Planning for Systems Management & Operations as part of Climate Change Adaptation

U.S. Department of Transportation
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Foreword

This paper is a deliverable on a technical support task for the FHWA Office of Operations. The objective of the task is to develop white papers on emerging and current topics of interest to the Office. Topics for white papers were primarily identified and prioritized based on internal listening sessions with Office of Operations personnel.

Notice

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16. Abstract This paper is a deliverable on a technical support task for the FHWA Office of Operations. The objective of the task is to develop white papers on emerging and current topics of interest to the Office. Topics for white papers were primarily identified and prioritized based on internal listening sessions with Office of Operations personnel. This white paper presents various effects of climate change, and how those effects will impact transportation system management and operations. Also presented are presents various options for agencies to assess the vulnerabilities of transportation systems and proposed changes to make transportation operations more resilient to climate change.		
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1. Introduction

Adaptation to climate change is a topic of recent and great interest in the transportation community. The US DOT Policy Statement on climate change adaptation (USDOT, 2011) states the following:

> *The United States Department of Transportation (DOT) shall integrate consideration of climate change impacts and adaptation into the planning, operations, policies, and programs of DOT in order to ensure that taxpayer resources are invested wisely and that transportation infrastructure, services and operations remain effective in current and future climate conditions. The climate is changing and the transportation sector needs to prepare for its impacts. Through climate change adaptation efforts, the transportation sector can adjust to future changes, minimize negative effects and take advantage of new opportunities.*

FHWA' s Sustainable Transport and Climate Change Team, under the Office of Planning, Environment, and Realty, Office of Natural and Human Environment[1] has been identifying climate change issues faced by State DOTs and Metropolitan Planning Organizations (MPOs), conducting workshops and peer exchanges on this topic and developing guidelines and tools to address their concerns. The USDOT Climate Change Clearinghouse (USDOT, 2012) is another important source of information on issues faced by agencies related to climate change. In June 2011, Transportation Research Board (TRB) published a research circular (TRB, 2011) assessing the state of the practice of adaptation strategies being considered by transportation agencies. All of these resources provide an emerging picture of the changes required at an agency level to address the challenges posed by climate change.

One of the gaps in the currently available literature and guidance is an assessment of how systems operations and maintenance adapt to climate change. The challenges posed by climate change to infrastructure design and long-term land-use planning are more easily described than how an agency needs to adapt their day to day operations strategy given the varied nature of evolving climate and travelers' responses to changing climate.

This paper addresses the "services and operations" portion of the above USDOT policy statement, highlighting potential issues, challenges, and approaches for State DOTs and local operating agencies to consider under shifting climate-related conditions. The scope of operations in this paper is limited to surface transportation activities and does not include air or water-borne transportation.

For the purposes of this paper, "effects" refer to climate change issues and "impacts" are the consequences that climate change effects have on transportation.

The paper includes the following sections:

- Section 2 provides an overview of climate change effects that will impact transportation in the U.S.

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[1] http://www.fhwa.dot.gov/environment/climate_change/

- Section 3 describes the impacts of the expected climate change effects on systems management and operations
- Section 4 identifies considerations and approaches to make systems management and operations more climate-resilient.

2. Climate Change Effects to Transportation System Management and Operations

Exhibit 1 – Climate Change Scenarios

Changes in future climate are determined from the output of general circulation models (GCMs). GCMs are complex models that simulate atmosphere, ocean, and land processes. They typically project changes in temperature and precipitation, from which changes in related parameters (e.g., incidence of wildfires, changes in water quality) are derived. GCMs generally have relatively low spatial resolution, on the order of 400 to 125 km (250 to 80 mi), so a technique called downscaling is used to obtain projections on regional and local scales.

GCMs simulate changes in climate under scenarios of future conditions. Scenarios are not predictions or forecasts of future events. Instead, a scenario represents a possible version of the future (IPCC, 2000). Scenarios are used when reliable projections of future conditions are not available, as is the case for climate change. They attempt to constrain the range of plausible future conditions, based on socio-economic variables and trends in global emissions of greenhouse gases and aerosols. Characteristics of the four basic scenario families used for current GCM projections are listed in Table 2.6 (IPCC, 2000). At present, it is not possible to predict which scenario is most likely to occur in the 21st century. As a result, GCMs are typically run under scenarios of high (A2) and low (B1) greenhouse gas emissions to provide a representative distribution of possible future climate conditions.

Summary of Climate Scenarios. [Adapted from IPCC, 2000]

Scenario	Economic Development	Global Population	Technology Changes	Theme
A1	Very rapid	Peaks around mid-21st century and declines thereafter	Rapid introduction of new and more efficient technologies	Convergence among regions; increased cultural and social interactions
A2	Regionally oriented	Continuously increasing	Slower and more fragmented than A1, B1, and B2	Self-reliance and preservation of local identities
B1	Rapid change toward service and information economy	Same as A1	Introduction of clean and resource-efficient technologies	Global solutions to economic, social, and environmental sustainability
B2	Intermediate levels of economic development	Continuously increasing, but not as fast as A2	Less rapid and more diverse changes than A1 and B1	Local solutions to economic, social, and environmental sustainability

This section provides an overview of the expected climate change effects that will impact the transportation community, focusing on impacts that will require operational responses as opposed to long-term behavioral or planning level responses. The adjacent exhibit (Exhibit 1) illustrates how changes in future climate are determined through the use of General Circulation Models under a variety of scenarios. The relevant climate change effects are separated into two general categories based on whether the effect is part of a **climate trend** (e.g., increasing annual average air temperatures) or it is associated with a distinct **climate event** (e.g., storm, flood, drought, heat wave), as these different categories of effects will necessitate different types of operational responses by transportation agencies

Tables A.1 and A.2 list the full range of relevant climate change effects for the transportation sector in the continental U.S. (CONUS) and Hawaii for the 21st century, along with the affected regions and projected date range for the effect to occur. Effects for Alaska are listed separately in Table A.3, since they are distinct in many ways from analogous effects in the tropics (Hawaii) and mid-latitudes (CONUS). When available, the associated certainty of an effect is also specified in Tables A.1-A.3. Certainty is designated using terms defined by the Intergovernmental Panel on Climate Change (IPCC) in their Fourth Assessment Report (Le Treut et al., 2007); these terms are listed in Table A.4 and Table A.5 in Appendix A. For simplicity, sources of the climate change effect information in this section were limited to summary reports, such as those from the IPCC, the Climate Change Science Program (CCSP), and U.S. Global Climate Change Research Program (USGCRP). Much of the data in the cited reports originated from the 2007 IPCC report; the next IPCC report is expected in 2013-14. The following sections highlight some of key climate trends and event-related effects of climate change.

2.1. Effects Associated with Climate Trends

The following effects are associated with climate trends leading to changing conditions over time.

2.1.1. Air Temperature

Rising concentrations of greenhouse gases in the global atmosphere during the 21st century are expected to cause a net warming of the Earth's surface, leading to higher average air temperatures. In general, GCMs run under scenarios of high greenhouse gas emissions (A2) project larger increases in air temperatures than scenarios of low emissions (B1). Furthermore, the magnitude of increases in air temperatures is projected to be greater toward the end of the 21st century. This acceleration in warming is a result of the cumulative effect of increasing levels of long-lived greenhouse gases in the atmosphere.

Since 1900, the global average temperature has increased by about 1.5 degrees Fahrenheit (USGCRP, 2009). GCMs indicate that average annual air temperatures across all of North America, including the CONUS and Alaska, will increase steadily during the 21st century. In fact, by 2039, annual average temperatures are anticipated to be above the range of current natural variability (Christensen et al., 2007). Projections of annual average temperatures (Figure 2.1) suggest that increases will be in the range of 1 to 3°C (1.8 to 5.4°F) by 2039 (Christensen et al., 2007). These changes will vary by season, with the largest increases expected to occur across the northern regions during the winter and the largest increases expected to occur in the Southwest during the summer (Christensen et al., 2007). The magnitude of average temperature increases during the summer is projected to be 3 to 5°C (5.4 to 9°F) across most of North America by the end of the 21st century (Christensen et al., 2007). Air temperature changes near the coasts are expected to show less seasonal variability due to warming of the oceans associated with climate change (Christensen et al., 2007).

Regional trends of annual and seasonal air temperatures in the CONUS are consistent with continental trends (Figures 2-2 and 2-3). Annual average air temperatures across the CONUS are expected to rise 7 to 11°F under the A2 (high) scenario and approximately 4 to 6.5°F under the B1 (low) scenario by 2100, and warming will be greatest during the summer (FHWA, 2010). By 2050, average air temperatures are projected to increase 2.5 to 4°F in winter and 1.5 to 3.5°F in summer in the Northeast (USGCRP, 2009) and 2.7°F ± 1.8°F in the Gulf Coast region (CCSP, 2008). In the Southeast and the southern and central Great Plains, increases in average air temperatures during the summer are projected to be larger than those in winter (USGCRP, 2009). In some areas of the Southwest, increases in air temperature during the summer are expected to be larger than annual average increases, and they will be exacerbated by localized urban heat island effects (USGCRP, 2009). Due to the increases in air temperatures across the U.S., electricity demand for air conditioning in most North American cities is anticipated to increase considerably in the 21st century, in order to cool homes and indoor work and recreation spaces (Field et al., 2007).

