the effects of increased CO_2 concentrations on vegetative growth and yield, greater frequency in extreme weather events, and increased stressors to forests and agriculture in the form of pests and weeds (Easterling *et al.* 2007).

The world's food crops, forests, and fisheries have evolved to be in tune with the present climatic environment. The productivity of these systems ultimately relies on the interaction of various climate factors including temperature, radiation, precipitation, wind speed, and water vapor pressure (Easterling *et al.* 2007). Threshold climatic conditions for crops and forests affect their growth and yield, and climatic conditions and their interaction influence the global distribution of agricultural and forest species (Porter and Semenov 2005, as cited in Easterling *et al.* 2007).

The sensitivity to climate change and exposure to various other stressors increases the vulnerability of the forest, food, and fiber systems (Easterling *et al.* 2007). Non-climate stressors such as soil erosion, overgrazing, loss of biodiversity, decreased availability of water resources, increased economic competition among regions, and the adaptive capacity of various species increase overall sensitivity to the climate and thus exacerbate the adverse effects of climate change (CCSP 2008b).

Climate change could also benefit agriculture and silviculture through the CO_2 fertilization effect. CO_2 is essential for plant growth; some research suggests that higher atmospheric concentrations lead to higher productivity of some food, fiber, and forest crops. Milder winters and longer growing seasons could also increase productivity in some regions.

Important examples that highlight the link between large-scale climate changes and the sensitivity of the food, fiber, and forest systems include the effects of ENSO, a relatively well-known phenomenon, on crop yield. In Australia, during ENSO years there is increased probability of a decline in farmers'

incomes by as much as 75 percent below the median income as compared to non-ENSO years (Tubiello 2005, as cited in Easterling *et al.* 2007). Another example is the extreme heat wave that occurred in Europe in 2003, which lowered maize yield by 36 percent in Italy and 30 percent in France (Ciais *et al.* 2005, as cited in Easterling *et al.* 2007). Uninsured losses for the entire European Union agriculture sector were estimated at 13 billion euros; 4 billion euros was lost in France alone (Sénat 2004, as cited in Easterling *et al.* 2007).

The most recent comprehensive and peer-reviewed literature on global climate impacts on the food and forestry sectors is from the IPCC Fourth Assessment Report. The SAP 4.3 Report provides an additional source of information on the impacts of climate change on agriculture, land resources, and biodiversity in the United States. Most of the evidence cited in this chapter focuses on the results of the IPCC report and SAP 4.3. However, because new evidence is continuously emerging on the subject of climate change impacts on the agriculture and forest systems, the discussion below also draws on results reported in more recent studies.

4.5.6.2.1 Projected Impacts of Climate Change for the United States

Forests

In the United States, the combination of human management and temperate climate has resulted in a productive and healthy forest system, as exemplified by the southern pine plantations (CCSP 2000). Forests are generally considered the most productive of the terrestrial ecosystems and provide important commodities like timber products. They are also key biodiversity sanctuaries and providers of ecosystem services. Currently, forests cover roughly one third of the land in the United States. Net growth of these forests (growth minus removals minus decomposition) accounts for removing about 883.7 $MMTCO_2$ per year, about 12.5 percent of gross national GHG emissions (EPA 2008b). Globally, forests account for the largest fraction of terrestrial ecosystem sequestered carbon, estimated to be roughly 1,640 petagrams of carbon (Sabine *et al.* 2004, as cited in CCSP 2008b). Climate change could directly affect the ability of forests to provide these key services and commodities in several ways.

One key impact of climate change is the extended risk and increased burn area of forest fires coupled with pathogenic stressors that damage fragile forest systems (Easterling *et al.* 2007). These impacts (forest fires, diseases, and pathogens) might be greatest between 2050 and 2100. It is projected that the forest fire season (summer) could be extended by 10 to 30 percent as a result of warmer temperatures (Parry *et al.* 2007). In the western states, the anticipated warmer spring and summer temperatures are expected to reinforce longer fire seasons and increased frequency of large wildfires. In turn, the carbon pools within forests are expected to be affected by changes in forest composition and reduced tree densities (Westerling 2006). More specifically, the Hadley and Canadian climate and ecological models project an increase in the fire season hazard by 10 percent in the 21st Century in the United States, with small regional decreases in the Great Plains and a 30-percent increase in Alaska and the Southeast (CCSP 2000). Highlighting the geographic differences even within a state, two climate models including the Geophysical Fluid Dynamics Laboratory and the Parallel Climate Model were run using “business as usual” (A2) and “transition to a low GHG emissions” (B1) IPCC SRES emissions scenarios. The results showed increases in fire risk in Northern California (15 to 90 percent), increasing with temperature, whereas, in Southern California, the change in fire risks ranged from a decrease of 29 percent to an increase of 28 percent. These results were largely driven by differences in precipitation between the different scenarios. In Southern California the drier conditions simulated in both the Geophysical Fluid Dynamics Laboratory model scenarios led to reduced fire risks in large parts of southern California, with fire risks increased in parts of the San Bernardino Mountains (Westerling and Bryant 2006).

Historical evidence indicates that the warmer periods in the past millennium correlated with increased frequency in wildfires, particularly in western forests (CCSP 2008b). General circulation models project increased wildfire activity in the western states, particularly from 2010 through 2029 (Flannigan *et al.* 2000, Brown *et al.* 2004, both as cited in CCSP 2008b). In 2060, models have projected forest fire severity increases of 10 to 30 percent in the southeastern states and 10 to 20 percent in the northeastern states (Flannigan *et al.* 2000, as cited in CCSP 2008b). Some models have projected even larger increases in wildfire activity, particularly in the southeastern region of the United States (Bachelet *et al.* 2001, as cited in CCSP 2008b). Potential losses to North American producers from increased disturbances (including wildfires, insects, and diseases) coupled with climate change impacts have been estimated to range from $1 to $2 billion per year averaged throughout the 21st Century (Sohngen and Sedjo 2005, as cited in Field *et al.* 2007).

Ancillary consequences of the projected increase in wildfire frequency across the United States include an increase in emissions expected to affect air quality and continue to be a source of GHGs. Although the GHGs that are released through wildfires could eventually be sequestered by forest regrowth, this carbon release might not be fully recovered in the short term and thus might be an important source of CO_2 in the atmosphere (Kashian *et al.* 2006, as cited in CCSP 2008b). Particularly in forests in the western United States, "If wildfire trends continue, at least initially this biomass burning will result in carbon release, suggesting that the forests of the western United States could become a source of increased atmospheric carbon dioxide rather than a sink, even under a relatively modest temperature increase scenario" (Westerling *et al.* 2006).

Invasive Species

The increasing occurrence of forest fires, which is likely to continue with projected warming temperatures, would impact ecosystem services, reduce the potential for carbon storage via forest management, and provide increased potential habitat for invasive species and insect outbreaks (Parry *et al.* 2007).

Since invasive species and pests are not constrained by the need for pollinators or seed spreaders, these species are more adaptable to the warming climate (Vila *et al.* 2007, as cited in CCSP 2008b). The northward movement of weed species, especially invasive weeds, is likely to be a result of higher projected temperatures and increased CO_2 concentration. This movement northward could further be accelerated, as some studies that have shown that the responsiveness of weeds to glyphosate, an important herbicide used in the United States, diminishes with increases in CO_2 concentration levels (Ziska *et al.* 1999, as cited in CCSP 2008b).

Disease and Pathogens

Warming temperatures might be allowing for the migration of diseases and pathogens (CCSP 2008b). More specifically, the increases in temperature are influencing the development of insect lifecycles, reducing winter mortality rates and "influence[ing] synchronization of mass attacks required to overcome tree defenses" (Ryan *et al.* 2008, as cited in CCSP 2008b).

The warming trends in the United States have already allowed for earlier spring insect activity and the increased proliferation of certain species (CCSP 2008b). These warming trends have also allowed for an increase in the survival rates of diseases and pathogens that affect crops, as well as plant and animal species. Recent research has linked the rising temperatures to increased outbreaks of the mountain pine beetle, the southern pine beetle, and the spruce beetle. Rising temperatures have also been correlated with the expansion of suitable range for the hemlock wooly adelgid and the gypsy moth (Ryan *et al.* 2008, as cited in CCSP 2008b). Not only are the boundaries of insects being shifted by climate change

but "tree physiology and tree defense mechanisms" are being altered as well (Kirilenko and Sedjo 2007). The damage to forests is expected to depend on seasonal warming: winter and spring increases in temperature might increase losses to insects such as the southern pine beetle (Gan 2004, as cited in Field *et al.* 2007). In the western United States, particularly in Colorado, a recent measurable decline in aspen trees has been linked to global warming. Unlike earlier episodes of aspen tree dieback, the current decline is occurring more rapidly and over larger areas. The dieback is caused by bark beetles that were not known to have existed in the area (Saunders *et al.* 2008). In effect, "the hotter, drier conditions recently present in Colorado's mountains have enabled these unexpected agents to so quickly kill so many aspen" (Saunders *et al.* 2008). The forest disturbances such as insect outbreaks "are increasing and are likely to intensify in a warmer future with drier soils and longer growing seasons" (Field *et al.* 2007, as cited in Saunders *et al.* 2008). The control of increased insect populations, especially in the projected warmer winters and in the southern regions, might require increased applications of insecticides. It is important to control these insect populations because of their ability to spread other pathogens, especially the flea beetle, which is known to be a conduit for the corn damaging bacteria Stewart's Wilt (CCSP 2008b).

Migration

Under future climate warming scenarios, plant and animal species are expected to shift northward and to migrate to higher elevations, thus redistributing North American ecosystems (Parry *et al.* 2007). The southeast and northwest forests could experience carbon losses as a result of increased drought (CCSP 2000). However, the projected increases in precipitation over dry regions might encourage forest growth and displace some grasslands (CCSP 2008b).

A marked change in forest composition and distribution has been noted in Alaska, as indicated by a northward migration of the subarctic boundary tree line by 6 miles, and the displacement of 2 percent of the Alaskan tundra in the past 50 years (Anisimov *et al.* 2007, as cited in CCSP 2008b). Also, as evidenced by remote sensing analysis, the growing season is increasing in length by roughly 3 days per decade (CCSP 2008b). Arctic vegetation is expected to shift northward and cause forests to overtake tundra (ACIA 2004, as cited in CCSP 2008b).

Crops and Agriculture

In the early part of the 21st century, moderate climate change will increase crop yields on agricultural land by 5 to 20 percent (Easterling *et al.* 2007). However, this is dependent on regional differences and for crops that rely on highly utilized water resources (Parry *et al.* 2007). Crops that are near the threshold of their productive temperature range (*i.e.*, crops that are "near the warm end of their suitable range"), such as wine grapes in California, are expected to decrease in yield or quality based on moderate climate change scenarios (Easterling *et al.* 2007).

Grain crops in the United States are likely to initially benefit from the increased temperature and CO_2 levels. However, as temperatures continue to rise, sensitivity of these grain crops could increase. This sensitivity is expected to an even greater extent for horticultural crops such as tomatoes and onions, compromising their productive yield (CCSP 2008b). Various studies have found differing thresholds for maize production in the United States, with one in particular showing a 17 percent reduction of maize yield per 1 degree Celsius increase in temperature (Lobell and Asner 2003, as cited, in CCSP 2008b). Other crops such as wheat are regionally and temporally dependent. Studies show that wheat yield in the Great Plains "is estimated to decline 7 percent per 1 degree Celsius increase in air temperature between 18 and 21 degrees Celsius and about 4 percent per 1 degree Celsius increase in air temperature above 21 degrees C" (Lobell and Field 2007, as cited in CCSP 2008b). Similarly, rice yields are projected to

decline about 10 percent per 1 degree Celsius increase for temperature profiles that are above current summer mean air temperatures (CCSP 2008b).

In the Great Lakes region, fruit production might benefit from climate change although there might be increased risk of winter thaws and spring frost (Bélanger *et al.* 2002 and Winkler *et al.* 2002, both as cited in Field *et al.* 2007). In New Jersey, higher summer temperatures are expected to depress the yields of a number of other economically important crops adapted to cooler conditions (*e.g.*, spinach, lettuce) by mid-century, while rising winter temperatures are expected to drive the continued northward expansion of agricultural pests and weeds (such as kudzu) (Frumhoff *et al.* 2007) . Cranberries are especially susceptible because of their requirement to be subjected to long periods of cold winter temperatures for development (Frumhoff *et al.* 2007).

Extreme Weather Events

The negative impacts of increased frequency of extreme weather events on crop yield might temper the beneficial effects of increased CO_2 concentrations with associated temperature increases and longer growing seasons on crop growth (CCSP 2008b).

In the United States, particularly in the north, the average increase in temperature is expected to lead to a longer growing season. However, temperature increases could also lead to increased climate sensitivity in the southeast and the Corn Belt (Carbone *et al.* 2003, as cited in CCSP 2008b). The Great Plains region is not expected to experience increased climate sensitivity (Mearns *et al.* 2003, as cited in CCSP 2008b). In terms of species migration as a result of climate change, the United States has experienced an incursion of perennial herbaceous species that limit the soil moisture available for other crops throughout the growing season (CCSP 2008b). The invasion of these nonnative species could impact how these regions adapt to climate change and could lead to the potential for more frequent wildfires by increasing vegetation density (Fenn *et al.* 2003 and Wisdom *et al.* 2005, both as cited in CCSP 2008b).

Multiyear droughts, which might have been a result of increased temperature conditions in lower-elevation forests in the southwestern region, have had a large impact on forest mortality rates (Breshears *et al.* 2005, as cited in CCSP 2008b). The mortality rate continued to increase even though growth at the forest tree line had been increasing previously (Swetnam and Betancourt 1998, as cited in CCSP 2008b). Forest productivity has decreased from climate change-induced warming in drought-prone regions (McKenzie *et al.* 2001, as cited in CCSP 2008b) and in subalpine regions (Monson *et al.* 2005 and Sacks *et al.* 2007, both as cited in CCSP 2008b).

Livestock

The livestock production infrastructure in the United States is likely to be influenced by the climate change-induced distributional and productivity changes to plant species. Livestock production during the summer season would *very likely* be reduced due to higher temperatures, but livestock production during the winter months could increase, again due to the projected increase in temperatures (CCSP 2008b).

The expected elevated CO_2 concentrations could diminish the grass feed quality. An increase in the carbon to nitrogen ratio would decrease the nutritional value of feed. In turn, grazing livestock that feed on lower quality grasses might be affected in terms of decreased weight and health (CCSP 2008b). Expected future average climate-change conditions could have less effect on livestock productivity and potential livestock loss than the effects of increased climate variability (*e.g.*, droughts and heat waves) (CCSP 2008b).

Climate models have projected decreases in livestock productivity in the United States simply due to projected temperature increases. In 2050, climate models project an average decrease in swine, beef, and milk production of 0.9 to 1.2 percent, 0.7 to 2.0 percent, and 2.1 to 2.2 percent, respectively (Frank *et al.* 2001, as cited in CCSP 2008b). Indeed, higher temperatures directly affect animals' ability to maintain homeostasis and consequently livestock must engage in altered metabolic thermoregulatory processes (Mader *et al.* 1997 and Davis *et al.* 2003, both as cited in CCSP 2008b). The induced thermal stress on livestock often results in a reduction in physical activity and ultimately diminishes feed intake. Livestock production losses and associated economic losses might be attributed to increasing temperatures that are "beyond the ability of the animal to dissipate [and] result in reduced performance (*i.e.*, production and reproduction), health, and well-being" (Hahn *et al.* 1992 and Mader, 2003, both as cited in National Science and Technology Council 2008).

