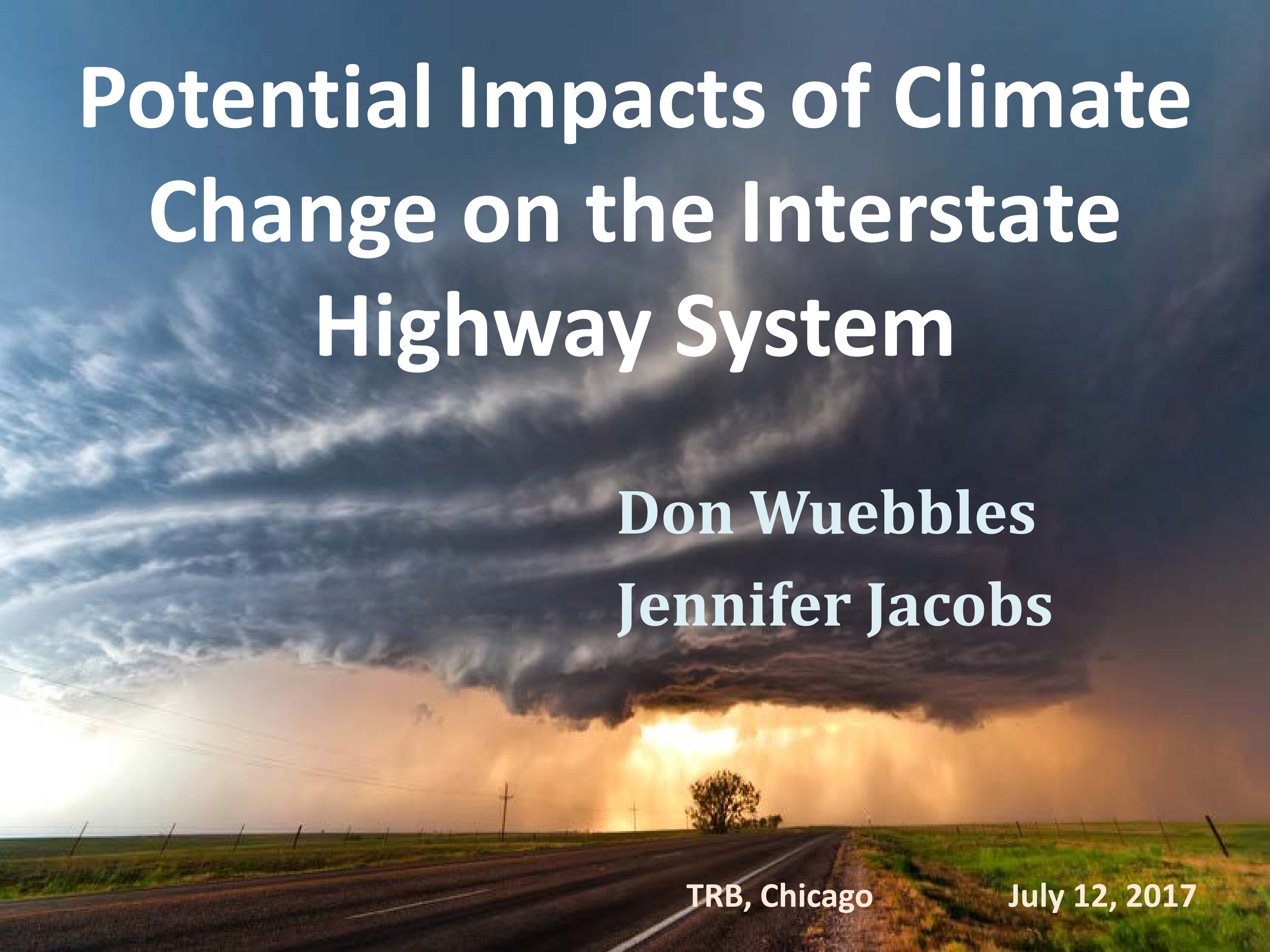


Potential Impacts of Climate Change on the Interstate Highway System

Don Wuebbles

Jennifer Jacobs

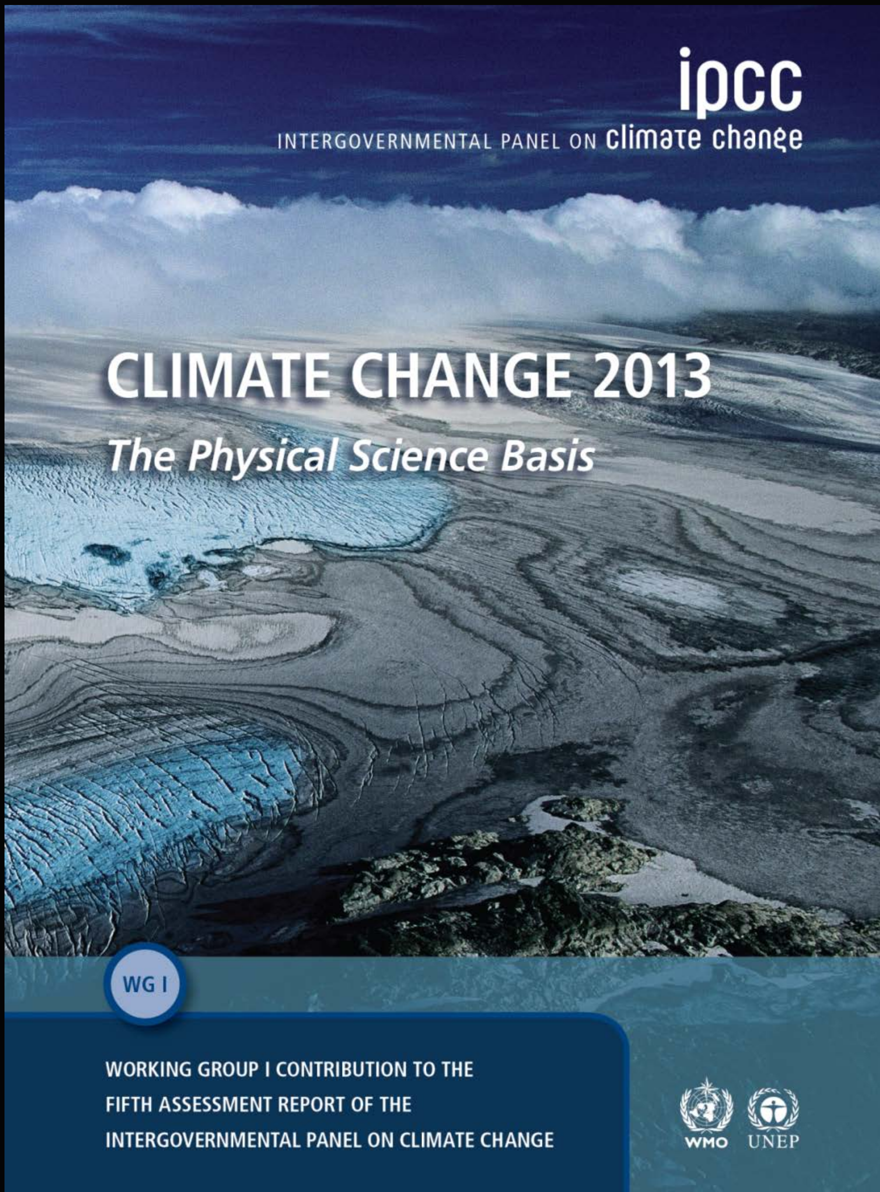
TRB, Chicago July 12, 2017

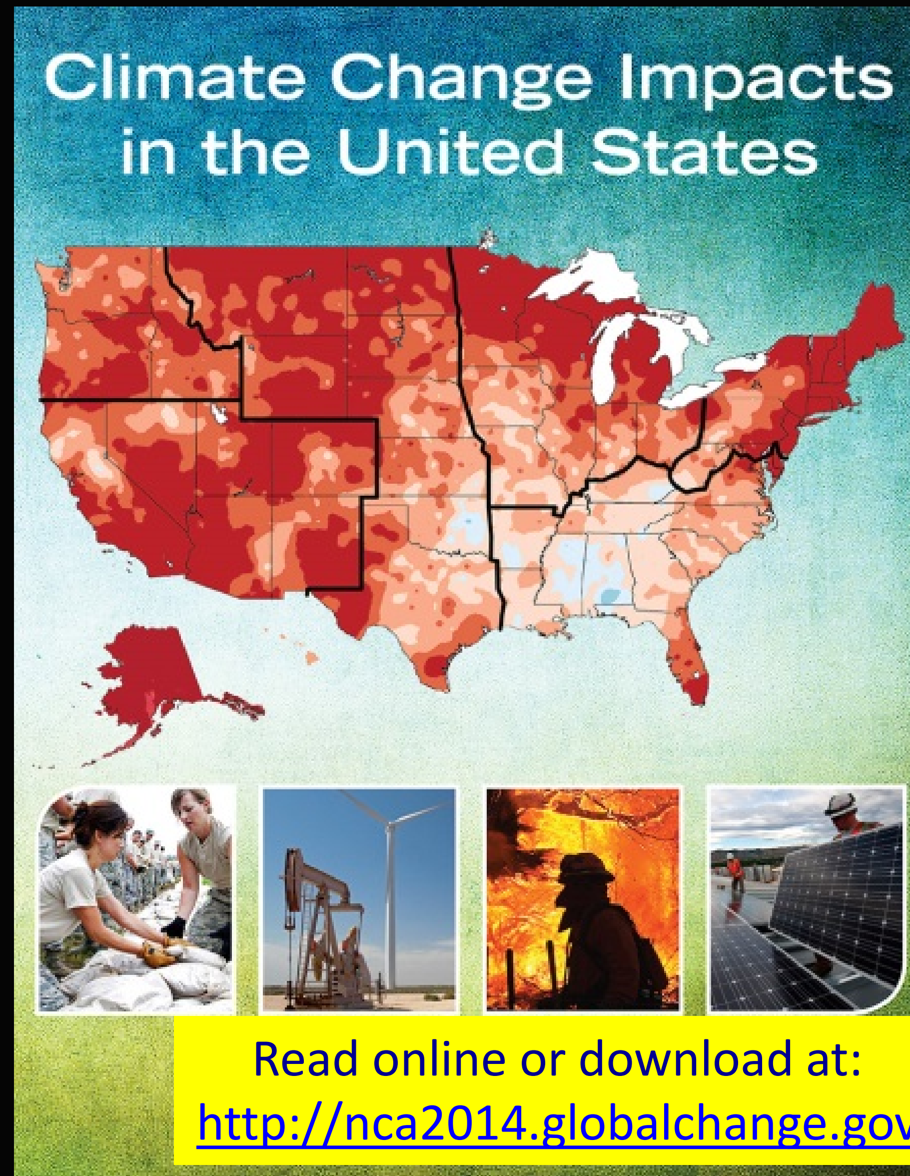
Introduction

- The U.S. Interstate Highway System is vital to the transport of people and goods across our country.
- One of the most important stresses on the IHS over coming decades is the changes occurring in the Earth's climate system.
- The transportation sector and the IHS are vulnerable to the changes occurring in climate.
- Many potential effects of climate change on the IHS are well understood.
- Given the long lifetime of IHS assets, effective resource investment and strategies would be well served by considering the likely effects to the IHS from climate change.