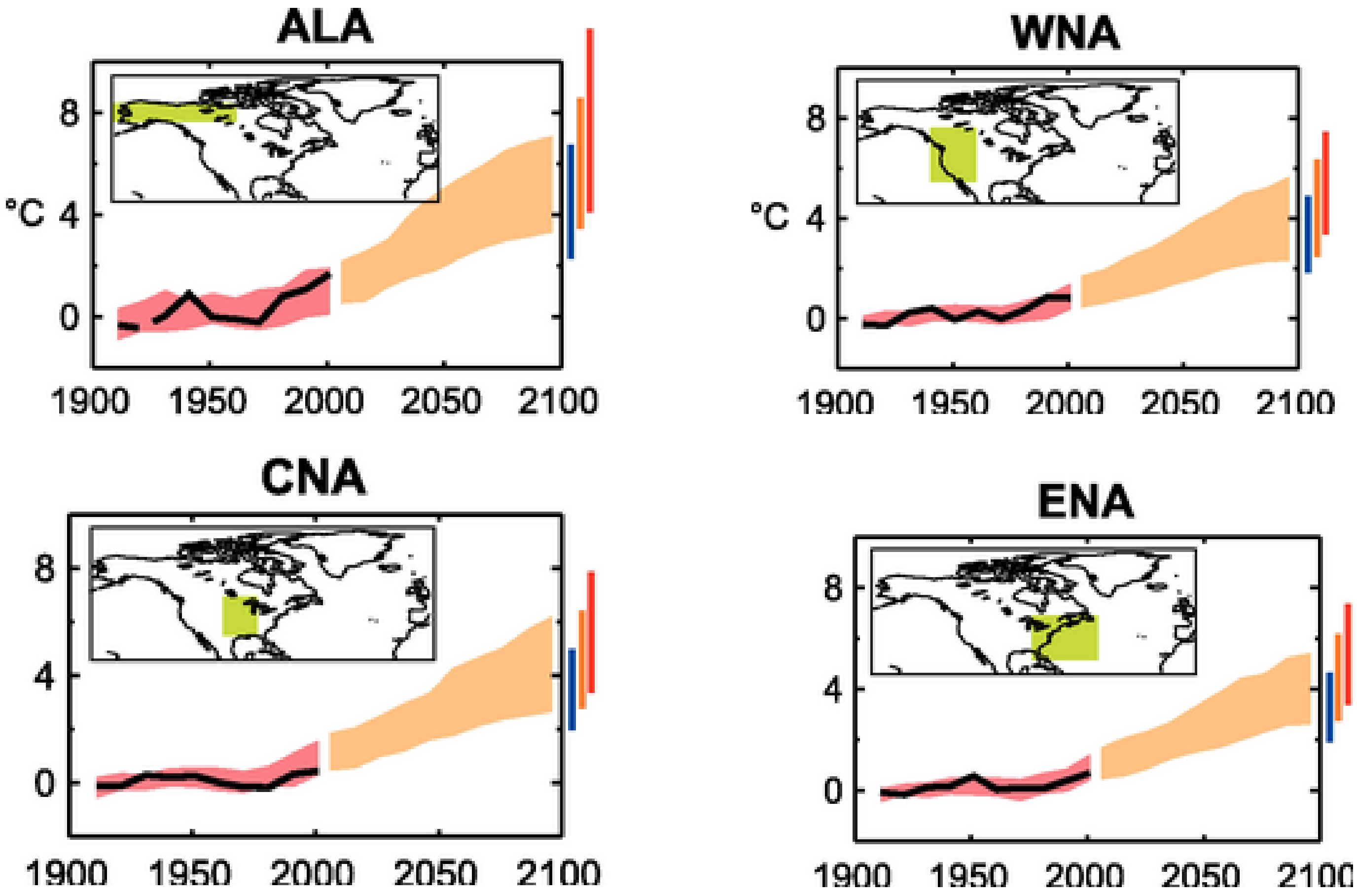

Figure 2.1. Changes in annual average air temperature relative to 1901-1950 averages for Alaska (ALA), Western North America (WNA), Central North America (CAN), and Eastern North America (ENA): observed for 1906-2005 (black line), simulated by climate models for 1906-2005 (red shading), and projected by climate models for 2001-2100 (orange envelope) under the A1B (moderate) scenario. The colored bars at the end of the orange envelope represent the range of projected changes for 2091-2100 under the B1 (low) scenario (blue), the A1B (moderate) scenario (orange), and the A2 (high) scenario (red). [Adapted from Christensen et al., 2007]

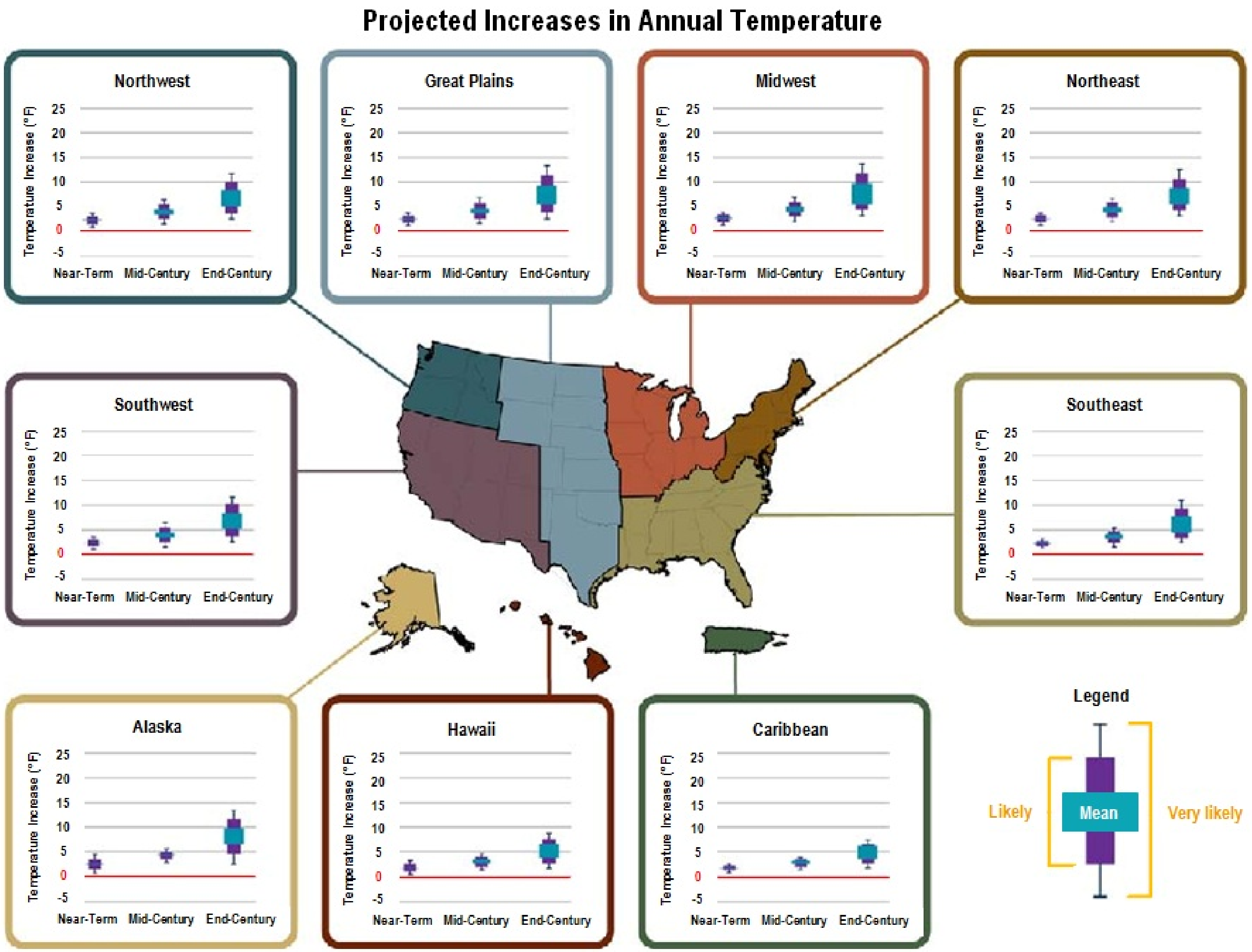

Figure 2.2. Projected changes in annual average air temperature for six regions of the U.S., Alaska, Hawaii, and the Caribbean through 2100, relative to 1961-1979 averages, compiled using the A2 (high) and B1 (low) scenarios. [Adapted from ICF International, 2010]