The increased temperature expected as a result of climate change could allow for easier migration of animal pathogens and diseases, especially in the northward transition from the low to mid-latitudes, which would adversely affect livestock well-being in the United States (White *et al.* 2003, Anon 2006, van Wuijckhuise *et al.* 2006, all as cited in CCSP 2008b).

Fisheries

Although fisheries in cold freshwater regions are expected to be adversely affected, fisheries in warm freshwater regions could benefit from climate change. The effects of temperature increases have caused northward shifts of fisheries systems and this is expected to continue in the future (CCSP 2008b). According to IPCC, "many warm-water and cool-water species will shift their ranges northward or to higher altitudes" (Clark *et al.* 2001 and Mohseni *et al.* 2003, as cited in Field *et al.* 2007).

An example of negative impacts that result from large-scale species migration is the recent migration of two protozoan parasites from the Gulf of Mexico northward into the Delaware Bay. This parasitic incursion, possibly as a result of climate change, has led to a substantially increased mortality rate of oysters in the region (Hofmann *et al.* 2001, as cited in CCSP 2008b).

According to IPCC, the survival of brook trout in the United States is directly correlated to its preferred cold groundwater seeps habitat. As temperatures increase, mortality rates also increase for certain species of trout (CCSP 2008b). The salmonid species are likely also to be negatively affected by rising temperatures as they, too, are cold-water species (Gallagher and Wood 2003, as cited in Field *et al.* 2007). It is *likely* that other coldwater marine species could "disappear from all but the deeper lakes; cool-water species will be lost mainly from shallow lakes; and warm-water species will thrive, except in the far south, where temperatures in shallow lakes will exceed survival thresholds" (CCSP 2008b). Stocks of the river-spawning walleye will likely decline due to lower lake levels and climate change impacts in Lake Erie (Jones *et al.* 2006, as cited in Field *et al.* 2007). Coastal fisheries are also expected to experience the negative impacts of climate change, including coral reef bleaching, due to increased ocean temperatures (CCSP 2008b). In Alaska, the spawning and migration behaviors of commercially fished species could be affected and increasing temperatures might cause an increase in the cooling needs for storage and processing of catch (CIER 2007).

Adaptation

Motivation to engage in specific adaptation strategies because of the impacts of climate change on the forest, fiber, and food systems of the United States is expected. Adaptive practices in the forestry sector include cultivar selection, replanting tree species that are appropriate for the new climate regime, and utilizing dying timber (CCSP 2000). These and other potential strategies should be taken in the context of overall demand, population, and economic growth. Adaptive measures could be especially

important to ensure the survival of forest, fisheries, and agriculture systems that are rich in biodiversity and productive value (CCSP 2000). It is possible that the current pace of climate change will make it difficult for many tree species to adapt as readily via migration as they have in previous periods of climate changes (Davis and Shaw 2001). It has been documented via pollen records that tree migration rates in the past have been roughly 20 to 40 km per century. In order to keep up with the projected climate changes in the future, tree migration rates would require migration patterns of roughly 300 to 500 km per century. Due to the projected pace of climate change, it is possible that "taxa that fail to adapt rapidly enough to tolerate these new and rapidly changing climate regimes will go extinct" (Davis and Shaw 2001). It is also possible that climate change could result in extinctions of many tree species (Davis and Shaw 2001).

4.5.6.2.2 Projected Global Impacts of Climate Change

Although the preceding section highlights anticipated climate change impacts in the United States, there are additional impacts that could affect forest and agriculture systems elsewhere in the world.

Crops

Globally, the agriculture and forest infrastructure will be affected by climate change. A recent Harvard report on Climate Change Futures states that a "changing climate will alter the hydrological regime, the timing of seasons, the arrival of pollinators and the prevalence, extent, and type of crop diseases and pests" (Anderson *et al.* 2005). Throughout the mid- to high-latitudinal regions, crop-specific productivity increases are projected for global mean temperature increases of 1 to 3 degrees Celsius. Beyond a 3-degrees Celsius increase in global mean temperature, crop productivity is expected to decrease in some regions (Easterling *et al.* 2007). Depending on the crop type, experiments on the effects of increased CO_2 concentrations, namely 550 parts per million as opposed to current levels of roughly 380 parts per million, suggest that crop yields could increase by 0 to 20 percent (Parry *et al.* 2007).

In a modest warming climate scenario, adaptive practices such as using various cultivars and altering planting and harvesting times might maintain cereal crop yields and possibly allow for an increase in productivity in the high latitudinal and temperate regions (Easterling *et al.* 2007). The adaptive practice in regions with 1 to 2 degrees Celsius increases in temperatures corresponds to an avoidance of a 10 to 15 percent reduction in yield for cereal crops (Parry *et al.* 2007). However, in the lower latitude dry regions, cereal crop productivity is projected to decrease for 1 to 2 degrees Celsius temperature increases, thereby exacerbating hunger issues for the population living in these regions (Parry *et al.* 2007).

According to IPCC the, "projected changes in the frequency and severity of extreme climate events will have more serious consequences for food and forestry production, and food insecurity, than will changes in projected means of temperature and precipitation" (Easterling *et al.* 2007). The low latitudinal regions might experience an increase in the frequency of extreme weather events like floods and droughts, which could adversely affect crop production, especially in the subsistence farming regions (Easterling *et al.* 2007). Extreme weather events, "reduce crop yield and livestock productivity beyond the impacts due to changes in mean variables alone, creating the possibility for surprises" (Parry *et al.* 2007). The reduced adaptive capacity of small-scale farmers such as subsistence and artisanal fisherfolk could result in increased vulnerability to extreme weather events, sea-level rise, and the spread of human disease, which could negatively affect agricultural and fish yields (Parry *et al.* 2007). Current climate change models do not yet include recent findings on precipitation extremes that are expected to impact agricultural production in areas such as southern Asia, northern Europe, and eastern Australia. These areas are expected to experience an impact on agricultural productivity as a result of projected increased precipitation extremes such as floods and droughts (Christensen *et al.* 2007, as cited in Easterling *et al.* 2007). Certain crops, such as wheat, are impacted by high precipitation events because wheat is,

"susceptible to insects and diseases (especially fungal diseases) under rainy conditions" (Rosenzweig and Hillel 1998, as cited in Anderson *et al.* 2005). On the other hand, during droughts, certain fungi, such as *Aspergillus flavus*, are stimulated and will feed on drought-weakened crops (Anderson *et al.* 2005).

Decreases in crop and forest yields in moderate warming scenarios for the low latitudes will likely result in increased dependence on food imports in these typically the developing countries. As such, agricultural exports to lower latitude countries are likely to increase in the short term (Parry *et al.* 2007).

There could be a marginal increase in the population at risk of hunger due to climate change, but this would occur in the context of an overall decrease in the global population at risk of hunger as a result of anticipated economic development (Parry *et al.* 2007).

Forests

Globally, commercially grown forests for use in timber production are expected to increase modestly in the short term, depending on geographic region (Easterling *et al.* 2007). Large regional and local differences are anticipated as is a shift in terms of production increase from the lower latitudes to the higher latitudes (Parry *et al.* 2007). This poleward shift of forests and vegetation is estimated at roughly 500 km or more for the boreal zones for climate scenarios with CO_2 concentrations of double the current levels (Kirilenko and Sedjo 2007). In terms of distributional production, net benefits will accrue to regions experiencing increased forest production, whereas regions with declining activity will likely face net losses (Kirilenko and Sedjo 2007).

Due to increases in CO_2 concentration, there is potential for a carbon fertilization effect on the growth of trees with some experiments showing up to an 80 percent increase in wood production for orange trees (Kirilenko and Sedjo 2007). There is evidence to support elevated growth for young, immature forests in response to higher CO_2 concentration levels (Parry *et al.* 2007). However, free-air CO_2 enrichment experiments indicate that mature forests show no appreciable response to elevated CO_2 concentrations. However, young, immature forests show elevated growth in response to higher CO_2 concentrations (Parry *et al.* 2007). It should be noted that there has been only one feasibility study regarding forest free air CO_2 enrichment (FACE) of 100-year-old tree stands in which little to no stem growth was recorded, but that this lack of growth might be explained by the relative difficulty of controlling for constant CO_2 levels (Kirilenko and Sedjo 2007). Many GCMs have projected increases in forest production in certain geographic regions with notable exceptions. For example, the Terrestrial Ecosystem Model and the Center for International Trade in Forest Products Global Trade Model have simulated a future harvest increase of 2 to 11 percent in western North America, a 10 to 12 percent increase in New Zealand, a 10 to 13 percent increase in South America and a harvest decrease in Canada (Kirilenko and Sedjo 2007).

It is important to contrast these possible short term benefits with the negative implications of a warming climate since, "continued warming favors more fungal and insect of forests, and more harsh weather will further weaken tree defenses against pests" (Anderson *et al.* 2005) The ability of forests to continue to function as providers of agriculture and energy as well as sequester carbon will be affected by climate change (Anderson *et al.* 2005). Overall, the "effects of future drought and decreased soil moisture on agriculture and natural vegetation (such as forests) are uncertain and may, at least in part, be temporarily offset by fertilization effects of higher atmospheric concentrations of CO_2" (Triggs *et al.* 2004, as cited in CIER 2007). These extreme weather events, in concert with increased damage from insect and pathogen outbreaks and wildfires, might result in large-scale deforestation, as evidenced by recent trends in the Amazon basin (Kirilenko and Sedjo 2007). Climate-vegetation models have indicated

that at CO_2 concentration levels of roughly three times current levels, the Amazon rainforests will eventually be lost due to climate change (Cox *et al.* 2004, as cited in Kirilenko and Sedjo 2007).

Fisheries

The aquaculture and fisheries sector are expected to incur negative development impacts as a result of the regional changes in the distribution and proliferation of various marine species (Easterling *et al.* 2007). As the distribution of certain fish species continues to be regionally rearranged, there is the potential for notable extinctions in the fisheries system, especially in freshwater species, in temperature ranges at the margin (Parry *et al.* 2007). Recent evidence indicates that the Meridional Overturning Circulation, which supplies nutrients to the upper layers of the Pacific and Atlantic Oceans, is slowing and thus adversely affecting regional production of primary food supply for fisheries systems (McPhaden and Zhang 2002, Curry and Mauritzen 2005, Gregg *et al.* 2003, Lehodey *et al.* 2003, all as cited in Easterling *et al.* 2007). In the North Sea, a shift in the distribution of warm water species such as zooplankton has resulted in a shift of fish species from whiting to sprat (Beaugrand 2004, as cited in CCSP 2008b).

The largest economic impacts associated with the fisheries sector as a result of climate change are expected to occur in coastal regions of Asia and South America (Allison *et al.* 2005, as cited in CCSP 2008b). Specifically, regional climate change could most affect species such as tuna and Peruvian anchovy (Barber 2001 and Lehodey *et al.* 2003, both as cited in CCSP 2008b).

Earlier spring ice melts in the Arctic and diminishing sea ice are affecting the distribution and productivity of marine species, particularly the upper-level sea organisms. In turn, fish harvests in the Arctic region are expected to change in the warming future. The freshwater species in the Arctic region are expected to be most affected by the increasing temperatures (Wrona *et al.* 2005, as cited in Field *et al.* 2007).

4.5.7 Industries, Settlements, and Society

This section defines these resources and describes the existing conditions and potential vulnerability of each to climate change impacts. In addition, this section briefly describes the potential vulnerability of cultural resources, including archaeological resources and buildings of historic significance to climate change impacts. The primary resource used in this section is the IPCC Fourth Assessment Report (Wilbanks *et al.* 2007); specifically, Chapter 7 for industry, settlement, and society.

The industries, settlements, and society sector encompasses resources and activities that describe how people produce and consume goods and services, deliver and receive public services, and live and relate to each other in society.

As defined by IPCC, this sector includes the following:

- Industry: manufacturing, transport, energy supply and demand, mining, construction, and related informal production activities (Wilbanks *et al.* 2007)
- Services: trade, retail, and commercial services, tourism, risk financing/insurance (IPCC 2007a)
- Utilities/Infrastructure: systems designed to meet relatively general human needs, often through largely or entirely public utility-type institutions (Wilbanks *et al.* 2007)

- Human Settlement: urbanization, urban design, planning, rural settlements (Wilbanks *et al.* 2007)
- Social Issues: demography, migration, employment, livelihood, and culture (Wilbanks *et al.* 2007)

4.5.7.1 Affected Environment

The industry, settlements, and society sector covers a very broad range of human institutions and systems, including the industrial and services sectors, large and small urban areas and rural communities, transportation systems, energy production, and financial, cultural, and social institutions.

A principal objective of human societies is to reduce their sensitivity to weather and climate. Recent experience with storms such as Hurricane Katrina reveals the limits to human control over climate-related impacts on industries, settlements, and society. Systems that are sensitive to climate change include air and water quality, linkage systems (transportation and transmission networks), building structures, resource supplies, social networks, and economic systems (Wilbanks *et al.* 2007).

This sector normally experiences and is generally resilient to variability in environmental conditions. Industries, settlements, and human society, however, can be vulnerable to extreme or persistent changes. Vulnerability increases when changes are unexpected or if resources or other factors inhibit the ability of this sector to respond to changes (Wilbanks *et al.* 2007).

Together, industry and economic services account for more than 95 percent of gross domestic product in highly developed economies and between 50 and 80 percent of gross domestic product in less developed economies (World Bank 2006, as cited in Wilbanks *et al.* 2007). Industrial activities are vulnerable to temperature and precipitation changes. For example, in Canada weather-related road accidents translate into annual losses of at least $1 billion Canadian annually, while more than a quarter of air travel delays in the United States are weather related (Andrey and Mills 2003, as cited in Wilbanks *et al.* 2007). Buildings, linking systems, and other infrastructure are often located in areas vulnerable to extreme weather events (flooding, drought, high winds). Trapp *et al.* (2007) found a net increase in the number of days in which severe thunderstorm environmental conditions could occur during the late 21st century using global and high-resolution regional climate models. The analysis suggests a future increase in these conditions of 100 percent or more in Atlanta, Georgia, and New York, New York. Such extreme events that can threaten linkage infrastructures such as bridges, roads, pipelines or transportation networks could cause industry to experience substantial economic losses (Wilbanks *et al.* 2007).

Institutional infrastructure is generally considered to be less vulnerable to weather and climate variation, as it embodies less fixed investment and is more readily adapted within the time scale of climate change. In some cases, experience with climatic variability can enhance the resilience of institutional infrastructure by triggering adaptive responses (Wilbanks *et al.* 2007).

Vulnerability to climate change impacts is determined by local geography and social context rather than large scale or aggregate factors (Wilbanks *et al.* 2007). Risk factors associated with local geography and social context are briefly described below.

4.5.7.1.1 Geography

Extreme weather events are more likely to pose risks to industry, settlements, and society than gradual climate change (Wilbanks *et al.* 2007). Resources and activities that are located in areas with higher susceptibility to extreme weather events (high temperatures, high winds, and flooding) are more

vulnerable to the impacts of climate change. Extreme weather events can damage transportation routes and other infrastructure, damage property, dislocate settlement patterns, and disrupt economic activity. Gradual climate change can change patterns of consumption, decrease or increase the availability of inputs for production, and affect public health needs. Such impacts are experienced locally, but can be linked to impacts on national and global systems (Wilbanks *et al.* 2007).

Archaeological resources and buildings of historic significance are fixed in location and are therefore vulnerable to the effects of extreme weather events and gradual changes associated with local geography. Extreme weather events can expose archaeological resources and damage structures. Over time, gradual changes to weather patterns can also erode protective cover around archaeological resources and increase the rate of deterioration of historic buildings. Vulnerability of these resources to climate change impacts is tied to the susceptibility of location and local geography to extreme and gradual changes to weather.