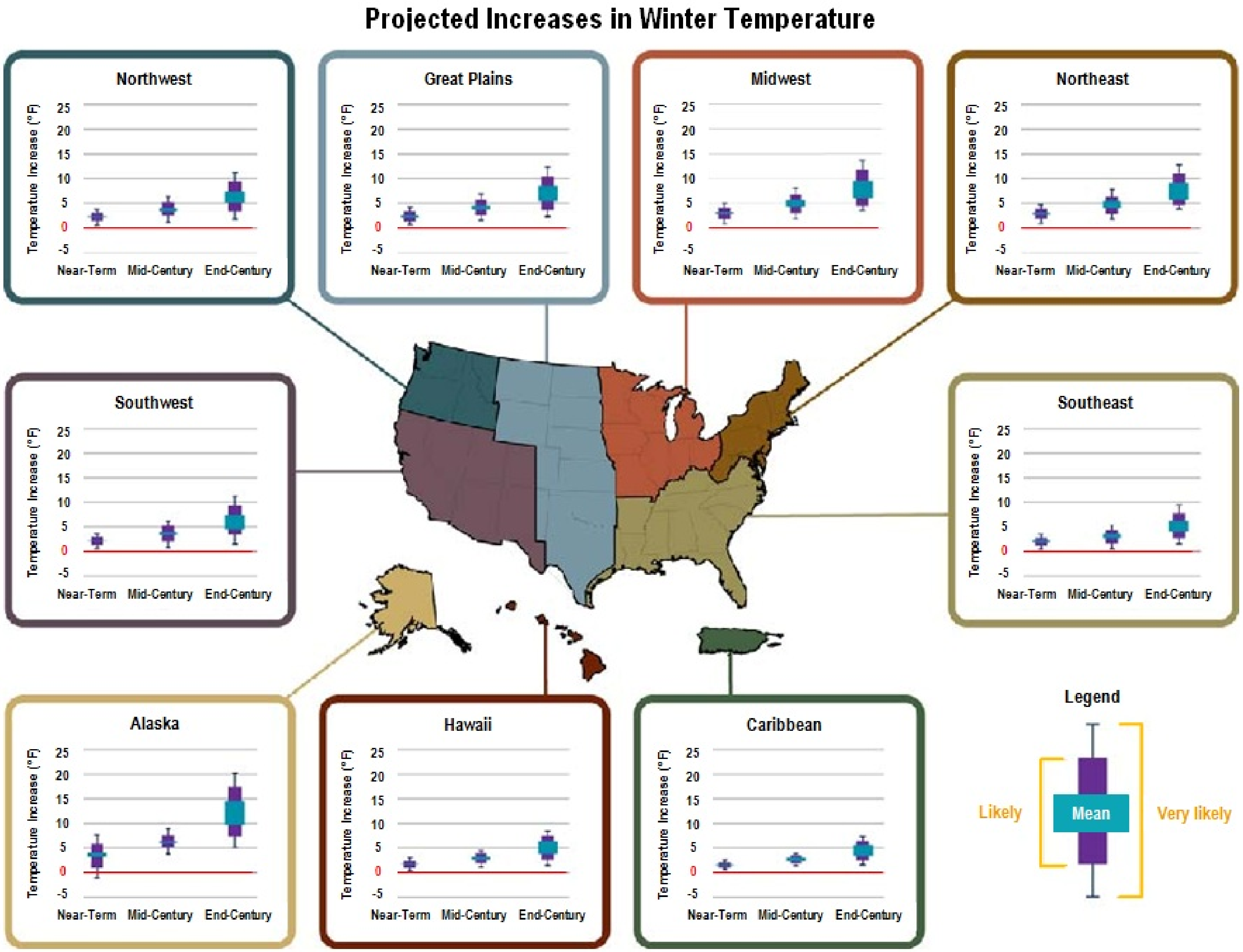

Figure 2.3. Projected changes in winter average air temperature for six regions of the U.S., Alaska, Hawaii, and the Caribbean through 2100, relative to 1961-1979 averages, compiled using the A2 (high) and B1 (low) scenarios. [Adapted from ICF International, 2010]

2.1.2. Precipitation

Higher air temperatures associated with rising concentrations of greenhouse gases are expected to increase the amount of water vapor in the atmosphere, leading to overall increases in global precipitation during the 21st century. It is important to note that GCM projections of temperature changes for a given region are generally consistent in sign and magnitude, but precipitation projections can vary widely across models due to the difficulty in simulating the myriad of factors that influence precipitation frequency, duration, and intensity. An additional complicating factor is that precipitation in the U.S. varies naturally on seasonal, annual, and inter-annual time scales. In model simulations, any precipitation changes associated with future climate change are overlaid on this natural variability, making it difficult for GCMs to resolve contributions from natural and anthropogenic influences. The result is increased uncertainty in expected precipitation changes associated with future climate change as compared to projections for temperature.

Figures 2.4 and 2.5 illustrate the expected range of regional changes in winter and summer precipitation in the U.S. through 2100. Model projections indicate that annual average precipitation will increase across the northern CONUS and decrease in the southern CONUS, particularly in the Southwest (Christensen et al., 2007; USGCRP, 2009). Overlaid on this annual change will be seasonal variations, with most of the increases in precipitation in the northern CONUS and most of the decreases in precipitation in the southern CONUS expected to occur in the winter and spring (ICF International, 2010).

Associated with the increasing air temperatures, snow season length and snow depth are projected to decrease across most of North America (Christensen et al., 2007). Figure 2.6 depicts projected changes in percent snow depth in North America during March in 2041-2070. The rain/snow line is expected to shift northward and to higher elevations, causing more winter precipitation to fall as rain and less as snow (ICF International, 2010). Furthermore, less overall snowfall and earlier snowmelt in the spring will lead to a general decrease in snow depth across snow-covered regions of the U.S. (Christensen et al., 2007), particularly in the Rocky Mountains.

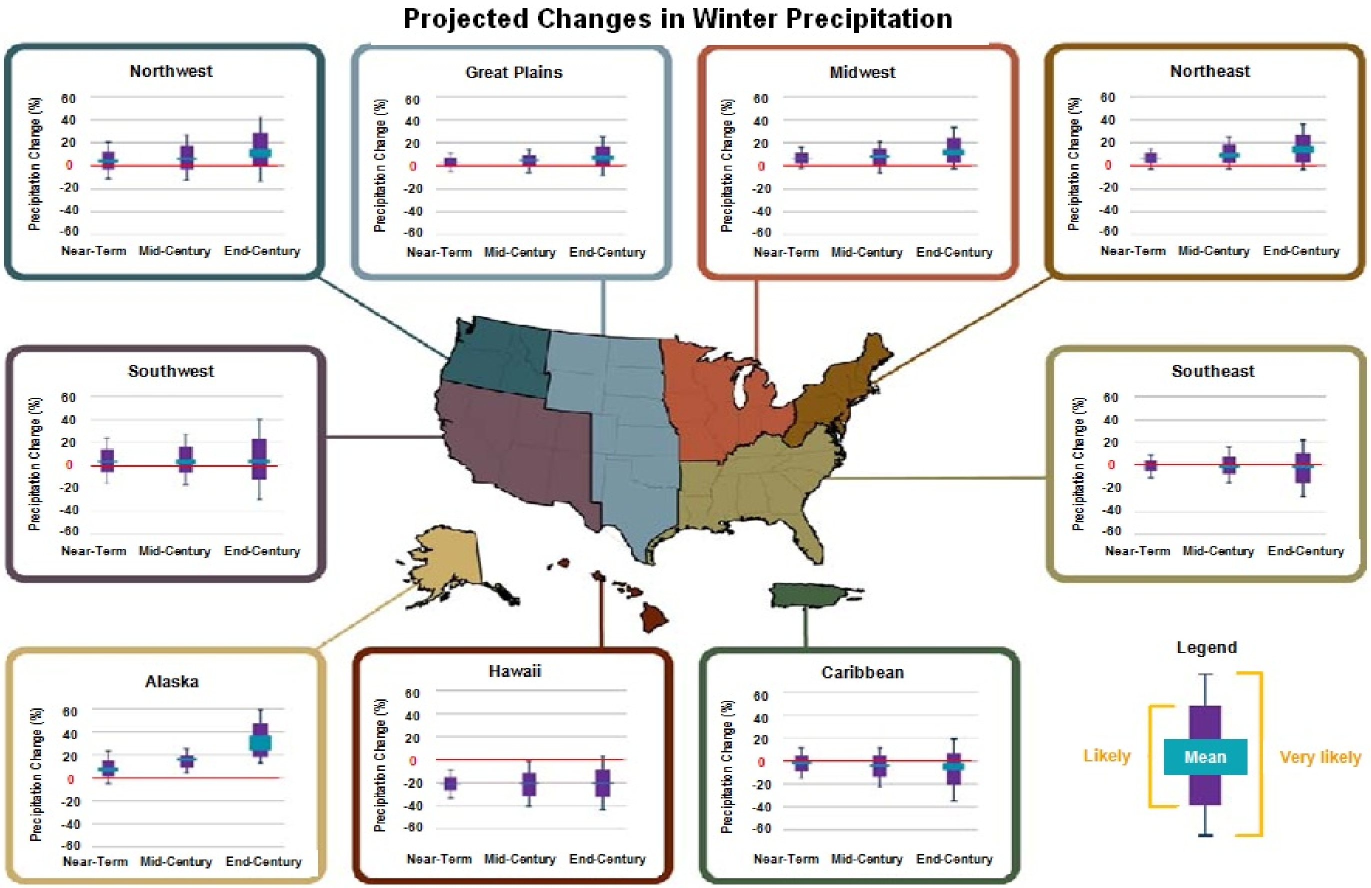

Figure 2.4. Projected changes in winter average precipitation for six regions of the U.S., Alaska, Hawaii, and the Caribbean through 2100, relative to 1961-1979 averages, compiled using the A2 (high) and B1 (low) scenarios. [Adapted from ICF International, 2010]

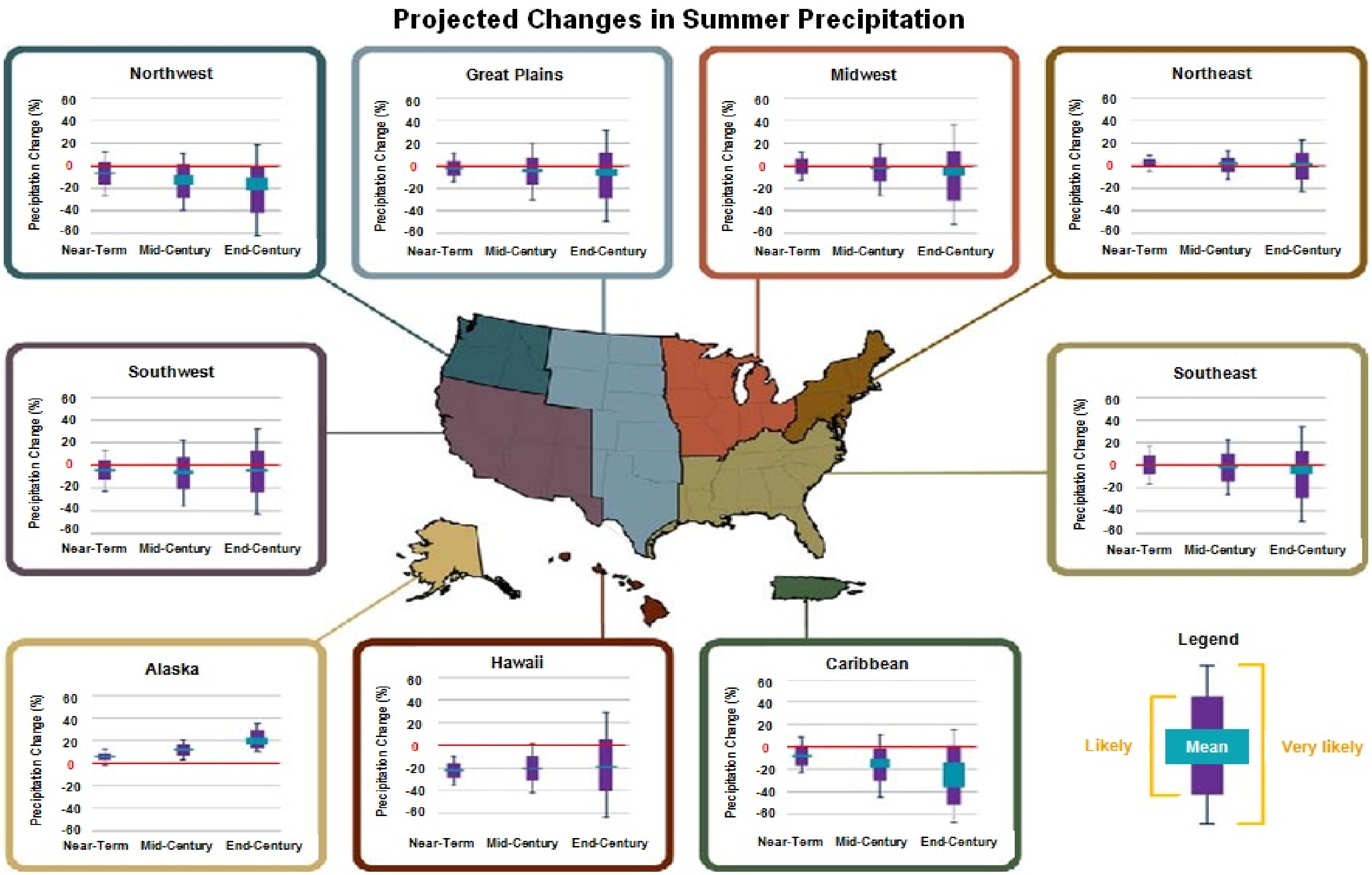

Figure 2.5. Projected changes in annual summer precipitation for six regions of the U.S., Alaska, Hawaii, and the Caribbean through 2100, relative to 1961-1979 averages, compiled using the A2 (high) and B1 (low) scenarios. [Adapted from ICF International, 2010]

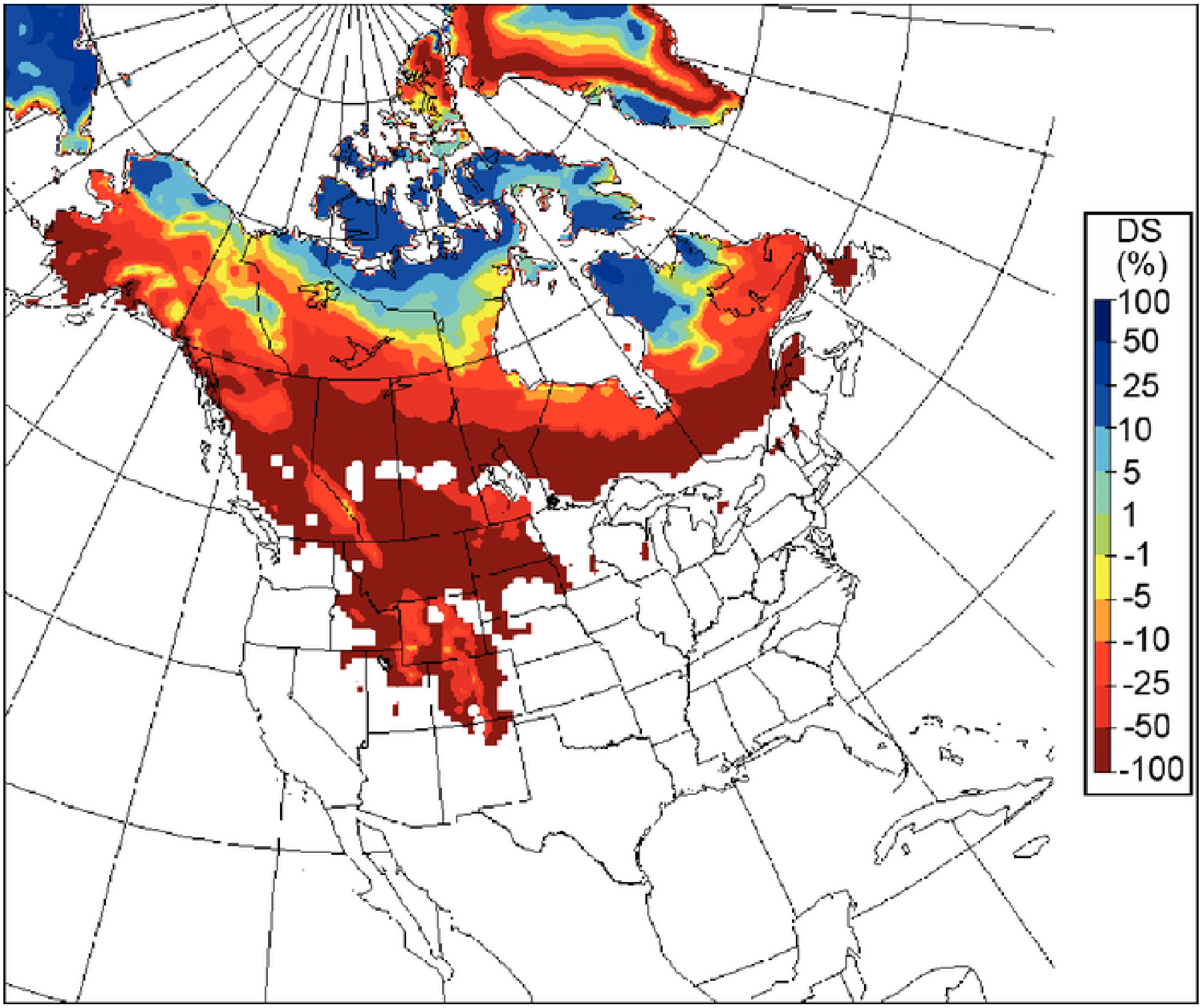

Figure 2.6. Projected change in percent snow depth (DS) in March for 2041-2070, relative to 1961-1990 averages, under the A2 (high) scenario. [Adapted from Christensen et al., 2007]

2.1.3. Coastal Effects

Climate change is projected to cause a rise in global sea levels of between 0.18 m to 0.59 m (7.1 in to 23.2 in) by 2099 due to thermal expansion of ocean water and melting of glaciers, though the rise will not be uniform(TRB, 2008). This rise in sea level will impact the Atlantic and Pacific coasts of the U.S., leading to coastal inundation and accelerated rates of coastal erosion (Field et al., 2007). Coastal erosion is also expected to be exacerbated by reductions in the extent and duration of sea ice, which will allow for more open water during the winter storm season (Field et al., 2007).

Along the Gulf Coast, sea level is projected to increase by at least 1 ft and up to 6 to 7 ft in some locations, such as central and western Louisiana and eastern Texas, where subsidence rates are highest (CCSP, 2008). In the Northeast, model predictions under a high (A2) scenario suggest that sea level will rise along the Atlantic coast more than the global average, leading to severe coastal flooding (USGCRP, 2009). For example, what is currently considered a 100-year flood event may occur twice as often by 2050 and up to ten times as often (an average of once per decade) by 2099 (USGCRP, 2009). In the Northwest, the south Puget Sound region is particularly vulnerable to sea level rise and increasing coastal erosion, including the cities of Olympia, Tacoma, and Seattle in Washington State (USGCRP, 2009). A potential increase in the number of landslides on coastal bluffs in the Northwest is also a concern, associated with more saturated soils from increased precipitation (USGCRP, 2009).

2.1.4. Human Health Effects

It is projected that U.S. residents over the age of 65 will represent 20% of the U.S. population by 2030. This population shift along with projected increases in the frequency, intensity, and duration of heatwaves suggests a future increase in heat-related deaths, particularly in highly developed areas where the urban heat island effect is present (USCCSP SAP 4.6, 2008). A warmer climate in the U.S. is also expected to make conditions more favorable for increases in pollen, some air pollutants, and Lyme disease, thereby increasing risks to human health. Higher temperatures are generally favorable for the expansion of tick distributions and greater abundance of vector-borne diseases like Lyme disease (USCCSP SAP 4.6, 2008). Rising air temperatures and high atmospheric carbon dioxide (CO_2) concentrations are anticipated to increase pollen concentrations in the CONUS (Field et al., 2007). Higher air temperatures may also increase concentrations of tropospheric (surface-level) ozone (O_3) and non-volatile fine particulate matter ($PM_{2.5}$), due to increased rates of associated gas-phase reactions (Field et al., 2007), which in turn may exacerbate and intensify the occurrence of respiratory illness, such as asthma (USCCSP SAP 4.6, 2008). In addition, as air temperatures increase, trees and plants emit more O_3 precursors, such as isoprene, which will also enhance production rates of O_3 (Field et al., 2007). By 2050, daily average ozone levels are projected to increase 3.7 parts per billion by volume (ppb) in the eastern U.S., and the number of summer days that exceed the 8-hour O_3 regulatory standard is expected to increase by 68% (Field et al., 2007).

2.1.5. Ecological Effects

Climate change may also have significant impacts on ecosystems in the CONUS. Model projections indicate that the growing season will expand during the 21st century, with earlier spring thawing and later fall freezing (Field et al., 2007). Less snow cover and more winter precipitation falling as rain will increase runoff, lengthen the erosion season, and enhance inland erosion (Field et al., 2007). Along the Atlantic and Pacific coasts, the salinity of estuaries, coastal wetlands, and tidal rivers is expected to increase due to saltwater intrusion, which will damage coastal ecosystems and possibly shift them farther inland (USGCRP, 2009). Climate change is projected to expand the geographic range of invasive species, which alter the structure and composition of ecosystems. Non-native insects that have expanded their ranges in the U.S. include the Asian long-horned beetle, hemlock woolly adelgid, the common European pine shoot beetle, and the emerald ash borer. Non-native invasive plant species have altered fire regimes in the western U.S.; cheatgrass is an invasive species now common in the Intermountain West, which has changed the fuel complex, increased fire frequency, and reduced habitat within this region (USCCSP SAP 4.4, 2008).