4.5.7.1.2 Social Context

Worldwide, many of the places where people live are under pressure from a combination of growth, social inequity, jurisdictional fragmentation, fiscal shortfalls, and aging infrastructure. These stresses can include scarcity of water, poor sanitation, inadequate governance structures, unmet resource requirements, economic inequities, and political instability. While these types of stresses vary greatly across localities, they can combine with climate change impacts to result in substantial additional stress at local, national, and global levels (Wilbanks *et al.* 2007).

The social impacts associated with climate change will be mainly determined by how the changes interact with economic, social, and institutional processes to minimize or magnify the stresses. From an environmental justice perspective, the most vulnerable populations include the poor, the very old and very young, the disabled, and other populations that have limited resources and ability to adapt to changes (Wilbanks *et al.* 2007).

4.5.7.1.3 Urbanization

It is estimated that one third of the world's urban population (nearly 1 billion people) lives in overcrowded and unserviced slums, and 43 percent of the urban population is in developing countries. More generally, human settlements are often situated in risk-prone regions such as steep slopes, ravines, and coastal areas. These risk-prone settlements are expected to experience an increase in population, urbanized area, and economic activity. The population in the near-coastal zone (*i.e.*, within 330 feet elevation and 60 to 65 miles distance from the coast) has been estimated to be between 600 million and 1.2 billion, or 10 to 23 percent of the world's population (Adger *et al.* 2005, McGranahan *et al.* 2006, both as cited in Wilbanks *et al.* 2007). Migration from rural to urban areas is a common response to calamities such as floods and famines (Wilbanks *et al.* 2007).

4.5.7.2 Environmental Consequences

Key climate change impacts on this set of human systems are likely to vary widely and depend on a range of location-specific characteristics and circumstances. Moreover, potential climate change impacts on this sector could be particularly challenging to determine because effects tend to be indirect rather than direct, for example changes in temperature—a direct effect of climate change—affect air pollution concentrations in urban areas thereby affecting human health and health care systems, which are all indirect effects (Wilbanks *et al.* 2007).

The human institutions and systems that comprise the industry, settlements, and society sector tend to be quite resilient to fluctuations in environmental conditions that are within the range of normal occurrence. However, when environmental changes are more extreme or persistent, these systems can exhibit a range of vulnerabilities "especially if the changes are not foreseen and/or if capacities for adaptation are limited" (Wilbanks *et al.* 2007). For this reason industry, settlements, and society in developing countries are expected to be more vulnerable to direct and indirect climate change impacts than they are in industrialized countries (Wilbanks *et al.* 2007).

Climate change is expected to affect industry, settlements, and society via a range of physical effects, including the frequency and intensity of tropical cyclones and storms, extreme rainfall and floods, heat and cold waves, drought, temperature extremes, precipitation, and sea-level rise. Following the approach in Wilbanks *et al.* 2007, the categories of human systems addressed in this section include industry, services, utilities and infrastructure, settlements, and social issues. Each category is described below, and potential climate impacts on each category are discussed. Key systems within these categories that are expected to experience impacts associated with climate change are then discussed in greater detail in subsequent sections.

Industry includes manufacturing, transport, energy supply and demand, mining, construction, and related informal production activities (Wilbanks *et al.* 2007). These activities can be vulnerable to climate change when (a) facilities are located in climate-sensitive areas such as coasts and floodplains, (b) the sector is dependent on climate-sensitive inputs such as food processing, or (c) the sector has long-lived capital assets (Ruth *et al.* 2004, as cited in Wilbanks *et al.* 2007). For the energy sector, in addition to possible infrastructure damage or destruction from the effects of climate change (*e.g.*, as could happen due to extreme weather events) effects could also include climate-driven changes in demands for energy. For example, demand for heating could decline in winter months while demand for cooling could rise in summer months (CCSP 2008f).

Services include trade, retail and commercial services, tourism, and risk financing or insurance (Wilbanks *et al.* 2007). Possible climate change impacts on trade include impacts on transportation from extreme weather events like snow and ice storms that could impede the ability to transport goods, or impacts on comparative advantage of a region or country due to temperature shifts that affect production. Climate change impacts on transportation could also affect retail and commercial services. Retail and commercial services could also be affected by climatic conditions that affect prices of raw materials and by potential damage to infrastructure such as facilities existing in climate sensitive areas like coastal regions. Extreme events such as hurricanes can also affect tourism infrastructure. Tourism services could also be affected by climate change impacts through temperature shifts and changes that affect the natural landscape of tourist destinations. Potential indirect effects of climate change on tourism include changes in availability of water and energy prices. With respect to the insurance sector, climate change impacts could lead to increasing risk, which could trigger higher premiums and more conservative coverage. A reduction in availability of or ability to afford insurance could in turn lead to impacts on local and regional economies.

Utilities and infrastructure includes systems that are "designed to meet relatively general human needs, often through largely or entirely public utility-type institutions" (Wilbanks *et al.* 2007). This includes physical infrastructure such as water, transportation, energy, and communication systems, as well as institutional infrastructure such as shelters, public health care systems, and police, fire, and emergency services. "These infrastructures are vulnerable to climate change in different ways and to different degrees depending on their state of development, their resilience, and their adaptability" (Wilbanks *et al.* 2007). In general, institutional infrastructure tends to be less vulnerable to climate change than physical infrastructure because it typically involves less investment in fixed assets and is more flexible over timeframes that are relevant to climate change. There are numerous points where

impacts on different infrastructures interact and the failure of one system can put pressure on others. At the same time, however, "this means that measures to protect one sector can also help to safeguard the others" (Wilbanks *et al.* 2007).

Human Settlement - Climate change interacts with other stresses in its impact on human settlements (Wilbanks *et al.* 2007). Potential impacts on human settlements could be experienced through several pathways. Sea-level rise threatens populations in coastal areas by accelerating the inundation of coastal wetlands, threatening vital infrastructure and water supplies, augmenting summertime energy demand, and affecting public health (Wilbanks *et al.* 2007). Changes in precipitation patterns could alter the availability of potable water while changes in temperature could affect air quality and contribute to an increase in incidents of heat stress and respiratory illnesses (Wilbanks *et al.* 2007). In urban areas, the Urban Heat Island effect (Wilbanks *et al.* 2007), which relates to the "degree to which built and paved areas are associated with higher temperatures than surrounding rural areas" (National Science and Technology Council 2008) might affect the manner in which climate change affects these areas.

Social Issues - Within human settlements, society could also experience a variety of effects associated with climate change. For example, communities could experience increasing stress on management and budget requirements for public services, if demands on public health care and disaster risk reduction grow (CCSP 2008f). There could be a loss of cultural and traditional groups of people, *e.g.* "indigenous societies in polar regions" (Wilbanks *et al.* 2007). Societal concerns that might be affected by the impacts of climate change include socioeconomic issues relating to developed versus developing areas and rich versus poor. Because the developing countries and poorer populations tend to have weaker infrastructure in place to begin with, their vulnerability to climate change effects is expected to be higher and their capacity to cope or adapt are expected to be lower than developed countries and wealthier populations (Wilbanks *et al.* 2007).

4.5.7.2.1 Projected Impacts of Climate Change for the United States

The research literature on climate impacts on United States industry, settlements, and society is relatively sparse. "At the current state of knowledge, vulnerabilities to possible impacts are easier to project than actual impacts because they estimate risks or opportunities associated with possible consequences rather than estimating the consequences themselves" (CCSP 2008f). In general, "climate change effects on human settlements in the United States are expected to occur as a result of interaction with other processes" (National Science and Technology Council 2008). These effects include those on health, water resources, physical infrastructure (notably transportation systems), energy systems, human settlements, and economic opportunities.

Impacts on human health and human health care systems are expected to arise because of temperature-related stress. Increases in cases of respiratory illness associated with high concentrations of ground-level ozone; water-, food-, and vector-borne diseases; and allergies related to higher concentrations of plant species are expected.

Effects on water are expected to include reductions in snowpack, river flows, and groundwater levels, saline intrusion in rivers and groundwater, an increase in water demand due to increasing temperatures, and impacts on sanitation, transportation, food and energy, and communication infrastructures from severe weather events.

The United States coastline, deltas, and coastal cities such as the Mississippi Delta and surrounding cities, are vulnerable to sea-level rise. "Rapid development, including an additional 25 million people in the coastal United States over the next 25 years will further reduce the resilience of

coastal areas to rising sea levels and increase the economic resources and infrastructure vulnerable to impacts" (Field *et al.* 2007, as cited in National Science and Technology Council 2008).

Effects on other key human systems are discussed in greater detail below. Because this section deals with such a broad set of human systems, the potential impacts of climate change and potential adaptations available to key human systems are discussed together. Given the enormous range of human systems that could be affected by climate change, the discussion here is focused on a few key systems where impacts can best be characterized or supported by sufficient information.

Impacts on Transportation Infrastructure

Climate affects the design, construction, operation, safety, reliability, and maintenance of transportation infrastructure, services, and systems. The potential for climate change raises critical questions about how changes in temperature, precipitation, storm events, sea-level rise, and other climate variables could affect the system of roads, airports, rail, public transit, pipelines, ports, waterways, and other elements of the nation's and the world's complex transportation systems.

Climate changes anticipated during the next 50 to 100 years include higher temperatures, changes in precipitation patterns, increased storm frequency and intensity, and rising sea levels globally, resulting from the warming of the world's oceans and decline in polar ice sheets. These changes could affect the transportation system in a wide variety of ways. Those of greatest relevance for the United States are summarized below.

- *Increases in very hot days and heat waves.* It is very likely that heat extremes and heat waves will continue to become more frequent, more intense, and last longer in most regions during the 21st century. This could increase the cost of transportation construction, operations, and maintenance.

- *Increases in Arctic temperatures.* Arctic warming is virtually certain as temperature increases are expected to be greatest over land and at most high northern latitudes. As much as 90 percent of the upper layer of permafrost could thaw under more pessimistic emission scenarios.

- *Rising sea levels.* It is virtually certain that sea levels will continue to rise in the 21st century as a result of thermal expansion and loss of mass from ice sheets. This could make much of the existing transportation infrastructure in coastal areas prone to frequent, severe, and/or permanent inundation.

- *Increases in intense precipitation events.* It is very likely that intense precipitation events will continue to become more frequent in widespread areas of the United States. Transportation networks, safety, and reliability could be disrupted by visibility problems for drivers, and by flooding, which could result in substantial damage to the transportation system.

- *Increases in hurricane intensity.* Increased tropical storm intensities, with larger peak wind speeds and more intense precipitation are likely, which could result in increased travel disruption, impacts on the safety and reliability of transportation services and facilities, and increased costs for construction, maintenance, and repair (Transportation Research Board 2008).

Numerous studies have examined ways of mitigating the transportation sector's contribution to global warming from GHG emissions. However, far less attention has been paid to the potential impacts of climate change on United States transportation and on how transportation professionals can best adapt to climate changes that are already occurring, and will continue to occur into the foreseeable future even if drastic mitigation measures were taken today. Since GHGs have long life spans they continue to impact global climate change for decades (Transportation Research Board 2008).

Scientific evidence confirms that climate change is occurring, and that it will trigger new, extreme weather events and could possibly lead to surprises, such as more rapid than expected rises in sea levels or temperature changes. Every mode of transportation will be affected as climate change poses new and often unfamiliar challenges to infrastructure providers (Transportation Research Board 2008).

Consideration of climate change-related factors in transportation planning and investment decisions should lead to a more resilient, reliable, and cost-effective transportation system in the coming decades. When decisionmakers better understand the risks associated with climate change, they can make better decisions about potential adaptation strategies and the tradeoffs involved in planning, designing, constructing, operating, and maintaining transportation systems (Transportation Research Board 2008).

Projected climate changes have profound implications for transportation in the United States (Transportation Research Board 2008). Climate change is likely to increase costs for the construction and maintenance of transportation infrastructure, impact safety through reduced visibility during storms and destruction of elements of the transportation system during extreme weather events, disrupt transportation networks with flooding and visibility problems, inundate substantial portions of the transportation system in low lying coastal areas, increase the length and frequency of disruptions in transportation service, cause substantial damage and incur costly repairs to transportation infrastructure, and impact the overall safety and reliability of the nation's transportation system (Transportation Research Board 2008).

Transportation systems across the United States are projected to experience both positive and negative impacts from climate change over the next century; the degree of impacts will be determined, in part, by the geographic region (Transportation Research Board 2008). Coastal communities are especially vulnerable to impacts associated with sea-level rise, increased frequency or intensity of storms, and damage to the transportation system due to storm surges and flooding. The literature indicates that the intensity of major storms could increase by 10 percent or more, which could result in more frequent Category 3 (or higher) storms in the Gulf Coast and along the Atlantic coast (Transportation Research Board 2008).Warming temperatures might require changes in the kinds of materials used for construction of transportation facilities, and in the operation and maintenance of transportation facilities and services. Higher temperatures could require the development and use of more heat-tolerant materials (Transportation Research Board 2008). Restrictions on work rules could increase the time and costs for labor for construction and maintenance of transportation facilities. Rail lines could be affected by higher temperatures and more frequent rail buckling, which would affect service reliability, safety and overall system costs and performance. Costs could increase for ports, maintenance facilities, and transportation terminals if higher temperatures require an increase in refrigeration and cooling (Transportation Research Board 2008); and higher temperatures could affect aircraft performance and the runway lengths required for safe operation (Transportation Research Board 2008). On the positive side, higher temperatures might open up northern transportation routes for longer periods of time and allow more direct routing for marine transportation (Transportation Research Board 2008).

Changes in precipitation patterns could increase short-term flooding, resulting in decreased safety, disruptions in transportation services, and costly damage to transportation infrastructure. Hotter climates could exhibit reduced soil moisture and average runoff, which might require changes in the management and maintenance of publicly owned right-of-way. The potential increase in heavy rainfall

might exceed the capacity of existing drainage systems, resulting in more frequent flooding and associated disruptions in transportation system reliability and service, increased costs for maintenance of existing facilities, and increased costs for construction of new facilities (Transportation Research Board 2008).

Relative sea-level rise might inundate existing transportation infrastructure and substantially increase the cost of provision of new transportation facilities and services. Some portions of the transportation infrastructure in coastal areas, or in areas prone to flooding, might have to be protected with dikes or levees – increasing the cost for construction and maintenance, and the potential for more serious flooding incidents associated with the failure of such dikes and levees (Transportation Research Board 2008).

Increased storm frequency and intensity might lead to greater transportation service disruption, and damage to transportation infrastructure in coastal and inland areas. Model results for the study of the Gulf Coast conservatively estimated a 22- to 24-foot potential surge for major hurricanes (Transportation Research Board 2008). During Hurricane Katrina (a Category 3 storm at landfall) surges exceeded these heights in some locations (Transportation Research Board 2008). While the specific location and strength of storm surges are difficult to predict due to the variation of the scale and trajectory of individual tropical storms, substantial portions of the coastal infrastructure across the United States are vulnerable to increased damage resulting from the impacts of climate change (Transportation Research Board 2008).

Disruptions in transportation system availability could result in substantial economic impacts associated with increased costs to construct or repair transportation infrastructure, and costs associated with disruptions in transportation for goods and services. Increasing fuel costs and delays in transportation service result in increased transport costs, which are then passed on to consumers. A substantial disruption in transportation (*e.g.,* destruction of a major transportation facility by hurricane, flood, or other extreme weather event) could affect the regional economy in many different ways. Communities are likely to require long periods of time to recover from these events, and some communities could be permanently affected (Transportation Research Board 2008).