2.2. Impacts Associated with Climate Events

The following impacts are associated with events that are expected to occur as a result of changing climate trends.

2.2.1. Air Temperature Events

Rising air temperatures in the U.S. during the 21st century mentioned in Section 2.1.1 are expected to cause increased incidences of heat waves and extreme temperature events. The frequency and duration of warm extremes are projected to increase across North America (Christensen et al., 2007). In the CONUS, the magnitude and duration of severe heat waves, characterized by stagnant, warm air masses and consecutive nights with high minimum temperatures, are predicted to increase in locations where heat waves already occur (Field et al., 2007). In the Gulf Coast region, the number of very warm days (high temperatures >90°F) is expected to increase significantly, and by 2050, there will be a 50% probability of 21 days per year with high temperatures ≥100°F (CCSP, 2008). Similarly, in the Northeast, GCMs run under the A2 (high) emissions scenario project that some cities, such as Hartford, CT, and Philadelphia, PA, will average almost 30 days per year with high temperatures >100°F (USGCRP, 2009). In the Midwest, the frequency, severity, and duration of heat waves are expected to increase, and by 2100, GCMs run under the A2 (high) emissions scenario project that severe heat waves could occur once every two years (USGCRP, 2009).

2.2.2. Precipitation Events

Changes in precipitation patterns associated with climate change will lead to changes in the incidences of extreme precipitation events and related phenomena, including floods and droughts. Extreme precipitation events, such as thunderstorms and heavy downpours, are projected to increase in frequency and intensity (Meehl et al., 2007; ICF International, 2010). Across the CONUS, the probability of a heavy downpour occurring in a given year is expected to increase from 5% to 20-75% by 2100 (ICF International, 2010). The intensity of individual rainfall events is projected to increase in the Gulf Coast region during the 21st century (CCSP, 2008).

In the Northeast, GCMs run under the A2 (high) emissions scenario project that 1-3 month droughts will occur every summer in the Catskill and Adirondack Mountains of New York and across New England (USGCRP, 2009). The frequency, duration, and intensity of droughts are expected to increase in the Southeast, Midwest, and Southwest as well (USGCRP, 2009). In the Northwest, more precipitation falling as rain and not snow is anticipated to cause winter flooding on the west side of the Cascade Mountains (USGCRP, 2009).

2.2.3. Storms and Coastal Flooding

Changes in atmospheric circulation, in conjunction with increases in air temperature and altered precipitation patterns due to climate change, will affect the development of storms, including tropical cyclones (hurricanes and tropical storms) and extra-tropical cyclones (large mid-latitude snowstorms and rainstorms). Climate change is expected to shift the jet stream over the U.S. northward (ICF International, 2010), resulting in a slight shift in mid-latitude extra-tropical cyclone storm tracks toward the North Pole (Christensen et al., 2007). The intensity of extra-tropical cyclones is anticipated to increase, but they will occur less frequently (Meehl et al., 2007).

Trends for tropical cyclones are less clear. As surface water temperatures in the Atlantic Ocean and Gulf of Mexico increase due to climate change, the intensity of hurricanes is expected to increase, possibly by 10% (CCSP, 2008). Some GCMs predict that hurricanes' peak wind speeds and rainfall intensity will increase (Meehl et al., 2007). Potentially stronger tropical cyclones combined with rising sea level are expected to result in higher storm surge and more severe coastal flooding (Field et al., 2007; USGCRP, 2009).

2.2.4. Wildfires

Warmer and drier conditions in the 21st century associated with climate change will increase the potential for wildfires. Across the CONUS, higher air temperatures during the summer are projected to increase the risk of fire ignition by 10-30% by 2100 (Field et al., 2007). In the Northwest, earlier mountain snowmelt in the spring combined with higher air temperatures are anticipated to create dry conditions during the summer that will increase the risk of forest fires (USGCRP, 2009).

2.2.5. Landslides

Increased heavy precipitation in the winter and spring suggest an increase in soil saturation and a compromise in slope stability, which is projected to cause an increased occurrence of landslides and/or mudslides. In coastal areas, bluff landslides will be exacerbated by the rise in sea level (USGCRP, 2009).

2.2.6. Dust Storms

Temperature and precipitation changes are projected to decrease vegetation cover, which protects the ground from erosion. As a result, it is suggested the occurrence of dust storms will increase (USCCSP SAP 4.3, 2008).

2.3. Climate Change Effects in the Arctic (Alaska)

2.3.1. Air Temperature

Air temperatures in Alaska are expected to increase throughout the 21st century, but at a faster rate than for the CONUS. Model projections indicate that the annual average warming in Alaska will exceed the global mean warming. The largest temperature increases are expected during the winter over northern Alaska, due to the positive feedback from reduced snow cover (Christensen et al., 2007) (Figure 2.3). The magnitude of warming is projected to vary from 7°C (12.6°F) in winter to 2°C (3.6°F) in summer by 2050 (Christensen et al., 2007; USGCRP, 2009).

2.3.2. Precipitation

Models are consistent in predicting an increase in annual average precipitation in Alaska, with most of the increase occurring during the winter months (Christensen et al., 2007; ICF International, 2010). As air temperatures rise, the ratio of rain to snow is expected to increase, so more precipitation should fall as rain and less as snow, particularly in locations in Alaska where average air temperatures are currently close to freezing (Anisimov et al., 2007). Changes in the frequency of extreme temperature and precipitation events in the Arctic are uncertain, but projections indicate that very warm and wet winters and summers will become more frequent in the 21st century (Christensen et al., 2007).

2.3.3. Ice, Snow Cover, and Permafrost

Increasing air temperatures will have a profound effect on ice, snow cover, and permafrost in Alaska. Recent observations suggest that higher temperatures are already causing earlier spring snowmelt, reduced sea ice, widespread glacier retreat, and permafrost warming in Alaska (USGCRP, 2009). The extent and thickness of Arctic sea ice is expected to continue to decrease, with reductions of 22 to 33% in the extent of annually averaged sea ice projected by 2080-2100 (Anisimov et al., 2007; Christensen et al., 2007). Most of the reduction in sea ice is expected during the summer (Anisimov et al., 2007). Additional loss of snow cover on land is also projected (Figure 2.3), with reductions in snow residence times expected to be greatest in spring (Anisimov et al., 2007). Warmer conditions are anticipated to shrink the extent of terrain underlain by permafrost. By 2050, models project that the permafrost area in the Northern Hemisphere will decrease by 20 to 35%, due to thawing of permafrost in both discontinuous (10 to 90% of land frozen) and continuous (90 to 100% of land frozen) zones (Anisimov et al, 2007).

3. Impact of Climate Change Effects on Transportation System Management and Operating Agencies

It is clear that many of the climate change effects listed in Section 2 require long-term changes to how transportation infrastructure is planned, designed, and constructed. Additionally, land-use planning and travel behavior modifications are important components of adaptation strategies. From a systems management and operations perspective, agencies face an uncertain future with respect to how they maintain, operate, and plan for the future. This section discusses the impact of climate change on transportation and systems management operations.

3.1. Increased System Maintenance Needs

Given the climate change effects listed in Section 2, specifically those related to increases in average air temperatures and shifts of the rain/snow line during the winter, transportation agencies will likely need to adapt by making changes to system maintenance. These changes could affect winter maintenance operations, require diversion to more resilient alternate routes, and prompt the deployment of "quick maintenance" patrols to address potentially more frequent potholes and buckling issues. Climate change effects to system maintenance needs are presented in Table 1.

Table 1. Climate Change Impacts and Potential Responses for System Maintenance Needs

Climate Change Effects	Climate Change Impacts	System Maintenance Response
Climate Trends Impacts		
Shifting rain/snow line	Fewer snow/ice precipitation events	Reduced need for winter maintenance operations resources and staff
	Less snowfall in areas that were previously impassable due to high and frequent snowfall	Potential for increased winter maintenance operations on routes currently inaccessible in winter
	Increased snowmelt/rain during the winter season increases the likelihood of flooding, which will generally affect specific roadways and locations, as opposed to the whole network	Shift in resources from winter maintenance to winter flooding monitoring and traveler information
	Temperatures in some areas may shift to or more frequently hover at the freezing point, increasing the probability of ice precipitation instead of snow	Shift in resources from snow to ice management
	Long-term shifting of snow/ice precipitation necessitates reassessment of winter maintenance needs	Monitoring trends to identify and forecast trends of increasing or decreasing snow/ice and frequency of extreme precipitation events
	Longer construction season due to higher temperatures, fewer days with temperatures below freezing, and less snow/ice precipitation	Altered construction and maintenance schedules
Changes in freeze/thaw cycle	Potential for longer duration and/or shifting of freeze/thaw period	Increased staff and resources to monitor vulnerable areas to post seasonal weight restrictions and make repairs.
Increased frequency, duration and intensity of droughts; increase in average air temperature	Roadside vegetation dies off	Changes to vegetation management activities
	Increased probability of wildfires	Increased staff and resources to monitor vulnerable areas and provide traveler information
Climate Event Impacts		
Increased coastal and inland flooding; increases in intense precipitation events	Greater frequency of flooded, blocked (e.g., trees, landslides), damaged, and washed out roads	Mandatory diversion to more robust alternate routes, reducing route options/redundancy
		Increased staff and resources to monitor vulnerable routes and provide traveler information
Increase in magnitude and duration of severe heat waves	Greater risk of structural damage to bridge joints and pavement, e.g., buckling or rutting	Mandatory diversion, particularly for freight, to more robust alternate routes
		Deploy “quick maintenance” patrols to address potholes and buckling issues
	Higher temperatures may inhibit construction activities during certain months, or times of day	Altered construction and maintenance schedules

Climate Change Effects	Climate Change Impacts	System Maintenance Response
Increase in dust storms	Greater frequency of reduced visibility conditions	Increased staff and resources to monitor vulnerable routes and provide traveler information

Increases in average air temperature and reduced snowfall have the potential to impact greatly operations required for winter maintenance. Currently, 70% of the nation's roads are in regions that receive over 5 in of annual average snowfall, requiring the expenditure of over $2.3 billion per year by state and local agencies for winter maintenance activities (FHWA, 2012). Additional millions of dollars are spent on infrastructure to repair damages caused by snow and ice (FHWA, 2012).