The analysis to date raises clear cause for concern regarding the vulnerability of transportation infrastructure and services in coastal areas, and across the United States. Addressing the risks associated with a changing climate in the planning and design of transportation facilities and services can help public agencies and private investors to minimize disruptions to the smooth and safe provision of transportation services; and can protect the substantial investments made in the nation's transportation infrastructure now and in the future (Transportation Research Board 2008).

According to the USCCSP's *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure Report* (Transportation Research Board 2008), four key factors are critical to understanding how climate change might affect transportation:

- *Exposure.* What is the magnitude of stress associated with a climate factor (sea-level rise, temperature change, severe storms, and precipitation) and the probability that this stress will affect a transportation segment or facility?

- *Vulnerability.* Based on the structural strength and integrity of the infrastructure, what is the potential for damage and disruption in transportation services from this exposure?

- *Resilience.* What is the current capacity of a system to absorb disturbances and retain transportation performance?

- *Adaptation.* What response(s) can be taken to increase resilience at both the facility (e.g., a specific bridge) and system levels?

New approaches to address climate change factors in transportation planning and decisionmaking could include:

- *Extending planning timeframes.* To address the long timeframe over which climate changes and environmental processes occur, planning time frames might need to be extended beyond the typical 20- to 30-year planning horizon. The fact that transportation infrastructure can last for many decades (or even more than 100 years) argues for planning for much longer time frames to examine the potential impacts of climate change and other elements of the natural environment on the location, construction techniques, and costs for transportation infrastructure investments that are expected to last for many decades (Transportation Research Board 2008).

- *Conducting risk assessment analysis for transportation investments.* Transportation investments face many uncertainties, including the potential impacts of climate change on construction, operation, and maintenance. Planners and decisionmakers can use iterative risk management analysis to evaluate potential risks of all types, and to identify potential ways to minimize the risks and increase the resiliency of transportation infrastructure. Transportation structures and facilities can be hardened, raised, or even relocated if needed. Where it is critical to safety, reliability and mobility, redundant systems might be necessary for the most critical elements of the transportation system (Transportation Research Board 2008).

Impacts on Energy Systems

Although the energy sector has been seen as a driver of climate change, the energy sector is also subject to the effects of climate change (Wilbanks *et al.* 2007). All major energy sources are subject to a variety of climate change effects, including temperature, wind, humidity, precipitation, and extreme weather events (Bhatt *et al.* 2007). The most direct climate change impacts for fossil fuel and nuclear power plants, for example, are related to power plant cooling and water availability (Bhatt *et al.* 2007). Each kilowatt of electricity generated by thermoelectric generation requires about 25 gallons of water. Power plants rank only slightly behind irrigation in terms of freshwater withdrawals in the United States (USGS 2004, as cited in Bhatt *et al.* 2007). In addition, about 10 percent of all United States coal shipments were delivered by barge in 2003, and consequently low river flows can create shortfalls in coal supplies at power plants (Bhatt *et al.* 2007).

USCCSP identified potential effects of climate change on energy production and use in the United States, which are stated in terms of likelihood (Wilbanks *et al.* 2007). Principal impacts and their likelihood are listed below:

- Climate change will reduce total energy demand for space heating; effects will differ by region (*virtually certain*).

- Climate change will increase total energy demand for space cooling; effects will differ by region (*virtually certain*).

- Net effects on energy use will differ by region. Overall impacts will be affected by patterns of interregional migration – which are likely to be in the direction of net cooling load regions – and investments in new building stock (*virtually certain*).

- Temperature increases will increase peak demands for electricity (*very likely*).
- Changes in the distribution of water availability will affect power plants; in areas with decreased water availability, competition for water supplies between energy and other sectors will increase (*virtually certain*).
- Temperature increases will reduce overall thermoelectric power generation efficiency (*virtually certain*).
- In some regions, energy resource production and delivery systems will be vulnerable to the effects of sea-level rise and extreme weather events, especially the Gulf Coast and the East Coast (*virtually certain*).
- Hydropower production will be directly and substantially affected by climate change, especially in the West and Northwest (*very likely*).
- Climate change concerns will affect perceptions and practices related to risk management behavior in investment by energy institutions (*very likely*).
- Climate change concerns are almost certain to affect public and private sector energy technology research and development investments and energy resource and technology choices by energy institutions, along with associated emissions (*virtually certain*).

USCCSP concluded that there is very little literature on adaptation of the energy sector to effects of climate change, and their following discussion is therefore largely speculative (Wilbanks *et al.* 2007). Both energy users and providers are accustomed to changing conditions that affect their decisions. The energy sector is among the most resilient of all economic sectors in terms of responding to changes within the range of historical experience (Wilbanks *et al.* 2007). Adaptations to the effects of climate change on energy use could focus on increased demands and rising costs for space cooling; likely responses include investing in more efficient cooling equipment and building envelopes. Increased demands for both peak and average electricity demands could lead to contingency planning for load-leveling, more efficient and expanded generation capacity, expanded inter-ties, and increased storage capacity (Wilbanks *et al.* 2007).

In terms of energy production and supply, the most likely near-term adaptation is expected to be an increase in perceptions of uncertainty and risk in long-term strategic planning and investment; with investors seeking to reduce risks through such approaches as diversifying supply sources and technologies, and risk-sharing arrangements (Wilbanks *et al.* 2007).

Impacts on Human Settlements

The impacts of climate change on human settlements are expected to be substantial in a number of ways. "Settlements are important because they are where most of the [United States] population lives, often in concentrations that imply vulnerabilities to location-specific events and processes" (Wilbanks *et al.* 2007). Among the general effects of climate change are increased stress on human settlements due to higher summer temperatures and decreased stress associated with warmer winter weather. Changes in precipitation and water availability, rising sea levels in coastal regions, and greater risks from extreme weather events such as storms, flooding, and droughts are also expected to affect human settlements to various degrees. At the same time, stresses due to cold weather extreme events, such as blizzards and ice storms, are expected to decrease (Wilbanks et al 2007).

Predicting climate change impacts on United States settlements is difficult because climate change is not forecast on a scale that is appropriate for local decisionmaking, and because climate is not the only change that settlements are confronting. A key example is the continuing population shift, particularly among persons who have reached retirement, toward the Sun Belt and coastal areas. This means an ever larger elderly population could be at risk especially from extreme weather events such as tropical storms, as well as some types of vector-borne diseases and heat related illnesses (CCSP 2008f).

Anticipated human impacts include the following:

- Increased respiratory and cardiovascular problems (Patz and Baldus 2001, as cited in CCSP 2008f).
- Changes in mortality rates caused by temperature extremes (Rozenzweig and Solecki 2001, as cited in CCSP 2008f).
- Increased water demands associated with warming accompanied by changes in precipitation that alters access to water (Gleick 2000, Kirshen 2002, Ruth *et al.* 2007, all as cited in CCSP 2008f).
- Damages or disruptions to services associated with urban infrastructure such as sanitation systems, electricity transmission networks, communication systems, and the like could occur as a result of storms, floods, and fires (CCSP 2008f).
- Sea-level rise could jeopardize many of the 673 coastal counties and threaten population centers (Neumann *et al.* 2000, Kirshen *et al.* 2004, both as cited in CCSP 2008f).
- Vulnerable populations such as the poor, elderly, those in ill health, the disabled, persons living alone, and individuals with limited rights (*e.g.*, recent migrants) are expected to be at greater risk from climate change (CCSP 2008f).

As a specific example with respect to urban infrastructure, the New York City Department of Environmental Protection assessed potential climate change impacts on the city's drainage and wastewater collection systems, noting that if rainfall becomes more intense, sewer system capacities could be exceeded leading to street and basement flooding (NY City DEP 2008). Additionally, extreme precipitation events could lead to an inundation of the Water Pollution Control Plants' (WPCPs) influent wells. Sea-level rise could threaten hydraulic capacity of WPCP outfalls by making peak flow discharges more difficult and also increase the salinity of influent to the WPCP which would upset biological treatment processes and lead to corrosion of equipment (NY City DEP 2008).

The vulnerability of human settlements and infrastructure in coastal areas to natural disasters such as hurricanes and tropical storms was demonstrated through the damages incurred by Hurricanes Katrina and Rita in the Southeastern region of the United States After Hurricane Katrina struck, a total of 90,000 square miles was declared a Federal disaster area, 80 percent of New Orleans was flooded, more than 1,700 lives were lost, 850,791 housing units were damaged, 2,100 oil platforms and over 15,000 miles of pipeline were damaged (Petterson *et al.* 2006, as cited in CIER 2007).

There are various possible adaptation strategies for human settlements. Assuring effective governance, increasing the resilience of physical and linkage infrastructures, changing settlement locations over a period of time, changing settlement form, reducing heat-island effects, reducing emissions and industry effluents, improving waste handling, providing financial mechanisms for increasing resiliency, targeting assistance programs for especially impacted segments of the population,

and adopting sustainable community development practices are some of them (Wilbanks *et al.* 2005, as cited in Wilbanks *et al.* 2007). Land use choices, specifically the discouragement of housing development in flood prone areas including areas below sea level and in deep flow plains, can help protect human settlements and preserve management flexibility for these areas (Isenberg *et al.*, 2008). The choice of strategies and policies for adaptation depend on their relationships with other social and ecological processes and level of economic development (O'Brien and Leichenko 2000, as cited in Wilbanks *et al.* 2007).

Impacts on Economic Opportunities and Risks

Communities or regions that are dependent on climate-sensitive resources or goods or whose comparative advantage could be affected are expected to be particularly vulnerable to climate change. The insurance sector is an example of an industry that could be highly vulnerable to climate impacts. If increasing trends of adverse weather events continue, claims made to private and public insurers are expected to climb (NAST 2001, as cited in CIER 2007). Overall risk exposure of insurers' has grown considerably, *e.g.*, the National Flood Insurance Program's exposure increased four-fold since 1980 to $1 trillion in 2005 and the Federal Crop Insurance Corporation's exposure grew up to $44 billion (U.S. GAO 2007, as cited in CIER 2007). To the extent that climate change increases costs for insurers or increases the difficulty in forecasting risks, the insurance sector might "withdraw (or make much more expensive) private insurance coverage from areas vulnerable to climate change impacts" (National Science and Technology Council 2008).

Trade, retail, and commercial services, and tourism are other economic areas that are expected to be affected by climate change impacts, largely as a result of impacts on the transportation and energy sectors. For example, impacts on transportation will affect distribution and receipt of goods for retail services. This could have a particular effect on the Midwest which is a heavy domestic freight and shipping route area. Approximately "$3.4 billion and 60,000 jobs rely on the movement of goods within the Great Lakes-St. Lawrence shipping route annually" (Easterling and Karl 2001, as cited in CIER 2007). A decline in water levels could jeopardize this mode of transporting manufacturing. In fact, "system connectivity is predicted to be come 25 percent impaired causing a loss of $850 million annually" (Easterling and Karl 2001, as cited in CIER 2007). Dredging 7.5 to 12.5 million cubic yards, costing $85-142 million, might be the only alternative to salvage this system if water levels decline substantially (Great Lakes Regional Assessment Group 2000, as cited in CIER 2007).

Tourism could be affected by "changes in the landscape of areas of tourist interest" as well as by changes in the availability of resources and energy costs (Wilbanks *et al.* 2007). In the United States, climate change impacts could affect winter recreation and tourism in the Northeast. Warmer winters would "shorten the average ski and snowboard seasons, increase snow making requirements, and drive up operating costs," possibly "prompting further closures and consolidation of ski areas northward toward the Canadian border" (Frumhoff *et al.* 2007).

Historical and Cultural Resources

A variety of cultural and historical resources are at risk from climate change. According to a recent study by UNESCO "The adverse impacts of climate change will have consequences for humanity as a whole including the products of human creativity...these consequences will be manifest in at least two principal ways: (1) the direct physical effects on the buildings or structures and (2) the effects on social structures and habitats" (Colette *et al.* 2007).

Alaska is the region expected to be most affected by climate change largely because of location (warming is more pronounced closer to the poles) and way of life (settlement and economic activities

based around Arctic conditions) (CCSP 2008f). Indigenous communities in Alaska are facing major economic and cultural impacts because they depend for subsistence on various climate-sensitive animals such as polar bears, walruses, seals, and caribou (National Science and Technology Council 2008). "Changes in species' ranges and availability, access to these species, a perceived reduction in weather predictability, and travel safety in changing ice and weather conditions present serious challenges to human health and food security, and possibly even the survival of some cultures" (ACIA 2004, as cited in National Science and Technology Council 2008).

In discussing the impacts of climate change on historic cities and settlements around the world, Colette *et al.* 2007 lists the following potential threats associated with climate change:

- Increased salt mobilization with resulting damage to surfaces and decoration as a result of increasing rate of heavy rainfall
- Changes in the amplitude of temperature and humidity can cause splitting, cracking, flaking and other damage to exposed surfaces
- Organic building materials such as wood could be subject to increase infestation as a result of migration of pests
- An increase in flooding can directly damage structures and promote growth of damaging micro-organisms such as molds and fungi
- In arid regions, desertification, salt weathering and erosion could threaten cultural and historic sites

Climate change could also create pressures that result in migration of populations, which in turn could result in the breakdown of communities and the loss of "rituals and cultural memory" (Colette *et al.* 2007).

4.5.7.2.2 Projected Global Impacts of Climate Change

As the discussion above suggests, the three major ways in which industry, settlements, and society are vulnerable to climate change are through impacts on economics, infrastructure, and health. The magnitude of impacts on industry, settlements, and society largely depends on location and the level of development of the area or region. The discussion below highlights anticipated impacts on key human systems at the global level.

Global Energy Sector Impacts

In terms of energy production and use, the expected global impacts will likely be similar to those discussed above for the United States. When the climate warms, less heating will be needed for industrial, commercial, and residential buildings, with changes varying by region and by season (Wilbanks *et al.* 2007). Electricity is used in areas around the world for cooling; coal, oil, gas, biomass, and electricity provide energy for heating. Regions with substantial requirements for both cooling and heating could see net increases in electricity demands while demands for other energy sources decline (Hadley *et al.* 2006, as cited in Wilbanks *et al.* 2007).

According to one study, by 2100 the benefits (reduced heating) will be about 0.75 percent of gross domestic product, and impacts (increased cooling) will be approximately 0.45 percent (Tol 2002a,

2002b, both as cited in Wilbanks *et al.* 2007). These percentages could be affected by migration from heating-intensive regions to cooling-intensive regions (Wilbanks *et al.* 2007).

Climate change could also affect global energy production and distribution if extreme weather events become more frequent or intense; and in regions dependent upon water supplies for hydropower or thermoelectric generation if there are substantial changes in rainfall/snowfall locations and seasonality. Reduced stream flows are expected to jeopardize hydropower production in some areas, but higher precipitation rates resulting in greater or more sustained stream flows could be beneficial (Casola *et al.* 2005, Viosin *et al.* 2006, both as cited in Wilbanks *et al.* 2007). More frequent or intense extreme weather events could threaten coastal energy infrastructures including electricity transmission and distribution facilities (Bull *et al.* 2007).

Warming temperatures resulting in melting of permafrost threaten petroleum production facilities and pipelines, electrical transmission towers, and nuclear power plants in the Arctic region (Nelson *et al.* 2001, as cited in Wilbanks *et al.* 2007). As with Alaska's North Slope facilities, structural failures in transportation and industrial infrastructure are becoming more common in northern Russia due to melting permafrost (Wilbanks *et al.* 2007).

Global Transportation Sector Impacts

The IPCC concludes, with *very high confidence*, that data since 1970 have demonstrated anthropogenic temperature rises have visibly altered ecosystems (Parry *et al.* 2007). Other stressors on the built environment and the ability of cities and countries to adapt to a changing climate make it difficult to discern the exact impacts of climate change on transportation systems around the world. Additional factors, such as projected population growth, are expected to exacerbate the effects of climate change. Development typically occurs in the coastal regions, especially in the newly developing third world countries. These areas are particularly vulnerable to the impacts of projected increases in extreme weather events such as hurricanes, cyclones, unusually heavy precipitation, and flooding. In addition these developing countries are less able to adapt to expected changes due to their limited resources and other pressing needs (Wilbanks *et al.* 2007).

Transportation system vulnerabilities in more developed countries often focus on physical assets and infrastructures and their economic value and replacement costs, along with linkages to global markets. Vulnerabilities in less developed countries often focus on human populations and institutions that are likely to have very different transportation needs and resources (Wilbanks *et al.* 2007). A warmer, drier climate could exacerbate many of the problems of developing countries, including drought and decreases in food production in areas of Africa and Asia (Wilbanks *et al.* 2007).

At a national scale, industrialized countries such as the United Kingdom and Norway can cope with most kinds of gradual climate change, but localized differences can show considerable variability in stresses and capacities to adapt (Environment Canada 1997; Kates and Wilbanks 2003, as cited in National Science and Technology Council 2008; London Climate Change Partnership 2004; O'Brien *et al.* 2004; Kirshen *et al.* 2006).

The impacts on the United States transportation systems described above apply in other countries as well. Based on information developed by the Transportation Research Board (2008) the potential impacts of climate change on transportation fall into the two major categories described below.

- Climate change will affect transportation primarily through increases in several types of weather and climate extremes, such as very hot days, intense precipitation events, intense hurricanes, drought, and rising sea levels, coupled with storm surges and land subsidence.

The impacts will vary by mode of transportation and region, but they will be widespread and costly in both human and economic terms and will require substantial changes in the planning, design, construction, operation, and maintenance of transportation systems.

- Potentially, the greatest impact of climate change on global transportation systems will be flooding of coastal roads, railways, transit systems, and runways because of rising sea levels coupled with storm surges, and exacerbated in some locations by land subsidence (National Science and Technology Council 2008).

Given the global nature of the impacts of climate change and the world economy, coordination within and among nations will become increasingly important (Wilbanks *et al.* 2007). Strong and complex global linkages and interactions occur throughout the world today and are likely to increase in the future. Climate-change effects cascade through interlinked systems for international trade, migration, and communication patterns producing a variety of direct and indirect effects. Some of these impacts might be anticipated. However, many might not, especially if the globalized economy becomes less resilient and more interdependent (Wilbanks *et al.* 2007).

The impacts of an extreme weather event in one location (*e.g.*, Hurricane Katrina in Louisiana) causes ripple effects throughout the transportation system in the United States and in areas around the world linked to the United States through the ports in the affected area (Transportation Research Board 2008).

There are now incidences in Europe, North America, and Japan, of new transportation infrastructure being designed and constructed with potential climate change in mind. For example, bridges and other infrastructure designed at higher elevations in anticipation of sea-level rise over the life span of these transportation system elements (Wilbanks *et al.* 2007).

Global Human Settlements Impacts

Human settlements are vulnerable to the effects of climate change in three major ways: (1) through economic sectors affected by changes in input resource productivity or market demands for goods and services; (2) through impacts on certain physical infrastructure; and (3) through impacts of weather and extreme events on the health of populations. The degree of vulnerability tends to be a function of the location (coastal and riverine areas are most at risk), economy (economies most dependent on weather-related sectors are at the highest risk), and size (larger settlements are at a greater aggregate risk, but they likely have greater resources to prevent the impacts of climate change and respond to events that result from climate changes such as hurricanes, floods, or other extreme weather events) (Wilbanks *et al.* 2007).

Shifts in precipitation patterns might affect already stressed environments. For example, mean precipitation in all four seasons of the year has tended to decrease in all main arid and semi-arid regions of the world, *e.g.*, northern Chile and northeast Brazil, West Africa, and Ethiopia, drier parts of southern Africa, and western China (Folland *et al.* 2001, as cited in Wilbanks *et al.* 2007). Increasing temperature could aggravate ozone pollution in many cities, which could affect quickly growing urban areas that, especially those in developing countries, are experiencing more air pollution problems (Wilbanks *et al.* 2007). Extreme weather events affect settlements and society in developing countries just as they do developed countries, through damage and destruction of infrastructure and loss of human life, although perhaps in slightly different ways. For example, in some urban areas of developing countries, informal settlements develop. These informal settlements are especially vulnerable as they tend to be built on hazardous sites and susceptible to floods, landslides, and other climate-related disasters (Cross 2001, UN-Habitat 2003, both as cited in Wilbanks *et al.* 2007). Another example is how "[i]n developing countries,

a common cause of death associated with extreme weather events in urban areas is electrocution by fallen power cables" (Few *et al.* 2004, as cited in Wilbanks *et al.* 2007).

Generally, low-income and other vulnerable populations would experience the same impacts from climate change as populations in comparable geographic areas described in this section, as well as sections 4.5.6, Food, Fiber, and Forest Products and 4.5.8, Human Health. However, as with environmental justice populations in the United States, climate change impacts would likely be differentially experienced by vulnerable populations. The magnitude of climate change impacts on residents of developing countries would be expected to be greater. For example, IPCC notes that the continent of Africa's "major economic sectors are vulnerable to current climate sensitivity, with huge economic impacts, and this vulnerability is exacerbated by existing developmental challenges such as endemic poverty, complex governance and institutional dimensions; limited access to capital, including markets, infrastructure and technology; ecosystem degradation; and complex disasters and conflicts. These in turn have contributed to Africa's weak adaptive capacity, increasing the continent's vulnerability to projected climate change" (Wilbanks *et al.* 2007).

As discussed in this section, the danger to human health from climate change will differentially affect developing countries. The IPCC states that "Adverse health impacts will be greatest in low-income countries. Those at greater risk include, in all countries, the urban poor, the elderly and children, traditional societies, subsistence farmers, and coastal populations" (Wilbanks *et al.* 2007). Section 4.5.8 describes in detail the potential health effects from climate change on developing countries; these impacts include:

- Increases in malnutrition, and related health impacts, in developing regions of the world due to declining crop yields
- Potential increases in water-related diseases, such as diarrhea-causing pathogens, due to higher temperatures
- Potential for continuation of upward trends in certain vector-borne diseases, such as malaria in Africa, which have been attributed to temperature increases
- Increases in temperature leading to increased ozone and air pollution levels in large cities with vulnerable populations

Section 4.5.6 and this section describe the effects of climate change on developing countries that would differ or be substantially more severe than similar effects experienced by developed nations. Because the developing world tends to depend more on small-scale farming and subsistence economic activities, individuals in these areas would be disproportionately affected by climate change impacts on agricultural and subsistence resources. In particular, these impacts could include:

- Decreases in precipitation in developing parts of the world, such as southern Africa and northern South America, leading to decreases in agricultural production and increased food insecurity
- Substantial potential for impacts on small-scale subsistence farmers resulting from increases in extreme weather events projected under global climate change, reducing agricultural production in some areas of the globe
- Changes in the range of fish and animals and species extinctions, affecting populations in developing nations that depend economically on these resources

- Declines in tourism, especially to coastal and tropical areas heavily affected by sea-level rise, with severe economic consequences for smaller, developing nations

- Sea-level rise and severe weather-related events affecting the long-term habitability of atolls (low coral reef-formed islands) (Barnett and Adger 2003)

Global Impacts on Economic Opportunities and Risks

Impacts vary by region and locality and cannot be generalized for all nations. Although impacts are expected to vary, a factor that developed countries have in common is that their access to material and financial resources provides them opportunities to adapt to the effects of a changing climate. By contrast, developing countries are expected to be less able to adapt to climate change because they lack both the physical and financial resources needed to bolster their resilience to the same extent that is possible in industrialized countries.

In developing countries "industry includes a greater proportion of enterprises that are small-scale, traditional, and informally organized…Impacts of climate change on these businesses are likely to depend on… location in vulnerable areas, dependence on inputs sensitive to climate, and access to resources to support adaptive actions" (Wilbanks *et al.* 2007). One specific industry that could become more vulnerable to direct and indirect impacts of climate change is the tourism industry. Impacts on this industry can be "especially significant for smaller, tourist-oriented countries often in the developing world" (Wilbanks *et al.* 2007). It seems "likely that tourism based on natural environments will see the most substantial changes due to climate change… Tropical island nations and low-lying coastal areas may be especially vulnerable as they may be affected by sea-level rise, changes in storm tracks and intensities, changes in perceived climate-related risks, and changes in transport costs…" (Wilbanks *et al.* 2007). The implications are most notable for areas in which tourism is a relatively large share of the local or regional economy, and those for which adaptation would represent a relatively substantial need and a relatively substantial cost (Wilbanks *et al.* 2007). Trade is another industry that could be affected by extreme weather events that temporarily close ports or transport routes and damage infrastructure critical to trade, both domestic and international. There could be "linkages between climate change scenarios and international trade scenarios, such as a number of regional and sub-regional free trade agreements" (Wilbanks *et al.* 2007). However, research on this topic is lacking.

4.5.7.2.3 Adaptation

People and societies have adapted to changing conditions in every phase of human history, and human societies have generally been highly adaptable (Ausubel and Landford 1977). Adaptation can be anticipatory or reactive, self-induced and decentralized, or dependent on centrally initiated policy changes and social collaboration. Adaptation measures can be gradual, occurring over long periods of time; or evolutionary based on reactions to abrupt changes in settlement patterns or economic activity, or in response to extreme weather events (Wilbanks *et al.* 2007).

Adaptation strategies vary widely depending on the exposure of a place or sector to dimensions of climate change, its sensitivity to such changes, and its capacities to cope with the changes. Some of the strategies are multisectoral, such as improving climate and weather forecasting at local and regional levels, emergency preparedness, and public education (Wilbanks *et al.* 2007). These strategies are likely to be more prominent in more fully developed countries, but are important tools to facilitate adaptation in all countries. Awareness, capabilities, and access to resources that facilitate adaptation to climate change are likely to be much less widely available in less developed countries, where industrial production and residential population often locate in areas vulnerable to flooding, coastal erosion, and extreme weather events (Wilbanks *et al.* 2007).

New warning systems and evacuation procedures are important adaptation strategies. New warning systems in areas prone to extreme weather events such as hurricanes, cyclones, tornados, and flooding can help to prevent weather-related deaths; and minimize damage to community infrastructure, including the transportation system. Adaptation strategies tend to be context-specific, within larger global markets and policy structures, although it generally takes place within the larger context of globalization (Benson and Clay 2003; Sperling and Szekely 2005).

"Adaptation strategies vary widely depending on the exposure of a place or sector to dimensions of climate change, its sensitivity to such changes, and its capacities to cope with the changes" (Wilbanks *et al.* 2007). In general, uncertainty about the distribution and timing of climate-change impacts at the local level makes judgments about the scale and timing of adaptation actions very difficult (Wilbanks *et al.* 2007).

4.5.8 Human Health

4.5.8.1 Affected Environment

Climate change has contributed to human mortality and morbidity (*very high* confidence; IPCC 2007b) with further projected increases. Climate change could increase the risk of flooding; increase incidence of heat waves; change the severity, duration, and location of extreme weather; increase surface temperature; and alter precipitation intensity and frequency. These events can affect human health either directly through temperature and weather or indirectly though changes in water, air, food quality, vector ecology, ecosystems, agriculture, industry, and settlements. Climate change can also affect health through social and economic disruption. Malnutrition, death, and disease brought on by climate-change are projected to affect millions of people (Confalonieri *et al*. 2007).

4.5.8.2 Environmental Consequences

4.5.8.2.1 Heat Waves

A heat wave is a period of abnormally high temperatures that can be accompanied by unusual humidity. This weather phenomenon is not formally specified by a time period or temperature reading. Conventionally, a heat wave lasts several days to several weeks, though a one-day event can qualify as a heat wave. The temperature to qualify as a heat wave is dependent upon what is considered unusually hot for that region, as increases in mortality can occur below temperatures considered extremely hot (Ebi *et al.* 2008). IPCC has found the number of hot days, hot nights, and heat-waves to have increased (Confalonieri *et al.*. 2007). Global warming has increased intensity of heat waves (Houghton *et al.* 2001, as cited in Epstein *et al.* 2006), due in part to the disproportionate warming at night (Easterling *et al.*1997, as cited in Epstein *et al.* 2006). Heat-wave events can trigger poor air quality and forest fires, leading to further increases in human mortality and morbidity (Bates *et al.* 2005, Goodman *et al.* 2004, Keatinge and Donaldson 2001, O'Neill *et al.* 2005a, Ren *et al.* 2006 all as cited in Ebi *et al.* 2008).

The impact of a heat wave on the affected population depends on the current health and economic status. In South Asia, those most sensitive to heat waves include the rural population, elderly, outdoor workers, very young, city-dwellers, those with less education, socially isolated, medicated people, mentally ill, and those without available air conditioning (Chaudhury et al 2000, as cited in Confalonieri *et al.*. 2007; Diaz *et al.* 2002, Klinenberg 2002, McGeehin and Mirabelli 2001, Semenza *et al.* 1996, Whitman *et al.* 1997, Basu *et al.* 2005, Gouveia *et al.* 2003, Greenberg *et al.* 1983, O'Neill *et al.* 2003a, Schwartz 2005, Jones *et al.* 1982, Kovats *et al.* 2004, Schwartz et al 2004a, Semenza *et al.* 1999, Watkins *et al.* 2001 all as cited in Ebi 2008). People in developed areas can be impacted substantially by heat waves as well. Existing electricity grids in the United States would be severely stressed by a major heat

wave, leading to brownouts and blackouts further contributing to increased heat-related illnesses (Epstein *et al.*, 2006).

The urban heat island effect could increase temperatures experienced in cities by 2 to 10 degrees Fahrenheit compared to neighboring rural and suburban areas (EPA 2005 as cited in Ebi *et al.* 2008). This increase in temperature occurs, in part, as the city pavement and buildings absorb a greater amount of incoming solar radiation compared to vegetation and trees; in addition, heat is also emitted from buildings and transportation (EPA 2005, Pinho and Orgaz 2000, Vose *et al.* 2004, Xu and Chen 2004, all as cited in Ebi *et al.* 2008). However, it has been demonstrated that during a heat wave, not all urban areas experience greater heat-related mortality than the surrounding rural and suburban areas (Sheridan and Dolney, 2003, as cited in Ebi *et al.* 2008).

4.5.8.2.2 Cold Waves

Human mortality and morbidity can also be caused by cold waves. Cold waves affect human health through death, hypothermia, frostbite, damage to organs such as kidney, pancreas, and liver, with greatest risk to infants and the elderly (NOAA 2001). Cold waves can cause further complications of heavy snow, ice, coastal flooding, and stranded motorists. As with a heat wave, the classification of a cold wave varies by region, with no formal definition for the minimum temperature reached, the rate of temperature fall, or the duration of the event. Populations in temperate countries tend to be more sensitive to cold weather (Honda *et al.* 1998, as cited in Confalonieri *et al.*. 2007). The human health reaction of a population to a cold wave can vary depending on the income, (Healy 2003, as cited in Ebi *et al.* 2008), age, topography, climate, (Curriero *et al.* 2002, Hajat 2006, both as cited in Confalonieri *et al.* 2007), race, (Fallico *et al.* 2005. as cited in Ebi *et al.* 2008), sex, (Wilkinson *et al.* 2004, as cited in Ebi *et al.* 2008), health, (Wilkinson *et al.* 2004, as cited in Ebi *et al.* 2008), dress, (Donaldson *et al.* 2001, as cited in Ebi *et al.* 2008), and fuel access (Healy 2003, as cited in Ebi *et al.* 2008). Cold days, cold nights, and frost days have become less common (IPCC 2007b) with the winter season projected to continue to decrease in duration and intensity (Alley *et al.* 2007, as cited in Ebi *et al.* 2008). This could lead to a decrease in cold-related health impacts, notwithstanding external factors, such as influenza outbreaks (Ebi *et al.* 2008).