Multiple impacts highlighted in Section 2 could reduce the need for winter maintenance, most notably the increase in average air temperatures with the largest magnitude of warming in northern regions during winter and the general shifting of the rain/snow line north and to higher altitudes. For some areas, these impacts might indicate fewer days below freezing and thus reduced incidence of precipitation causing snow or ice conditions. For these areas, there may be a reduced need for resources to be dedicated to winter maintenance operations. However, there may also be opportunities to shift winter maintenance operations to areas that currently have seasonal closures, but will be easier to maintain with reduced snowfall under a changing climate.

Similarly, increases in average air temperature that cause the rain/snow line to shift north are likely to also influence subgrade freeze/thaw cycles. While a frozen subgrade provides a solid foundation for heavy vehicles on roadways, heavy vehicles traveling on a roadway with a poor subgrade can cause potholes and rutting that may require additional system maintenance for repairs. Alternatively, imposing weight restrictions during the spring freeze/thaw period may help ease this issue. Either way, additional staff and resources may be required to monitor the subgrade temperatures and pavements to know when weight restrictions should be imposed and repairs are required.

Furthermore, with the potential for increased frequency and intensity of extreme precipitation events, added winter maintenance operations resources may be imperative to maintain functionality of the transportation network. Winter storm disasters alone have caused over $29 billion in damages (adjusted for inflation) since 1980 (NOAA, 2012), and increases in intensity of extreme precipitation events may cause greater damages in the future. Winter flooding is projected in the Northwest due to more precipitation falling as rain and not snow, which would alter the response required from system maintenance personnel from winter maintenance operations to system monitoring and traveler information regarding flooding and closures.

Although severe damages from winter storms are often caused by ice damage to trees and power lines requiring cleanup and repairs, many winter storms produce only snowfall, which causes no significant damages, but simply impedes mobility on the transportation network until routes can be cleared. Increases in average air temperature may affect the type of precipitation that occurs in an area as the rain/snow line moves northward and to higher elevations, and the frequency of ice storms for particular regions may also shift northward.

Winter maintenance operations are already difficult to predict, since snowfall is quite variable - one year, 6 ft of snow might fall in a given location, and the next year no snow might fall at all. Climate change effects may influence trends overall such that snowfall extremes are more pronounced from year to year, or that the annual average amount of snow and ice precipitation is either reduced or increased for an area. Signs of changing trends must be monitored by transportation agencies, as they could severely impact winter operations of surface transportation. Necessarily, agencies may struggle to justify spending on resources and staff that remain unused or underutilized from year to year, and therefore be left unprepared for major snow events that occur on a less frequent basis.

A recurring consequence of many aforementioned climate change effects might be mandatory diversion to more robust alternate routes. This requirement might affect routes that traverse areas that are more prone to flooding due to sea level rise or increased precipitation, for example, or that contain lower quality pavements that are more susceptible to warmer temperatures. In both cases, transportation agencies will have to monitor vulnerable routes to provide traveler information via dynamic message signing, websites, or radio, for example, as well as have staff on hand to deploy signage and physically close impacted routes, as necessary. Impacts of warmer temperatures on pavements may require diversion of freight traffic more so than passenger traffic, in which case either static or dynamic weight restrictions might be imposed on those routes. Today, transportation agencies frequently recommend diversion for flooded areas using methods listed above; but with climate change effects, agencies should strategically expand their capacity for making these recommendations by deploying monitoring devices for roadways that are likely to be most affected.

Similarly, increases in magnitude and duration of severe heat waves are likely to increase issues related to potholes and buckling in pavements. The Iowa DOT reports that in a typical year an average of \$400,000 is spent to make temporary and permanent repairs related to pavement buckling due to thermal expansion forces; costs may be \$2000 for a single repair (IDOT, 2012). In particular, this might impact pavements that may not have been designed with a changing climate in mind. It is likely that warmer regions that experience these severe heat waves will begin incorporating pavement designs with increased tolerances for higher temperatures; however, some segments are likely to contain historic, lower quality pavement that is more susceptible to potholes and buckling. Transportation agencies may find it beneficial to deploy “quick maintenance” patrols for potholes and buckling issues, especially during extreme high temperature events when the buckling is most likely to occur. These “quick maintenance” patrols might operate in a manner similar to freeway service patrols (FSPs), or actually be an added service of FSPs. Just as FSPs are deployed on freeways to quickly address and clear incidents or stopped vehicles to maintain mobility, “quick maintenance” patrols would be available to quickly repair potholes or buckling pavement that is impacting mobility or safety on the roadway. For example, during extreme heat events, Virginia DOT puts crews on special alert to be prepared for emergency repairs to the state’s roadways (VDOT, 2012).

In general, increases in average air temperatures could alter the timing of construction activities throughout the year, particularly in northern areas where construction activities tend to be more limited in the winter (FHWA, 2011). Additionally, increases in the frequency and duration of heat waves could shift the timing of construction activities to occur at cooler parts of the day.

Finally, with changes to precipitation and temperature, roadside vegetation is likely to be affected. While drier conditions are likely to reduce the need for mowing operations, in general, increases in the frequency, duration, and intensity of drought conditions will precipitate the need for new, drought-resistant species that can survive dry conditions and serve as erosion control.

3.2. Changes to System Operations Practices and Strategies

Numerous impacts due to more widespread, higher intensity storms or tropical cyclones will create the need for broader disaster and evacuation preparedness. In general, planning for these events will come with increased uncertainty, as it pertains to personnel and resources. Likewise, rising sea levels and flood risks may increase the need to monitor vulnerable roadways in order to restrict access, given real-time conditions. Additionally, spikes in energy consumption due to warmer temperatures may cause localized power outages that could disrupt Traffic Management Centers' communications. Climate change effects to system operations are presented in Table 2.

Table 2. Climate Change Effects to and Potential Responses by System Operations

Climate Change Effects	System Operations Response
Climate Event Impacts	
Increased recurring coastal and inland flooding; rising sea levels	Mandatory diversion to more robust alternate routes
	Increased staff and resources to monitor vulnerable routes and provide traveler information
Increase in intensity of tropical cyclones; increased occurrence of wildfires	Broader preparedness for potential evacuation
	Increased TMC staff and Intelligent Transportation System (ITS) resources to provide traveler information during evacuations
	More frequent disaster preparation, operations, and recovery actions
Climate Trends Impacts	
Increase in energy demand for air conditioning	Increased need for more resilient TMC communications and backup power to maintain real-time information feeds

Increased inland and coastal flooding might increase the need to monitor a wider and different set of roadways and restrict access given forecasted or real-time conditions. With higher chances for flooding on a greater number of roadways, given more intense precipitation events, for example, there is a greater need for monitoring of these high-risk flood prone roadways for increased traveler information. Numerous examples of weather monitoring exist in which the TMC monitors flood gauges to alert travelers to real-time conditions.

Regarding hurricanes, increased intensity of storms coupled with rising sea levels will cause greater impacts over a broader area given the potential for shifting storm tracks, stimulating the need for a widened area for preparedness for evacuations. Thirty-one hurricane events have caused $417 billion (adjusted for inflation) in damage in the United States since 1980 (NOAA, 2012); more intense storms will likely increase the amount of damage and require faster and more comprehensive responses. This includes the need for greater TMC support for traveler information and for ITS to assist motorists during an evacuation. Additionally, more frequent disaster preparation, operations, and recovery actions will be needed to prepare those who may be impacted by these events. However, because of the likelihood of reduced frequency for such storms, there will be increased uncertainty in planning for hurricanes, in terms of personnel and resources. Similar actions may be required for inland areas that are impacted by flooding due to increased inland flooding, or for areas that are expected to experience increased wildfires.

Finally, with increases in extreme high temperature events and the intensity, frequency, and duration of heat waves, there will likely be an increase in energy demand for air conditioning during summer months. This could lead to spikes in energy usage that cause local power outages. This prompts the need for more resilient TMC communications and backup power in the field to maintain real-time information to drivers.

3.3. Changing Travel Behavior

Climate change effects are likely to affect greatly individuals' transportation decisions and safety on the roadways. For example, because temperature and precipitation can impact decisions to use transit, bike, or walk, regional changes could increase or decrease individuals' motivation to use alternate modes. This phenomenon has been investigated in a study on how weather affects Chicago transit ridership (Guo, et al., 2007). The data-driven study findings, which are shown in Table 3, showed that CTA bus ridership and weekend ridership are more sensitive to extreme weather than rail ridership and weekday, respectively, and that some weather conditions like fog or blizzards can increase transit ridership (Guo, et al., 2007). The study found that weekend ridership changed more than weekday ridership (Guo, et al., 2007). Localized climate change effects could also affect individuals' routes and destinations, as well as exposure to weather-induced hazardous driving conditions. Climate change effects and potential responses that might change traveler behavior are presented in Table 4.

Table 3. Correlation between Weather Conditions and Chicago Transit Administration (CTA) Bus and Train System-wide One-Day Ridership

Weather Condition	Bus Ridership Impact*		Rail Ridership Impact*	
	Low	High	Low	High
Temperature (one degree increase)	+700	+1100	+200	+700
Rain (one inch increase)	-16,000	-88,000	-5000	-45,000
Snowfall (one inch increase)	-10,000	-188,000	Inconsistent/Not Significant	Inconsistent/Not Significant
Wind (one mph increase)	-700	-2700	Negligible	Negligible
Fog (moderate)	Not significant	Not significant	+8000	+10,000

*Note: on average, one-million and a half-million rides are taken on the CTA bus and rail systems, respectively.

Source: Guo, et al., 2007.

Table 4. Climate Change Effects and Potential Changes in Travel Behavior

Climate Change Effect	Changes to Travel Behavior
	Climate Event Impacts
Increased exposure to hazardous driving conditions (e.g., flooding, road surface conditions, smoke from wildfires)	Less consistent mode split impacting day-to-day congestion and safety issues
	Potential mode shift to/from alternate modes, e.g., using transit, biking, or walking
	Increased TMC monitoring of more reliable routes to provide enhanced traveler information
	Increased emphasis on carpooling and teleworking to reduce impacts to highways
	Investigate regional climate change impacts to understand how impacts may affect traveler mode and route choice in both the short- and long-terms
	Climate Trend Impacts
Human health effects	Potential mode shift from alternate modes, e.g., transit, biking, or walking
	Increased emphasis on carpooling and teleworking to reduce impacts to highways

Many of the climate change effects listed in Section 2 will increase individuals' exposure to hazardous driving conditions, which include reduced visibility, flooding, hazardous road surface conditions, landslides, and wildfires. All of these effects, individually, are likely to reduce driver safety and increase the likelihood for crashes. In addition, it is likely to reduce mobility with increased travel times due to the need to drive slower in adverse weather conditions or take alternate routes.

Clearly, climate change effects will vary by region with some mode shift to alternate, non-driving modes occurring in areas with less precipitation or more mild winters, for example; other areas may see mode shift to cars if extreme temperatures and increased precipitation occur. These mode shifts could affect operations on a day-to-day basis, potentially causing increased congestion and safety issues on highways for some days and on transit on other days. The relationship between weather and mode choice is complicated. Mode shift away from alternate, non-driving modes may also be induced by human health effects caused by higher pollen counts and pollution, i.e., higher concentrations of tropospheric (surface) ozone and non-volatile particulate matter ($PM_{2.5}$). Moreover, travelers may avoid certain routes that are more vulnerable to climate change effects, e.g., flooding, which could increase congestion on more robust alternate routes. In general, transportation agencies should investigate the regional climate change effects to understand clearly how these effects may affect traveler mode and route choice, and thus affect operations on a day-to-day basis. Some regions may expect alternate, non-driving modes to see increased ridership, overall. In this case, an increased operations focus on traveler information and resources for these modes may be in order. Other regions may expect a reduction in the use of alternate, non-driving modes. For this case, increased emphasis on carpooling and teleworking may be necessary to reduce impacts to highways.

Over time, climate change effects could cause long-term changes in travel behavior. Individuals or businesses may choose not to reside in low-lying coastal areas that are more vulnerable to sea level rise and increased storm surge associated with coastal storms and hurricanes. Given individuals' inclination to live near the coast despite the risk of hurricanes, it is uncertain whether this inland shift will occur, or whether individuals will choose to adapt in place. Regardless, transportation agencies should be mindful of the potential for long-term travel shifts, in addition to those that occur in the short-term.

3.4. Changes to Freight Transportation

In addition to the impacts that climate change effects are expected to have on the transportation network as a whole, there might be unique impacts to freight transportation. Multiple climate change effects could disrupt inland waterways, impacting freight flows and diverting freight to trucks on highways. Roadways with pavements affected by increased temperatures might require dynamic or seasonal truck weight or speed restrictions for specific roadways or different regulations for the industry as a whole. Expected climate change effects to freight transportation are presented in Table 4.

First, there are several potential climate change effects that might affect shipments on inland waterways. Increased occurrence of flooding and drought, coupled with changes in seasonal precipitation and river flow patterns, could disrupt freight flows to other inland waterways, such as the Mississippi and Ohio Rivers, which might add trucks to highways. Lower water levels in the Great Lakes might restrict boat access to ports and shipping channels in that system. The 2007 Commodity Flow Survey showed that about 423 million tons of goods (3% of all tonnage) and about 176 billion ton-miles (5% of all ton-miles) were carried by water, with the Mississippi River system being the most active freight waterway (RITA, 2007). Either high water or low water could affect shipping, but reduced reliability of this mode might also encourage a shift to trucks or rail.

Table 5. Climate Change Effects to and Potential Responses by Freight Transportation

Climate Change Effect	Freight Transportation Response
Climate Event Impacts	
Increased frequency, duration, and intensity of droughts; increased coastal and inland flooding	Restricted access to ports and shipping channels for inland waterways
	Mode shift from inland waterways to trucking due to reduced reliability
Longer duration and/or shifting of springtime freeze/thaw period	Mandatory freight diversion to more robust alternate routes
Increase in magnitude and duration of severe heat waves	Mandatory freight diversion to more robust alternate routes or modes
	Dynamic or seasonal restrictions for trucks or rail during times of high heat, reducing either acceptable speed or weight
	Policy and regulation changes to restrict truck size and weights for the entire roadway network or specific highway classes
	Deploy "quick maintenance" patrols to address potholes and buckling issues

Increases in average air temperature during the winter are likely to influence subgrade freeze/thaw cycles. As mentioned previously, a frozen subgrade provides a solid foundation for heavy vehicles on roadways, weight restrictions may be required for roadways with a poor subgrade to prevent potholes and rutting. Areas that experience more days above freezing during the winter may have to extend or shift the period of time during which weight restrictions are imposed.

As mentioned previously, the impact of severe heat waves on pavements that were not designed to withstand such heat might cause potholes or buckling issues. Although this issue might be addressed in the long-term as new pavement designs are implemented to withstand these higher temperatures, in the short-term there may be some roadways in which this remains an issue. For these roadways, there may be a need to implement dynamic or seasonal restrictions for trucks during times of high heat, reducing either acceptable truck speed or weight. Currently, truck weight or size restrictions are not uncommon for routes with deficient infrastructure, e.g., bridges and tunnels, and similar restrictions might need to be imposed for affected roadways using dynamic or static signage. Alternatively, changes to policy and regulations could be implemented to restrict truck size and weights for an entire roadway network or for specific highway classes. Such restrictions may also affect freight transport through trains.

4. Agency Considerations for Assessing Vulnerability of Transportation Systems and Making O&M Climate-Resilient

Sections 2 and 3 illustrated the climate change effects and the potential impacts on operating agencies. While adaptation to climate change will involve the entire transportation industry and stakeholders, ultimately many of the changes that will occur will manifest themselves as challenges to personal and freight mobility and safety. However, the nature of these changes will vary based on the region and the agency. While many questions remain, agencies with operational responsibility need to assess vulnerabilities for their regions and develop new capabilities and processes to adapt to climate change. Primarily, agencies need to increase levels of capability for dealing with climate events and plan for emerging changes due to long-term climate trends. Each of these is discussed in more detail.

4.1 Increasing capability to manage more frequent and more severe climate events

As section 2.2 describes, climate change will manifest itself in a potential increase in the number and nature of severe weather events. Established approaches and practices provide the tactics to ensure a reasonable level of service to the travelers. However, there is a limit to the effectiveness of these tactics based on the type and intensity of the weather events. For more large-scale but rare events, the volumes and the geographical and temporal scales of the operational responses overwhelm the traditional tactics used for routine events. In these situations, there are short-term behavioral changes by travelers (people reacting to mandatory hurricane evacuations, trying new roads, for example) and multiple points of system failures. During these events, agencies try to ensure that their systems absorb the shocks in a resilient manner without complete failure. With the potential of more frequent and more severe events in locations, requires an agile approach to operations. Characteristics in an agency for agile emergency transportation operations may include:

Increased and flexible monitoring systems - Most operations adaptation actions rely on improved situational awareness at an operating agency for improved monitoring of flash floods, bridge scour, road weather conditions, landslides, etc. Traditionally, fixed detection infrastructure has been the dominant approach to collect situational data. The challenge posed by climate change is that potentially, a greater and different set of locations will need to be monitored over time. While monitoring using fixed infrastructure will continue to play an important role, it is unlikely that an agency can greatly increase the coverage of such sensors. Mobile observations promise to fill that coverage gap for operating agencies, from agency fleet vehicles (such as maintenance trucks) or from private sector data. Another source is crowd-sourced data directly from the traveling public. Emerging approaches using social media during disaster and even routine weather events promise to greatly increase the coverage and situational awareness of the operating agency.

Integration of sophisticated weather information at transportation operations centers – Better decision-making during weather events requires not only understanding of the current conditions but also the forecast conditions. Precipitation start times, intensity, and types are important determinants in the tactics used for responses. Sophisticated weather forecasting models are constantly being refined to provide transportation-specific forecasts including road weather conditions at the right times and geographic scales. However, integration of such data in TMC is both hampered by the lack of awareness of the existence of such tools, and the difficulty in interpreting the forecasts to make operational decisions.

Greater intra and inter-agency cooperation - Transportation operations in recent years is truly a collaborative activity involving multiple agencies and jurisdictions. Larger events today involve activation of multi-agency emergency operations centers (EOCs). Current levels of capabilities must continue to grow to deal with the anticipated impacts.

Rapid mobilization and deployment teams – One of the biggest challenges to operations is the multiple points of system failures that exist during weather events. Especially for flash flooding and other impacts with very short lead times, the ability to rapidly deploy operational personnel for site management, maintenance, debris removal, and other recovery efforts are critical.

Flexible resource allocations – Greater variability in the type, nature and intensity of events also poses a unique challenge to budget resources. While this is easier said than done in an agency framework, static or silo-ed resource allocation approaches for operations might be over-funded in one year and under in others. Different needs between winter seasons might change the mix of how resources are allocated between jurisdictions.

Cross-training of staff - Since a greater number of events are expected and it is unlikely that staffing levels are going to increase at agencies, cross-training of transportation agency staff in emergency transportation operations becomes critical.

Training for unusual events - While still related to training, climate change is going to force agencies to respond to conditions that either occur very rarely or have never occurred in their regions. Training programs for emergency transportation operations need to focus on what would be considered unusual events in regions.