4.5.8.2.3 Extreme Weather Events

Climate change is anticipated to affect the number, severity, and duration of extreme weather events (Fowler and Hennessey 1995, as cited in Sussman *et al.* 2008). Extreme weather events include floods, tropical and extra-tropical cyclones, tornadoes, windstorms, and drought. Extreme weather can further trigger additional extreme events such as wildfires, negatively affecting infrastructure, including sanitation, human mortality and morbidity, and mental health (Confalonieri *et al.* 2007). The loss of shelter, large-scale population displacement, damage to community sanitation and health care, and reduction in food availability can extend the level of mortality and morbidity beyond the actual event (Curriero *et al.* 2001b, as cited in Sussman *et al.* 2008). Factors that influence population vulnerability to extreme weather include location, population density, land use, age, income, education, health, health care response, and disaster preparedness (Blaikie *et al.* 1994, Menne 2000, Olmos 2001, Adger *et al.* 2005, Few and Matthies 2006, all as cited in Confalonieri *et al.* 2007).

Adverse weather conditions create safety hazards and delays in the Nation's transportation systems, especially on the nation's highways. The Federal Highway Administration (FHWA) estimates that about 25 percent of highway crashes occur during adverse weather resulting in about 17 percent of highway fatalities (AMS, 2004), while the Federal Motor Carrier Safety Administration (FMCSA) found

that the factor "environmental conditions" was the critical reason[22] for 3 percent of large truck crashes (FMCSA, 2007). Extreme weather events that increase adverse weather conditions on the nation's highways could potentially affect highway safety.

Floods occur with the greatest frequency compared to other extreme weather events (EM-DAT 2006, as cited in Confalonieri *et al.* 2007). The intensity of a flood is dependent on rainfall, surface runoff, evaporation, wind, sea level, and local topography (Confalonieri *et al.* 2007). Health impacts related to flood events include deaths and injuries sustained during a flood event; increased transmission and prevalence of infectious diseases; and toxic contamination of supplies and food (Greenough *et al.* 2001, Ahren *et al.* 2005, both as cited in Confalonieri *et al.* 2007; Hajat et al 2003, Kalashnikov *et al.* 2003, Tuffs and Bosch 2002 (all as cited in Epstein *et al.* 2006)).

Drought is an abnormal period of dry weather that has led to substantial decrease in water availability for a given location (Huschke 1959). The health impacts associated with a drought include mortality, malnutrition, infectious diseases, and respiratory diseases (Menne and Bertollini 2000, as cited in Confalonieri *et al.* 2007). Aggravating this situation, malnutrition increases the susceptibility of contracting an infectious disease (Confalonieri *et al.* 2007) and drought-related population displacement can reduce access to adequate and safe water, food, and shelter, leading to increased malnutrition and infectious diseases. Further health impacts can spiral, such as a change in the transmission of mosquito-borne diseases during and after the drought event (Confalonieri *et al.* 2007). Impacts on the agricultural productivity affect health through risk of under- and malnutrition (Epstein *et al.* 2006), and increased dust storm activity and frequency of forest fires. Drought conditions weaken trees' defenses against pests and can result in increased threats to human health from forest fires (Mattson and Haack 1987, Boyer 1995, Holsten *et al.*, 2000, all as cited in Epstein *et al.* 2006).

4.5.8.2.4 Air Quality

Climate change can affect air quality through altering local weather patterns and/or pollution concentrations. Ground-level ozone, particulate matter, and airborne allergens contribute to poor air quality, leading to respiratory ailments and premature mortality. Increasing exposure to these pollutants would have substantial negative health impacts (Confalonieri *et al.* 2007).

Ground-level ozone contributes to urban smog, and occurs both naturally and as a secondary pollutant formed through photochemical reactions of nitrogen oxides and volatile organic compounds.[23] These reactions are accelerated with increasing sunlight and temperatures; thus ozone concentrations tend to peak during late afternoon and early evening in the warmer season; however, some locations demonstrate no such seasonality in ozone concentration (Bates 2005, as cited in Confalonieri *et al.* 2007). The concentration of ground-level ozone for a particular location varies as a function of temperature, wind, solar radiation, atmospheric moisture, atmospheric mixing, and cloud cover. Studies have found increasing levels of ground-level ozone in most regions (Wu and Chan 2001, Chen *et al.* 2004, both as cited in Confalonieri *et al.* 2007). A recent study found increases in CO_2 concentrations lead to increases in water vapor and temperatures. These lead to higher ozone concentrations in polluted areas, resulting in

[22] FMCSA conducted the Large Truck Crash Causation Study (LTCCS) sample of 963 crashes involved 1,123 large trucks and 959 motor vehicles that were not large trucks between 2001 and 2003. The LTCCS defines the Critical Reason as the immediate reason for the critical event (*i.e.*, the failure leading to the critical event). The critical reason is assigned to the vehicle coded with the critical event in the crash. It can be coded as a driver error, vehicle failure, or environmental condition (roadway or weather). Other causal coding includes a Critical Event and Associated Factors.

[23] Nitrogen oxides are emitted, in part, through the burning of fossil fuels. Volatile organic compounds are emitted from varying sources including burning of fossil fuels, transpiration, evaporation from stored fuels, solvents and other chemicals.

an increase in ozone-related deaths by 40 percent (Jacobson 2008). Climate change is anticipated to increase ozone-related diseases (Sussman *et al.* 2008).

Ozone exposure is associated with respiratory ailments such as pneumonia, chronic obstructive pulmonary disease, asthma, allergic rhinitis, chest pain, shortness of breath, and premature mortality (Mudway and Kelly 2000, Gryparis *et al.* 2004, Bell *et al.* 2005, 2006, Ito *et al.* 2005, Levy *et al.* 2005, all as cited in Confalonieri *et al.* 2007,; American Lung Association, 2008). Asthmatics are considered a sensitive population (Ebi *et al.* 2008). Long-term exposure to elevated amounts of ozone has been shown to affect lung efficiency (Ebi et al 2008; American Lung Association 2008).

Particulate matter comprises solid and liquid particles suspended in the atmosphere varying in both chemical composition and origin. Concentrations of particulate matter are affected by emission rates and local weather conditions such as atmospheric stability, wind, and topography. Some particulates display seasonal variability directly linked to seasonal weather patterns (Alvarez *et al.* 2000, Kassomenos *et al.* 2001, Hazenkamp-von Arx *et al.* 2003, Nagendra and Khare 2003, Eiguren-Fernandez *et al.* 2004, all as cited in Confalonieri *et al.* 2007). In Mexico City and Los Angeles, local weather conditions can create a stagnant air mass, restricting dispersion of pollution. Seasonal weather patterns can further enhance the chemical reactions of emissions, thereby increasing secondary particulate matter (Rappengluck *et al.* 2000, Kossmann and Sturman 2004, both as cited in Confalonieri *et al.* 2007).

Breathing particulate matter can cause respiratory ailments, heart attack, and arrhythmias (Dockery *et al.* 1993, Samet *et al.* 2000, Pope *et al.* 1995, 2002, 2004, Pope and Dockery 2006, Dominici *et al.* 2006, Laden *et al.* 2006, all as cited in Ebi *et al.* 2008). Populations at greatest risk could include children, the elderly, and those with heart and lung disease, diabetes (Ebi *et al.* 2008), and high blood pressure (Künzli *et al.* 2005, as cited in Ebi *et al.* 2008). Chronic exposure to PM could decrease lifespan by 1 to 3 years (Pope 2000, as cited in American Lung Association 2008). Increasing PM concentrations will have a measurable adverse impact on human health (Confalonieri *et al.* 2007).

Forest fires contribute to poor air quality conditions. During the 5th largest United States wildfire in 1999, medical visits at the Hoopa Valley National Indian Reservation increased by 52 percent with symptoms affecting lower respiratory tract and preexisting cardiopulmonary conditions (Mott *et al.* 1999). Human health ailments associated with forest fires include burns, smoke inhalation, mortality, eye illnesses, and respiratory illnesses (Confalonieri *et al.* 2007; Ebi *et al.* 2008). Certain regions are anticipated to experience an increase in frequency and intensity of fire events with projected changes in temperature and precipitation. Pollution from forest fires along with other pollutants, such as carbon monoxide, ozone, desert dust, mould spores and pesticides, can be transported thousands of kilometers on time scales of 4 to 6 days affecting populations far from the sources (Gangoiti *et al.* 2001, Stohl *et al.* 2001, Buchanan *et al.* 2002, Chan *et al.* 2002, Martin *et al.* 2002, Ryall *et al.* 2002, Ansmann *et al.* 2003, He *et al.* 2003, Helmis *et al.* 2003, Moore *et al.* 2003, Shinn *et al.* 2003, Unsworth *et al.* 2003, Kato *et al.* 2004, Liang *et al.* 2004, Tu *et al.* 2004, all as cited in Confalonieri *et al.* 2007).

4.5.8.2.5 Water-borne and Food-borne Diseases

Substantial morbidity and childhood mortality has been linked to water- and food-borne diseases. Climate change is projected to alter temperature and the hydrologic cycle through changes in precipitation, evaporation, transpiration, and water storage. These changes, in turn, potentially affect water-borne and food-borne diseases, such as salmonellosis, campylobacter, leptospirosis, and pathogenic species of vibrio. They also have a direct impact on surface water availability and water quality. It has been estimated that over 1 billion people in 2002 did not have access to adequate clean water (McMichael *et al.* 2003, as cited in Epstein *et al.* 2006). Increased temperatures, greater evaporation, and heavy rain events have been associated with adverse impacts on drinking water through increased waterborne

diseases, algal blooms, and toxins (Chorus and Bartram 1999, Levin *et al.* 2002, Johnson and Murphy 2004 (all cited in Epstein *et al.* 2006)). In the United States, 68 percent of all waterborne diseases between 1948 and 1994 happened after heavy rainfall events (Curriero *et al.* 2001a, as cited in Epstein *et al.*, 2006). Climate change could further impact a pathogen by directly affecting its life cycle (Ebi *et al.* 2008). The global increase in the frequency, intensity, and duration of red tides could be linked to local impacts already associated with climate change (Harvell *et al.* 1999, as cited in Epstein *et al.* 2006); toxins associated with red tide directly affect the nervous system (Epstein *et al.* 2006).

Many people do not report or seek medical attention for their ailments of water-borne or food-borne diseases; hence, the number of actual cases with these diseases is greater than clinical records demonstrate (Mead et al 1999, as cited in Ebi *et al.* 2008). Many of the gastrointestinal diseases associated with water-borne and food-borne diseases can be self-limiting; however, vulnerable populations include young children, those with a compromised immune system, and the elderly.

4.5.8.2.6 Vector-borne Diseases

Infections can be spread by the bite of an infected arthropod (termed vector-borne), such as mosquitoes, ticks, sandflies, and blackflies, or through non-human vertebrates such as rodents, canids, and other mammals. Such diseases include typhus, malaria, yellow fever, dengue fever, West Nile virus, Western Equine encephalitis, Eastern Equine encephalitis, Bluetongue virus, and lyme disease. Increased insect density has been correlated with milder seasonal variability (Confalonieri *et al.* 2007) and tick distributions tend to expand with higher minimum temperatures (Ebi *et al.* 2008). In general, climate and weather are important constraints on the range of transmission for vector-borne diseases. For example, temperature and flooding are key constraints on the range of mosquitoes, which serve as a primary vector for malaria and other diseases (Epstein *et al.* 2006). Changes in seasonal duration and increases in weather variability reduce/eliminate these constraints (Epstein *et al.* 2006). In southern Mozambique a the number of malaria cases increased four to five times over long-term averages in the days and weeks following a severe flooding event in 2000 (Epstein *et al.* 2006). Temperature and the availability of water can both play key roles in regulating population size as well. For the deer tick, the disease vector for Lyme disease, off-host survival is strongly affected by these two variables, and thus climate is the primary factor determining size and distribution of deer tick populations (Needham and Teel 1991, Bertrand and Wilson 1996, both as cited in Epstein *et al.* 2006). Changes in land use practice or to the habitat and behavior of wildlife hosts of the insect can also impact latitudinal or altitudinal shifts in the disease carrying species (Confalonieri *et al.* 2007).

4.5.8.3 Projected Health Impacts of Climate Change on the United States

Human health is projected to be adversely affected by rising temperatures, increasing ground-level ozone concentrations, changes in extreme weather events, and increasing food and water-borne pathogens. The impact of the varying health-related event is dependent on location. The United States is anticipated to sustain fewer cases of illness and death associated with climate change compared with the developing world (CCSP 2008f). The current health infrastructure along with the United States government's disaster planning and emergency response systems are key assets to enable the United States to meet changing health effect demands associated with climate change. These health impacts will vary in scope across the United States.

In the United States, there have been 20,000 heat and solar-related deaths from 1936 to 1975, with the heat wave of 1980 accounting for over 1,250 deaths (NOAA 2005). There could be a rise in heat-related morbidity and mortality in the coming decades (CCSP 2008f) due, in part, to an aging population. By 2010, 13 percent of the population of the United States is projected to be over the age of 65, and 20 percent by 2030 (Day 1996, as cited in Ebi *et al.* 2008). Studies have shown a decline in heat-

related mortality over the past decades, possibly due to increased air conditioning usage and improved health care (Davis *et al.* 2002, Davis *et al.* 2003a, Davis *et al.* 2003b, Carson *et al.* 2006 (all cited in Ebi *et al.* 2008)). Heat waves are anticipated to increase in severity, frequency and duration, particularly in the Midwest and Northeast sections of the country (CCSP 2008f; Frumkin 2008).

The northern latitudes of the United States are likely to experience the greatest increases in average temperature and concentrations of many of the airborne pollutants (CCSP 2008f). In particular, urban centers in the West, Southwest, Mid-Atlantic and Northeast regions are projected to incur the largest increases in average temperatures (Frumkin 2008). A regional climate simulation projected air quality to worsen in Texas but to improve in the Midwest in 2045 to 2055 compared with 1995 to 2005 (Leung and Gustafson 2005, as cited in Ebi *et al.* 2008). In urban areas, ground-level ozone concentrations are anticipated to increase in response to higher temperatures and increases in water vapor concentration (CCSP 2008f; Jacobson 2008). Climate change could further cause stagnant air masses that increase pollution concentrations of ground-level ozone and PM in populated areas. For example, one study projected an increase in the upper Midwest stagnant air between 2000 and 2052 (Mickley *et al.* 2004, as cited in Ebi *et al.* 2008). Further, Frumkin (2008) found that climate change is likely to alter the air pollution contribution from natural sources and increase the creation of secondary pollutants; however, an alternative study found an increase in evaporative losses from nitrate particles reduces PM levels (Aw and Kleeman 2003, as cited in Ebi *et al.* 2008). A recent study concluded that continuous local outdoor CO_2 emissions can increase the respective CO_2 concentration for that area, thereby increasing ozone levels (Jacobson 2008).