4.2 Planning for Operations in an uncertain future

The major challenge to agencies is how to plan for operations an uncertain future in a fiscally responsible manner. The relationship between the probability of an impact and the severity of impact versus the cost of investment continues be a difficult equation for agencies to solve. Given the latency from planning to implementation inherent in transportation operations (i.e., future operations are dependent on plans being considered today), there is an urgency to include climate change considerations in transportation plans today. System Operations historically has been a reactive industry. Often, a disaster provides the impetus for various operational capability improvements in a region. However, with diminishing fiscal constraints and a higher expectation from the traveling public, agencies no longer can afford to be reactive, and they need to assess actively how their systems are vulnerable to climate change.

Recent guidance and best practices are starting to emerge for planning for operations with an emphasis on system performance and driven by regional objectives. Driven by policy objectives such as congestion, safety, economic competitiveness, agencies are starting to better integrate operations into the planning process. Into this paradigm of objective-driven performance-based planning, climate change considerations have to be included. While many questions remain, two main actions are worth investigation as part of planning for operations efforts

Introducing risk assessment in transportation operations planning – Risks are an inherent part of transportation planning. However, assessing the risk posed by climate change to operations is new to the field. Climate change risks vary across regions and times, they vary in scale of impacts, and there is inherent natural and modeling uncertainty in future climate scenarios. The assessment approaches may vary from qualitative assessments to quantitative but primarily needs to answer questions regarding levels of likelihood and levels of consequence of the event. Good examples for such risk assessments in transportation that might translate to this field may be found in States with high seismic activity such as California and Washington.

Integration with other adaptation efforts – An immediate approach for operating agencies is to be part of statewide climate change action plans and adaptation efforts. Integration of operations considerations such as evacuation procedures, alternate routings, monitoring systems all are worthwhile considerations as part of the larger State climate change action plans.

5. Conclusions

The paper begins to explore the effects of climate change on operations. Effects are going to manifest both due to specific weather events/phenomena but also long term trends in air temperature. The link between weather events and climate is not simplistic, but recent severe weather events point to the challenges posed to operations. The scale, frequency, and intensity of events will change how operation agencies are organized and function in the country. Similarly, long-term trends will result in behavior changes and changes to freight operations that may tax operating agencies in different ways. While many questions remain, the role of operations as part of overall climate change adaptation needs to be emphasized.

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Appendix A – Climate Change Impact Tables

Table A.1. Transportation-Relevant Climate Change Effects Associated with Climate Trends.

Category	Climate Impact	Region	Date Range	Certainty	Reference
Air Temperature	Increase in average annual air temperature	CONUS	2001-2100	Very likely	Christensen et al., 2007
		CONUS	2010-2029; 2040-2059	Very likely	ICF International, 2010
	Increase in diurnal air temperature ranges	Western U.S.	2001-2100		Christensen et al., 2007
	Increase in electricity demand for air conditioning during summer and decrease in electricity demand for heating in winter	CONUS	2001-2100	High confidence	Field et al., 2007
	Increase in average winter temperatures	CONUS	2010-2029; 2040-2059	Very likely	ICF International, 2010
Precipitation	Increase in average annual precipitation	CONUS except south and southwestern U.S.	2001-2100	Very likely	Christensen et al., 2007
		Northeast U.S. Northwest U.S. Midwest U.S.	2010-2029; 2040-2059	Very likely	ICF International, 2010
		Hawaii	2040-2059	Very likely	ICF International, 2010
		U.S. Great Plains	2010-2029	Very likely	ICF International, 2010
		U.S. Great Plains	2040-2059	Likely	ICF International, 2010
	Decrease in average annual precipitation	Southwest U.S.	2001-2100	Likely	Christensen et al., 2007
	Increase in average precipitation during winter	Northern U.S.	2001-2100		Christensen et al., 2007
		Northeast U.S. Northwest U.S. Southwest U.S. U.S. Great Plains Midwest U.S.	2010-2029; 2040-2059	Very likely	ICF International, 2010
	Decrease in average precipitation	Southern U.S.	2001-2100		Christensen et al., 2007

Category	Climate Impact	Region	Date Range	Certainty	Reference
	during summer	Northwest U.S. Southwest U.S. Southeast U.S. U.S. Great Plains Midwest U.S. Hawaii	2010-2029; 2040-2059	Very likely	ICF International, 2011
	Change in seasonal precipitation and river flow patterns	CONUS	2001-2100		Field et al., 2007
Sea Level and Coastal Impacts	Rise in sea level	Atlantic and Pacific coasts of U.S.	2001-2099	High confidence	Meehl et al., 2007
	Accelerated coastal erosion	Atlantic and Pacific coasts of U.S.	2001-2100	Likely	Field et al., 2007
Freshwater Resources	Increase in precipitation runoff	CONUS	2001-2100		Field et al., 2007
	Increase in length of erosion season and enhancement of inland erosion	CONUS	2001-2100	Likely	Field et al., 2007
	Decrease in water quality	CONUS	2001-2100	High confidence	Field et al., 2007
	Decrease in snow season length and snow depth	CONUS	2001-2100	Very likely	Christensen et al., 2007
	Earlier melting and significant reductions in snowpack	Rocky Mountains	2001-2100	High confidence	Field et al., 2007
	Lower water levels	Great Lakes	2001-2100	High confidence	Field et al., 2007
	Decreased recharge of heavily utilized groundwater-based systems	Southwest U.S.	2001-2100	High confidence	Field et al., 2007
	Local, regional, or state-wide shortages of drinking water	CONUS	2001-2017		Field et al., 2007
	Reduction in winter ice cover	Great Lakes	2001-2100		USGCRP, 2009
	Shorter ice cover period in shallow inland lakes	Northern U.S.	2001-2100		Field et al., 2007

Category	Climate Impact	Region	Date Range	Certainty	Reference
	Decrease in surface and bottom water temperatures of lakes, reservoirs, rivers, and estuaries	CONUS	2001-2100		Field et al., 2007
Human Health Impacts	Increase in concentrations of tropospheric (surface) ozone and particulate matter ($PM_{2.5}$)	CONUS	2001-2050		Field et al., 2007
	Increase in respiratory illness	CONUS	2001-2100		USCCSP SAP 4.6, 2008
	Increase in pollen production	CONUS	2001-2100	Likely	Field et al., 2007
	Increase in heat-related deaths	CONUS	2001-2100		USCCSP SAP 4.6, 2008
	Increase in extent of Lyme disease	Northern U.S.	2001-2080		Field et al., 2007
Ecological Impacts	Increase in length of growing season	CONUS	2001-2100	Medium confidence	Field et al., 2007
	Expanded range of invasive species (general)	CONUS	2001-2100		USCCSP SAP 4.4, 2008

Table A.2. Transportation-Relevant Climate Change Effects Associated with Distinct Climate Events.

Category	Climate Impact	Region	Date Range	Certainty	Reference
Air Temperature Events	Increase in intensity, frequency, and duration of heat waves	CONUS	2001-2100	High confidence	Field et al., 2007
		Midwest U.S.	by 2100		USGCRP, 2009
	Increase in frequency and duration of extreme high temperature events and decrease in extreme low temperature events	CONUS	2001-2100		Christensen et al., 2007
Precipitation Events	Increase in intensity and frequency of extreme precipitation events	CONUS	2001-2100		Christensen et al., 2007
	Greater variability in precipitation events	CONUS	2001-2100		Meehl et al., 2007
		Southwest U.S.			USGCRP, 2009
Storms and Coastal Flooding	Slight poleward shift in storm tracks of extra-tropical cyclones	Mid-latitudes (30-60 °N)	2001-2100		Christensen et al., 2007
	Increase in intensity but reduction in frequency of extra-tropical cyclones	Mid-latitudes (30-60 °N)	2001-2100		Christensen et al., 2007; Meehl et al., 2007
	Increase in peak wind speeds and precipitation intensities of hurricanes	Atlantic and Eastern Pacific coasts of U.S.	2001-2102		Meehl et al., 2007
	Increase in frequency and severity of coastal flooding events	Atlantic and Pacific coasts of U.S.	2001-2100	Very high confidence	Field et al., 2007
	Increase in storm surge	Atlantic and Pacific coasts of U.S.	2001-2101	High confidence	Field et al., 2007
Wildfires	More frequent wildfires that cover larger geographic areas	CONUS	2001-2100		Field et al., 2007

Table A.3. Transportation-Relevant Climate Change Effects for Alaska.

Category	Climate Impact	Region	Date Range	Certainty	Reference
Air Temperature	Increase in average annual air temperature at higher rate than CONUS	Alaska	2001-2100	Very likely	Christensen et al., 2007
Precipitation	Increase in average annual precipitation	Alaska	2001-2100	Very likely	Christensen et al., 2007
		Alaska	2010-2029; 2040-2059	Very likely	ICF International, 2010
	Increase in frequency of very warm and wet winters and summers	Alaska	2001-2100		Christensen et al., 2007
	Increase in average precipitation during winter	Alaska	2010-2029; 2040-2059	Very likely	ICF International, 2010
Ice, Snow, and Permafrost	Thinning and reduction in extent and thickness of annually averaged Arctic sea ice	Alaska	2001-2100	Very likely	Christensen et al., 2007
	Warming, thawing, and decrease in areal extent of terrain underlain by permafrost	Alaska (Arctic)	2001-2100		Anisimov et al., 2007
	Reduction in seasonal snow cover on land	Alaska (Arctic)	2001-2101		Anisimov et al., 2008
Storms	Reduction in medium-strength extra-tropical cyclones	Poleward of 70 °N	2001-2100		Christensen et al., 2007

Table A.4. Likelihood Terminology for Climate Change Effects. [Adapted from Le Treut et al., 2007]

IPCC Likelihood Terminology	Likelihood of the Impact
Virtually certain	> 99% probability
Extremely likely	> 95% probability
Very likely	> 90% probability
Likely	> 66% probability
More likely than not	> 50% probability
About as likely as not	33 to 66% probability
Unlikely	< 33% probability
Very unlikely	< 10% probability
Extremely unlikely	< 5% probability
Exceptionally unlikely	< 1% probability

Table A.5. Confidence Terminology for Climate Change Effects. [Adapted from Le Treut et al., 2007]

IPCC 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

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