The spring pollen season has been shown to begin earlier than usual in the Northern Hemisphere (D'Amato *et al.* 2002, Weber 2002, Beggs 2004 all cited in Confalonieri *et al.* 2007). There is further evidence suggesting a lengthening of the pollen season for some plant species (Confalonieri *et al.* 2007). A recent study determined that the density of air-borne pollen for some species has increased, however, it is not understood what the allergenic content of this additional pollen is (Huynen and Menne 2003, Beggs and Bambrick 2005, both as cited in Confalonieri *et al.* 2007). Additionally, climate change could alter the pollen concentration of a given plant species as the species reacts to increased concentration of CO_2. Current findings demonstrate that ragweed pollen production and the length of the ragweed pollen season increase with rising CO_2 concentrations and temperatures (Wan *et al.* 2002, Wayne *et al.* 2002, Singer *et al.* 2005, Ziska *et al.* 2005, Rogers *et al.* 2006a all cited in Confalonieri *et al.* 2007). Invasive plant species with high allergenic content such as ragweed and poison ivy have been found to be spreading in particular locations around the world, increasing potential health risks (Rybnicek and Jaeger 2001, Huynen and Menne 2003, Taramarcaz *et al.* 2005, Cecchi *et al.* 2006 all cited in Confalonieri *et al.* 2007).

Extreme weather events are likely to be altered by climate change, though there is uncertainty predicting the frequency and severity of events. Some regions in the United States might experience drought conditions due to the reduction in rainfall, while other sections of the country are likely to experience increased frequency of heavy rainfall events, leading to potential flood risk (Frumkin 2008). On the west coast, water quality could be adversely affected as water supplies reduce with decreases in regional precipitation and depletion of mountain snowpacks (Frumkin 2008). It is considered *very likely* (greater than 90 percent certainty) that over the course of this century there will be an increase in the frequency of extreme precipitation (IPCC 2007a). The Southeast, Intermountain West and West are likely to experience an increase in frequency, severity and duration of forest fires (CCSP 2008f, Brown *et al.* 2004, Fried *et al.* 2004 (all cited in Ebi *et al.* 2008)). Impacts to respective vulnerable populations could change in the future as shifts occur in population, suburban development, and community preparedness. It is very likely that a large portion of the projected growth of the United States population will occur in areas considered to be at risk for future extreme weather events (Ebi *et al.* 2008). Hence, even if the rate of health impacts were to decrease, the growth in population in risk areas will still cause an increase in the total number of people affected.

Pathogen transmission depends on many climate-related factors such as temperature, precipitation, humidity, water salinity, extreme weather events, and ecological shifts, and could display seasonal shifts (Ebi *et al.* 2008). Few studies have projected the health impact of vector-borne diseases. Vector-borne illnesses are likely to shift or expand northward and to higher elevations with the possible introduction of new vector-borne diseases (CCSP 2008f, Frumkin 2008), while decreasing the range of tick-borne encephalitis in low latitudes and elevation (Randolph and Rogers 2000, as cited in Ebi *et al.* 2008). Malaria and dengue fever in the United States are unlikely to be affected by climate change variables given the housing quality, land use patterns, and vector control (Frumkin 2008).

Overall, populations within certain regions of the United States regions could experience climate change-induced health impacts from a number of pathways simultaneously. For instance, populations in coastal communities could experience an extreme weather event, such as a tropical cyclone and flooding, adding to health burdens associated with sea-level rise or coastal erosion.

4.5.8.3.1 Adaptation

The United States has a number of organizations and activities that identify and plan for the prevention of adverse health impacts associated with weather and climate although recent experiences following extreme weather and vector-borne disease outbreaks have demonstrated there is a need for improvement (Confalonieri *et al.* 2007, as cited in Ebi *et al.* 2008). The regions where there is an anticipated increase in the health impacts of climate change are very likely to have a greater proportion of poor, elderly, disabled, and uninsured residents. In addition, the American Academy of Pediatrics has determined children are a vulnerable population, recommending the United States government give children particular attention when developing emergency management and disaster response systems (American Academy of Pediatrics 2007; McMichael and Githek 2001; U.S. Department of Health and Human Services 2007, as cited in American Academy of Pediatrics 2007).

The public health sector has divided the activities associated with preventing diseases into one of three classifications: primary, secondary and tertiary. Primary prevention protects the unaffected population from contracting diseases. Secondary prevention focuses on the response action that starts at the onset of a disease. Tertiary prevention deals with an existing disease and focuses on reducing suffering and long-term health difficulties. Primary prevention tends to be the most effective and least costly compared to secondary or tertiary prevention (Ebi *et al.* 2008).

Adaptation policies and measures to address impacts to human health due to climate change should be continually managed as climate change is dynamic. Such adaptation might include the:

- Support and maintenance of the public health infrastructure (Frumkin 2008)
- Improvement and dissemination of preventive care in the public health infrastructure (Frumkin 2008)
- Continued use of nationwide surveillance as a tool to identify, track and map vector-borne diseases (Frumkin 2008)
- Utilization of preparedness tools to identify and assist vulnerable populations during extreme weather events (Frumkin 2008)
- Strengthening of infrastructure to withstand extreme weather events

4.5.8.4 Projected Global Health Impacts of Climate Change

Globally, climate change is anticipated to contribute to both adverse and beneficial health impacts. Projected adverse health impacts include malnutrition leading to disease susceptibility (*high confidence*); increased heat-wave, flood, storm and fire-induced mortality (*high confidence*); decrease in cold-related deaths (*high confidence*); increased diarrheal disease burden (*medium confidence*); increased levels of ground-level ozone (*high confidence*); and altered geographic distribution of some infectious disease vectors (*high confidence*) (Confalonieri *et al.* 2007). A decrease in cold-related mortality and some pollutant-related mortality, increased crop yields in certain areas, and restriction of certain diseases in certain areas (if temperatures or precipitation rises above the critical threshold for vector or parasite survival) are examples of projected beneficial health impacts (Confalonieri *et al.* 2007). The adverse impacts, however, greatly outweigh the beneficial impacts, particularly after the mid-century mark (Confalonieri *et al.* 2007).

Regionally, the impact on human health will vary. Some Asian countries could experience increasing malnutrition by 2030 with crop yields decreasing later in the century, rendering the population in the region particularly vulnerable to malnutrition-associated diseases and disorders (Confalonieri *et al.* 2007). Certain coastal areas will experience flooding by 2030 impacting human mortality (Confalonieri *et al.* 2007). By 2080, lyme disease is projected to have moved northward into Canada, due to a two- to four-fold increase in tick abundance (Confalonieri *et al.* 2007). By 2085, climate change is projected to increase the population at risk to dengue fever to a total of 3.5 billion people (Confalonieri *et al.* 2007).

Heat waves have been experienced globally: thousands of deaths incurred in India over the eighteen heat-waves recorded between 1980 and 1998 (De and Mukhopadhyay 1998, Mohanty and Panda 2003, De *et al.* 2004 all cited in Confalonieri *et al.* 2007). In August 2003, approximately 35,000 deaths were linked to a heat-wave experienced in Europe, with France alone incurring over 14,800 deaths (Hemon and Jougla 2004, Martinez-Navarro *et al.* 2004, Michelozzi *et al.* 2004, Vandentorren *et al.* 2004, Conti *et al.* 2005, Grize *et al.* 2005, Johnson *et al.* 2005 all cited in Confalonieri *et al.* 2007). Around 60 percent of the heat-wave related deaths in France were people at or over 75 years of age (Hemon and Jougla, 2004, as cited in Confalonieri *et al.* 2007). Overall, studies have linked high temperatures to about 0.5-2 percent of annual mortality in the elderly European population (Pattenden *et al.* 2003, Hajat *et al.* 2006, both as cited in Confalonieri *et al.* 2007).

In 2003, floods in China affected 130 million people (EM-DAT 2006, as cited in Confalonieri *et al.*2007). In 1999, storms with floods and landslides in Venezuela killed 30,000 people (Confalonieri *et al.* 2007).

The World Health Organization (WHO) estimates that a high proportion of those in dry regions (approximately 2 billion) experience malnutrition, infant mortality, and water-related diseases (WHO 2005, as cited in Confalonieri *et al.* 2007). Children in low-income countries are particularly vulnerable to loss of life due to diarrhea. The transmission of the enteric pathogen appears to increase during the rainy season for children in the sub-Saharan Africa (Nchito *et al.* 1998, Kang *et al.* 2001, both as cited in Confalonieri *et al.* 2007). In Peru, higher temperatures have been linked to periods of increased diarrhea incidence experienced by adults and children (Checkley *et al.* 2000, Speelmon *et al.* 2000, Checkley *et al.* 2004, Lama *et al.* 2004, all as cited in Confalonieri *et al.* 2007).

Cholera outbreaks associated with floods can occur in areas of poor sanitation. A study in Sea surface temperatures in the Bay of Bengal demonstrated a bimodal seasonal pattern that translated to increased plankton activity leading to increases in cholera in nearby Bangladesh (Colwell 1996, Bouma and Pascual 2001, both cited in Confalonieri *et al.* 2007).

Dengue is considered the most important vector-borne viral disease (Confalonieri *et al.* 2007). A strong correlation exists between climate-based factors such as temperature, rainfall and cloud cover with the observed disease distribution in Colombia, Haiti, Honduras, Indonesia, Thailand and Vietnam (Hopp and Foley 2003, as cited in Confalonieri *et al.* 2007). Favorable climate conditions for dengue exist to about one-third of the world's population (Hales *et al.* 2002, Rogers *et al.* 2006b, both as cited in Confalonieri *et al.* 2007).

Malaria is a vector-borne disease spread by mosquitoes. Depending on location, malaria outbreaks could be influenced by rainfall amounts and sea-surface temperatures in southern Asia, Botswana, and South America (Kovats *et al.* 2003, Thomson *et al.* 2005, DaSilva *et al.* 2004, all as cited in Confalonieri *et al.* 2007). A recent study of malaria in East Africa found that the measurable warming trend the area has experienced since the 1970s can be correlated with the potential of disease transmission. (Pascual *et al.* 2006, as cited in Confalonieri *et al.* 2007) However, southern Africa was not shown to exhibit the same trend (Craig *et al.* 2004, as cited in Confalonieri *et al.* 2007). External factors are also influencing the number of cases of the disease in Africa, such as drug-resistant malaria, and parasite and HIV infection. Studies did not provide clear evidence that malaria in South America or the continental regions of the Russian Federation have been affected by climate change (Benitez *et al.* 2004, Semenov *et al.* 2002, both as cited in Confalonieri *et al.* 2007). In general, however, higher temperatures and more frequent extreme weather occurrences (such as floods and droughts) are predicted to have a stronger influence on the wider spread of malaria with increasing climate change (McMichael *et al.* 1996, as cited in Epstein *et al.* 2006).

Temperature has been shown to affect food-borne and water-borne diseases. Several studies have found increases in salmonellosis cases (food poisoning) within 1 to 6 weeks of the high-temperature peaks (controlled by season). This could be due, in part, to the processing of food products and the population varying its eating habits during warmer months (Fleury *et al.* 2006, Naumova *et al.* 2006, Kovats *et al.* 2004, D'Souza *et al.* 2004, all as cited in Ebi *et al.* 2008). High temperatures have been shown to increase common types of food poisoning (D'Souza *et al.* 2004, Kovats *et al.* 2004, Fleury *et al.* 2006, all as cited in Confalonieri *et al.* 2007). Increasing global temperatures could contribute to a rise in salmonellosis cases (Ebi *et al.* 2008). There is further concern that projected increasing temperatures from climate change will also increase leptospirosis cases, a disease that is resurging in the United States.

The effects of climate change on air quality are expected to adversely impact people suffering from asthma and other respiratory ailments. Increases in temperature, humidity, the prevalence and frequency of wildfires, and other factors are expected to result in more smog, dust, and particulates that exacerbate asthma. Widespread respiratory distress throughout many regions of the world is a possible result of climate change. Current asthma treatment and management plans might be overwhelmed, leading to major increases in asthma-related morbidity and mortality (Epstein *et al.* 2006).

Warm climates are more apt to support the growth of the pathogenic species of Vibrio, leading to shell-fish related death and morbidity that might affect the United States, Japan and South-East Asia (Janda *et al.* 1988, Lipp *et al.* 2002, both as cited in Ebi *et al.* 2008, 2-10; Wittmann and Flick 1995, Tuyet *et al.* 2002, both as cited in Confalonieri *et al.* 2007). If temperatures increase, the geographic range and concentration of the Vibrio species could expand. For example, as the waters of the northern Atlantic have warmed, the concentration of Vibrio species has also (Thompson *et al.* 2004, as cited in Ebi *et al.* 2008). Future ocean warming might also lead to the proliferation of harmful algal blooms, releasing toxins that contaminate shellfish and lead to food-borne diseases (Confalonieri *et al.* 2007). Algal blooms such as red tide can also increase if fecal bacteria concentrations and nutrient loading increases from storm water runoff during heavy precipitation events (Frumkin 2008).

In 2000, WHO estimated that climate change has caused the loss of more than 150,000 lives (Campbell-Lendrum *et al.* 2003, Ezzati *et al.* 2004, McMichael 2004 (as cited in Confalonieri *et al.* 2007)). The projected risks in 2030 described by the WHO study vary by health outcome and region; most of the increase in disease is due to diarrhea and malnutrition. More cases of malaria are predicted in those countries that are situated at the edge of the current distribution. The projected health impact associated with malaria is mixed, with some regions demonstrating increased burden and others exhibiting decreased burden.

4.5.8.4.1 Adaptation

Climate change is considered to pose a risk to the health of both the United States and global populations (Ebi *et al.* 2008). Developed societies such as the United States are more likely to implement effective adaptation measures reducing the magnitude of severe health impacts. For example, the risk and impact of floods on a population can be reduced with changes in water management practices, improved infrastructure, and land use practices (EEA 2005, as cited in Confalonieri *et al.* 2007). Unblocking drains also helps to reduce the transmission of enteric pathogens (Parkinson and Butler 2005, as cited in Confalonieri *et al.* 2007). However, improvements world-wide in adaptive capacity are needed (*high confidence*; Confalonieri *et al.* 2007). Many governments have increased their efforts to cope with extreme climate events moving from disaster relief to risk management. Efforts in Portugal, Spain, France, UK, Italy and Hungary focus on short-term events such as heat waves (Pascal *et al.* 2006, Simón *et al.* 2005, Nogueira 2005, Michelozzi *et al.* 2005, NHS 2006, Kosatsky and Menne 2005, all as cited in Confalonieri *et al.* 2007) while other efforts have undertaken long-term strategies addressing policies for agriculture, energy, forestry and transport (Confalonieri *et al.* 2007).

4.6 ENVIRONMENTAL JUSTICE

4.6.1 Affected Environment

Executive Order (EO) 12898, *Federal Actions to Address Environmental Justice in Minority Populations and Low Income Populations*, directs federal agencies to "promote nondiscrimination in federal programs substantially affecting human health and the environment, and provide minority and low income communities access to public information on, and an opportunity for public participation in, matters relating to human health or the environment." EO 12898 also directs agencies to identify and consider disproportionately high and adverse human health or environmental effects of their actions on minority and low-income communities, and provide opportunities for community input in the NEPA process, including input on potential effects and mitigation measures. CEQ, the entity responsible for compliance with EO 12898, has provided agencies with general guidance on how to meet the requirements of the EO as it relates to NEPA in *Environmental Justice Guidance Under the National Environmental Policy Act*. This guidance document also defines the terms "minority" and "low-income community" in the context of environmental justice analysis. Members of a minority are defined as: American Indians or Alaskan Natives, Asian or Pacific Islanders, Blacks, and Hispanics. Low-income communities are defined as those below the poverty thresholds from the U.S. Census Bureau.

In compliance with EO 12898, NHTSA provides in this FEIS a qualitative analysis of the cumulative effects of the proposed action with climate change and other identified relevant actions on these populations.

Environmental justice populations tend to be concentrated in areas with a higher risk of climate-related impacts. USCCSP notes that this geographic placement might put these communities at higher risk, "from climate variability and climate-related extreme events such as heat waves, hurricanes, and tropical and riverine flooding" (CCSP 2008f).

4.6.2 Environmental Consequences

4.6.2.1 Non-climate Change Effects

With consideration of the reasonably foreseeable increase in CAFE standards for MY 2016-2020, the minimum threshold for which has already been established by Congress as 35 mpg, a further decrease in oil consumption and production is predicted. These changes would further the trends affecting environmental justice populations described in Section 3.5.

NHTSA predicts that oil refining would decrease as a result of the reductions predicted to result from the MY 2011-2015 CAFE standards, which could cause a decrease in related air pollutant discharges and a local improvement in air quality for residents near oil refineries. This improvement could represent a small positive impact on environmental justice populations near these facilities.

All six criteria air pollutants regulated by EPA under the Clean Air Act and all but one of vehicle emission toxic air pollutants would decrease overall with adoption of any of the action alternatives and the foreseeable MY 2011-2015 standards (see Section 4.3). However, increases in VMT due to the rebound effect are still projected to cause increases in some criteria and toxic air pollutants in some air quality nonattainment areas. The large size of each nonattainment area, the uniform distribution of increases in VMT, and the minor emissions increases in affected nonattainment and other areas make it unlikely that there would be disproportionate effects to environmental justice populations.

4.6.2.2 Effects of Climate Change in the United States

Environmental justice populations in the United States, as defined by EO 12898, would experience the same general impacts as a result of global climate change felt by the U.S. population as a whole and described in Sections 4.5.6, Food, Fiber, and Forest Products; 4.5.7, Industries, Settlements, and Society; and 4.5.8, Human Health. However, the USCCCP notes that the general climate change impacts to the U.S. population might be differentially experienced by environmental justice populations, explaining that "[e]conomic disadvantage, lower human capital, limited access to social and political resources, and residential choices are social and economic reasons that contribute to observed differences in disaster vulnerability by race/ethnicity and economic status" (CCSP 2008f). A general description of the potential impacts of climate change on the population of the United States is provided below. These impacts are similar to those that would be experienced globally, although the severity of impacts experienced by developing countries would likely be disproportionately larger than those experienced in developed nations, such as the United States. The most likely anthropogenic climate change impacts include:

- *Human Health* – increased mortality and morbidity due to excessive heat, increases in respiratory conditions due to poor air quality, increases in water- and food-borne diseases and changes to the seasonal patterns of vector-borne diseases, increases in malnutrition (*see* Section 4.5.7 for details)

- *Services* – disruption of ability to transport goods and services, shifts in the location of certain crops, disaster-related damage to transportation infrastructure (roads, rail, ports), tourism location shifts, insurance premium increases (*see* Section 4.5.6 for details)

- *Utilities and Infrastructure* – more frequent droughts and increases in demand for irrigation or drinking water, flood-related impacts on sewage systems with potential water quality impacts, and disaster-related damage to transportation, power, and communications systems (*see* Section 4.5.6 for details)

- *Human Settlement* – synergistic effects with existing resource scarcities (energy and water), inundation of inhabited coastal areas due to sea-level rise, urban temperature increases (*see* Section 4.5.6 for details)

- *Social Issues* – increased stress on public services and disruptions to traditional cultures (*see* Section 4.5.6 for details)

- *Agriculture* – changes in crop yields, more intense droughts and floods, changes in the length of growing seasons (*see* Section 4.5.6 for details)

- *Forest and Ecosystem Services* – increased risk of forest fires, redistribution and extinction of economically or culturally important wildlife species, expanded ranges for pests and invasive species (*see* Section 4.5.6 for details)

Environmental justice populations would likely be disproportionately affected by some of these potential impacts. The rest of this section discusses, qualitatively, the most substantial areas of potential disproportionate impact for these populations in the United States.

4.6.2.2.1 Human Health

Low-income and minority communities exposed to the direct effects of extremes in climatic conditions might also experience synergistic effects with pre-existing health risk factors, such as limited availability of preventative medical care and inadequate nutrition (CCSP 2008f).

As stated in Section 4.5.7, increases in heat-related morbidity and mortality as a result of higher overall and extreme temperatures is likely to disproportionately affect minority and low-income populations, partially as a result of limited access to air conditioning and high energy costs (CCSP 2008f, O'Neill *et al.* 2005a). Urban areas, which often have relatively large environmental justice populations, would likely experience the most substantial temperature increase due to the urban "heat island" effect and could be particularly vulnerable to this type of health impact (CCSP 2008f, Knowlton *et al.* 2007).

Increasing temperatures could also lead to expanded ranges for a number of diseases (CCSP 2008f). As described in Section 4.5.8, the number and severity of outbreaks for vector-borne illnesses, such as the West Nile Virus, could become more frequent and severe. Because the vectors of these diseases (such as mosquitoes) are more likely to come into contact with environmental justice populations, disproportionate impacts might occur. For example, an outbreak of the mosquito-borne dengue fever in Texas primarily affected low-income Mexican immigrants living in lower quality housing without air conditioning, leading a team researching the outbreak to conclude that the low prevalence of dengue in the United States is primarily due to economic, rather than climatic, factors (Reiter *et al.* 2003).

4.6.2.2.2 Land Use

In the United States, two primary types of geographical environmental justice communities are likely to be affected by global climate change: urban areas, because of their relatively high concentrations of low-income and minority residents, and indigenous communities. Environmental justice communities in urban areas, because of previously mentioned heat exposure and health issues, are likely to experience climate change impacts more acutely. Additionally, environmental justice populations in coastal urban areas (vulnerable to increases in flooding as a result of projected sea-level rise, larger storm surges, and human settlement in floodplains) are less likely to have the means to quickly evacuate in the event of a natural disaster (CCSP 2008f, National Science and Technology Council 2008). USCCSP, as an example, notes that flooding in Louisiana following the 2005 Hurricane Katrina primarily killed poor and elderly residents having no means to flee (National Science and Technology Council 2008). As stated in Section 4.5.7, indigenous communities in the United States, particularly Alaska, could face major impacts on their subsistence economies from climate change. These impacts would result from their partial reliance on arctic animals, such as seals and caribou, for food and the potential destruction of transportation infrastructure due to ground thaw.

In coastal and floodplain areas prone to flooding because of larger storm surges and generally more extreme weather, increases in flood insurance premiums could disproportionately affect environmental justice populations unable to absorb the additional cost. Lack of sufficient insurance coverage might render these populations more financially vulnerable to severe weather events.

Potential food insecurity as a result of global climate change, particularly among low-income populations in the United States and abroad, is an often mentioned concern (Wilbanks *et al.* 2007, CCSP 2008f). Climate change is likely to affect agriculture by changing the growing season, limiting rainfall and water availability, or increasing the prevalence of agricultural pests (*see* Section 4.5.6 for more information). In the United States, the most vulnerable segment of the population to food insecurity is likely to be low-income children (Cook and Frank 2007, as cited in CCSP 2008f).

4.7 NON-CLIMATE CUMULATIVE IMPACTS OF CO_2

4.7.1 Affected Environment

In addition to its role as a GHG in the atmosphere, CO_2 is exchanged from the air to water, plants, and soil. CO_2 dissolves easily in water and more easily in salt water such as oceans. In water, CO_2 combines with water molecules to form carbonic acid. The amount of CO_2 dissolved in oceans is related to its concentrations in the air. This process reduces the amount of CO_2 in the atmosphere as a GHG, but also increases the acidity of the ocean. Increasing levels of CO_2 are having a global effect on the oceans. By 2100, ocean pH could drop 0.5 units from pH levels of the 1900s (Hall-Spencer *et al.* 2008).

Plants remove CO_2 from the air through photosynthesis and use the carbon for plant growth. This uptake by plants can influence annual fluctuations of CO_2 on the order of 3 percent from growing season to non-growing season (Schneider and Londer 1984, as cited in Perry 1994). Increased levels of CO_2 essentially act as a fertilizer influencing normal annual plant growth.

In addition, CO_2 concentrations affect soil microorganisms. Only recently have the relationships between above-ground ecosystems and below-ground components of ecosystems been considered significant; there is increasing awareness of the fact that feedbacks between the above-ground/below-ground components play a fundamental role in controlling ecosystems processes. For example, the organic carbon required for below-ground decomposition is provided by plants. Plants also provide the resources for root-associated microorganisms (Wardle *et al.* 2004). The "decomposer subsystem in turn breaks down dead plant material and indirectly regulates plant growth and community composition by determining the supply of available root nutrients" (Wardle *et al.* 2004).

Specific plant species, depending on the quantity and quality of resources provided to below-ground components, might have greater impacts on soil biota and the processes regulated by those biota than do other plants. Variation in the quality of forest litter produced by co-existing species of trees, for instance, "explains the patchy distribution of soil organisms and process rates that result from 'single tree' effects" (Wardle *et al.* 2004). The composition of plant communities has a consistent and substantial impact on the composition of root-associated microbes; however, the effects of plant community composition on decomposer systems are apparently context-dependent. In one example cited, manipulating the composition of plant communities in five sites in Europe produced distinctive effects on decomposer microbes, while root-related soil microbes experienced no clear effect (Wardle *et al.* 2004).

The amount of carbon stored in soils of temperate and boreal forests is about four times greater than the carbon that is stored by vegetation and is "33 percent higher than total carbon storage in tropical forests" (Heath *et al.* 2005). Terrestrial communities contain as much carbon as the atmosphere. Forest soils are also the longest-lived carbon pools in terrestrial ecosystems (King *et al.* 2004). Several experiments involving increases of atmospheric CO_2 resulted in increasing carbon mass in trees, but a reduction of carbon sequestration in soils. This is associated with increasing soil microorganism respiration (Heath *et al.* 2005, Black 2008); respiration is associated with "root herbivory, predation, consumption of root exudates, and the decomposition of root and leaf litter" (King *et al.* 2004). In future real-world scenarios, however, the reduction of soil carbon via increased soil respiration could be countered by an increase in litter on the forest floor.

4.7.2 Environmental Consequences

4.7.2.1 Ocean Acidification

One of the large-scale non-climatic effects of an increase in CO_2 emissions is the potential for ocean acidification. The ocean exchanges huge quantities of CO_2 with the atmosphere, and when atmospheric concentrations rise (due to anthropogenic emissions), there is a net flux from the atmosphere to the oceans. This lowers the pH of the oceans (the water becomes more acidic), which reduces the ability of shell-forming organisms to produce their shells. Most shells are made of calcium carbonate, which dissolves under acidic conditions (Hall-Spencer *et al.* 2008, Kleypas *et al.* 2006). According to Kleypas *et al.* (2006), under increasing atmospheric CO_2, "A variety of evidence indicates that calcification rates will decrease, and carbonate dissolution rates increase, as $CaCO_3$ (calcium carbonate) saturation state decreases." Studies have also shown that long-term ocean acidification, such as a pH drop of 0.7 units, has negative effects on fish through reduction in metabolic rates, reproductive dysfunction, growth reduction and survivorship reduction (Michaelidis *et al.* 2005, Shirayama and Thronton 2005, Pane and Barry 2007, all as cited in Keller *et al.* 2008).

In conjunction with rapid climate change, ocean acidification could pose severe threats to coral reef ecosystems. Reef building and reef dissolution are always occurring, but dissolution of coral reefs is expected to increase, and surpass reef building, as anthropogenic CO_2 in the atmosphere increases. If the water column above reefs becomes saturated with the CO_2 from the atmosphere, the water could be less able to hold the CO_2 respired by microorganisms in the reef environment. Although the interactions are complex and difficult to project, a possible scenario is that the excess CO_2 in the reef environment could prevent reef-building. Thresholds for calcium carbonate dissolution exceeding calcification varies for different reef systems (Kleypas *et al.* 2006).

A recent study found that one-third of the 704 zooxanthellate reef-building coral species assessed are at risk of extinction (Carpenter *et al.* 2008). This number has increased dramatically in recent decades due to bleaching and diseases driven by elevated sea surface temperatures. Because NHTSA cannot quantify the impacts of this rulemaking action on threatened species or critical habitat, a Section 7 consultation is not possible. NHTSA discussed this issue with the U.S. Fish and Wildlife Service as part of the development of the FEIS.

4.7.2.2 Plant Growth and Soil Microorganisms

In contrast to its potential adverse effect on the productivity of marine ecosystems, higher CO_2 concentrations in the atmosphere could increase the productivity of terrestrial systems. Plants use CO_2 as an input to photosynthesis. The IPCC Fourth Assessment Report (IPCC 2007a) states that "On physiological grounds, almost all models predict stimulation of carbon assimilation and sequestration in response to rising CO_2, referred to as 'CO_2 fertilization'" (Denman *et al.* 2007).

Under bench-scale and field-scale experimental conditions, several investigators have found that higher concentrations have a fertilizing effect on plant growth (*e.g.*, Long *et al.* 2006, Schimel *et al.* 2000). IPCC reviewed and synthesized field and chamber studies, finding that:

> There is a large range of responses, with woody plants consistently showing net primary productivity (NPP) increases of 23 to 25 percent (Norby *et al.* 2005), but much smaller increases for grain crops (Ainsworth and Long 2005). Overall, about two-thirds of the experiments show positive response to increased CO_2 (Ainsworth and Long 2005, Luo *et al.* 2005). Since saturation of CO_2 stimulation due to nutrient or other limitations is

common (Dukes *et al.* 2005, Köerner *et al.* 2005), the magnitude, and effect of the CO_2 fertilization is not yet clear.

The CO_2 fertilization effect could mitigate some of the increase in atmospheric CO_2 concentrations by resulting in more storage of carbon in biota.

The current annual exchange in CO_2 between the atmosphere and terrestrial ecosystems is estimated at nine to ten times greater than annual emissions produced as a result of burning fossil fuels. Even a small shift in the magnitude of this exchange could have a measurable impact on atmospheric CO_2 concentration (Heath *et al.* 2005). The above-ground/below-ground processes and components in terrestrial ecosystems typically sequester carbon. Studies are now confirming that variations in atmospheric CO_2 have impacts not only on the above-ground plant components, but also on the below-ground microbial components of these systems.

In one study, CO_2 levels were artificially elevated in a forest for the purpose of studying the effect of atmospheric CO_2 on soil communities. An *indirect* impact of the increased CO_2 was that distinct changes in the composition of soil microbe communities occurred as a result of increased plant detritus (BNL 2007, Science Daily 2007). In another study, an increase in CO_2 *directly* resulted in increased soil microbial respiration. However, after 4 to 5 years of increased exposure to CO_2, "the degree of stimulation declined" to only a 10- to 20-percent increase in respiration over the base rate (King *et al.* 2004). Additionally, the degree of stimulation was linked to variability in seasonal and interannual weather (King *et al.* 2004).

The increase in microbe respiration could, therefore, diminish the carbon sequestration role of terrestrial ecosystems. Upon reaching a certain level of CO_2 in the atmosphere, carbon sinks in soils could become net carbon emitters (Heath *et al.* 2005, Black 2008). Because of the number of factors involved in determining soil respiration and carbon sequestration, the threshold for substantial changes in these activities varies spatially and temporally (King *et al.* 2004).

As with the climatic effects of CO_2, the changes in non-climatic impacts associated with the alternatives is difficult to assess quantitatively. In the Reference Case, atmospheric CO_2 concentrations increase from current levels of about 380 ppm to as much as 800 ppm in 2100 (Kleypas *et al.* 2006). Whether the distinction in concentrations is substantial across alternatives is not clear because the damage functions and potential existence of thresholds for CO_2 concentration are not known. However, what is clear is that a reduction in the rate of increase in atmospheric CO_2 would reduce the ocean acidification effect and the CO_2 fertilization effect.