An Overview of Climate Change and its Impacts

Every 4-6 Years Scientists Assess the Science of the Changing Climate and its Societal Impacts



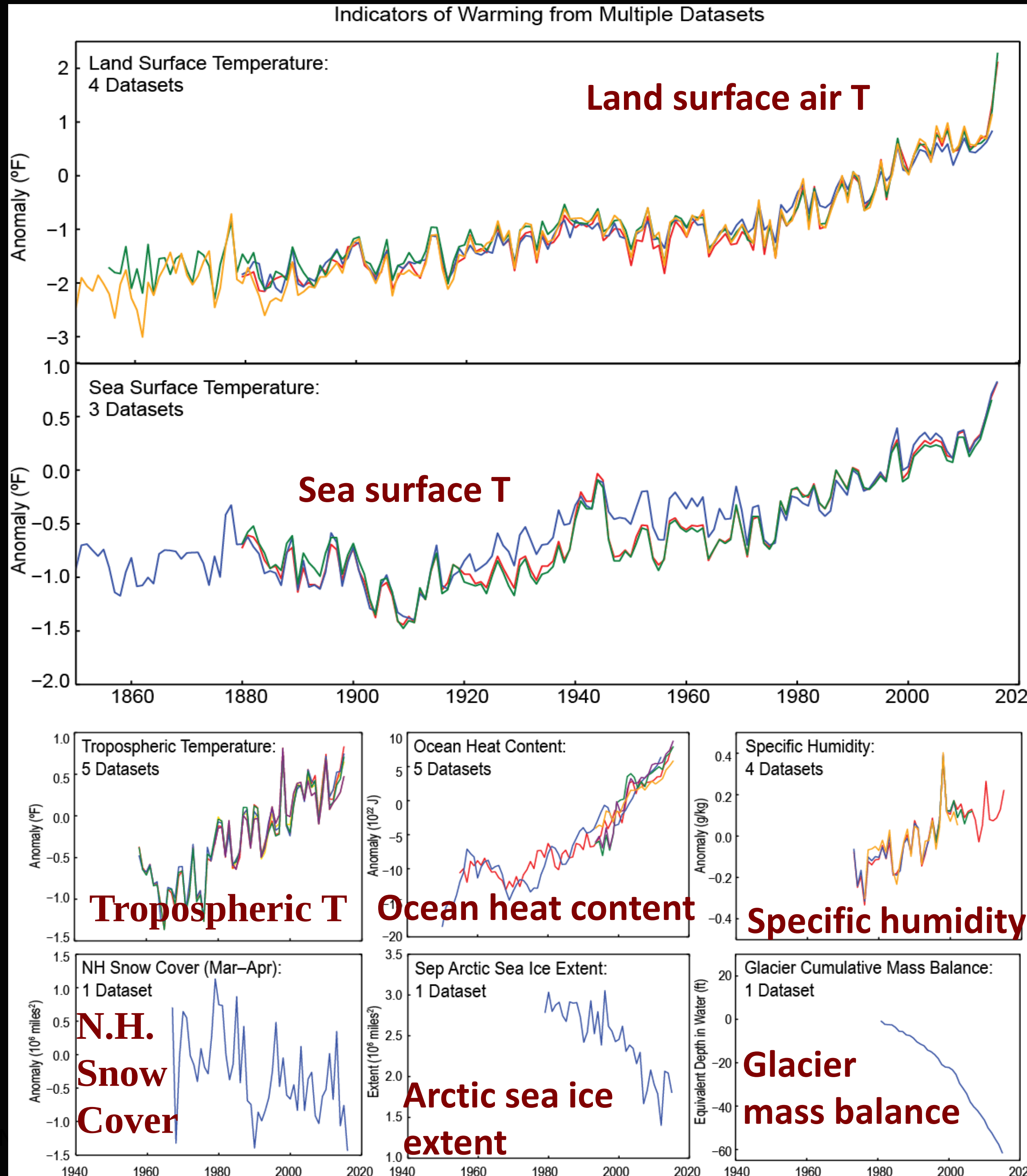


Read online or download at:
http://nca2014.globalchange.gov

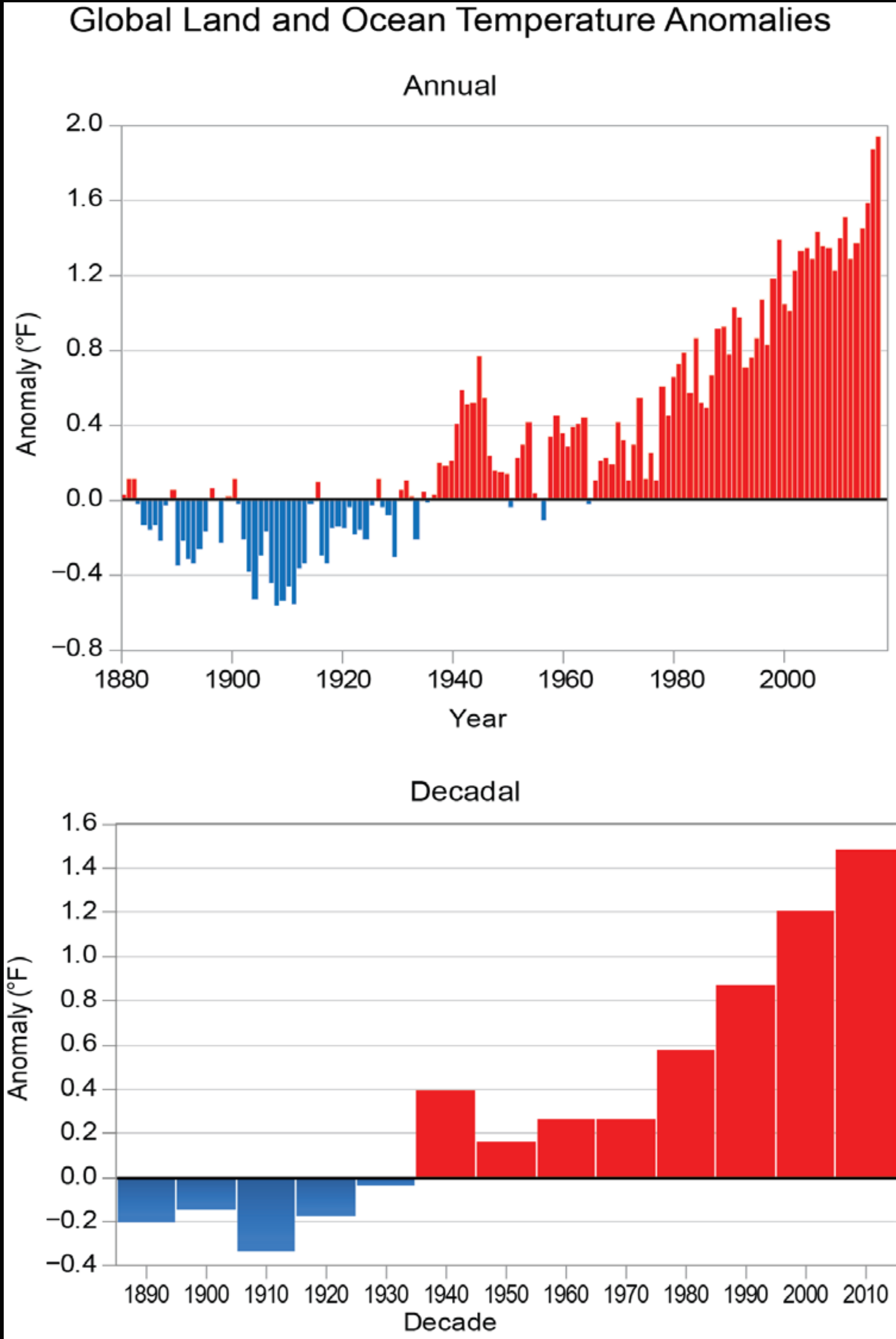
The Science: Key Findings

Our climate is changing,
It is happening now;
It is happening extremely rapidly;
Severe weather is becoming more intense;
Sea levels are rising;
It is largely happening because of human activities;
The climate will continue to change over the coming decades.

There are Many Observed Indicators of a Changing Climate



Updated Global Annually Averaged Temperature Record (from NOAA through 2016)



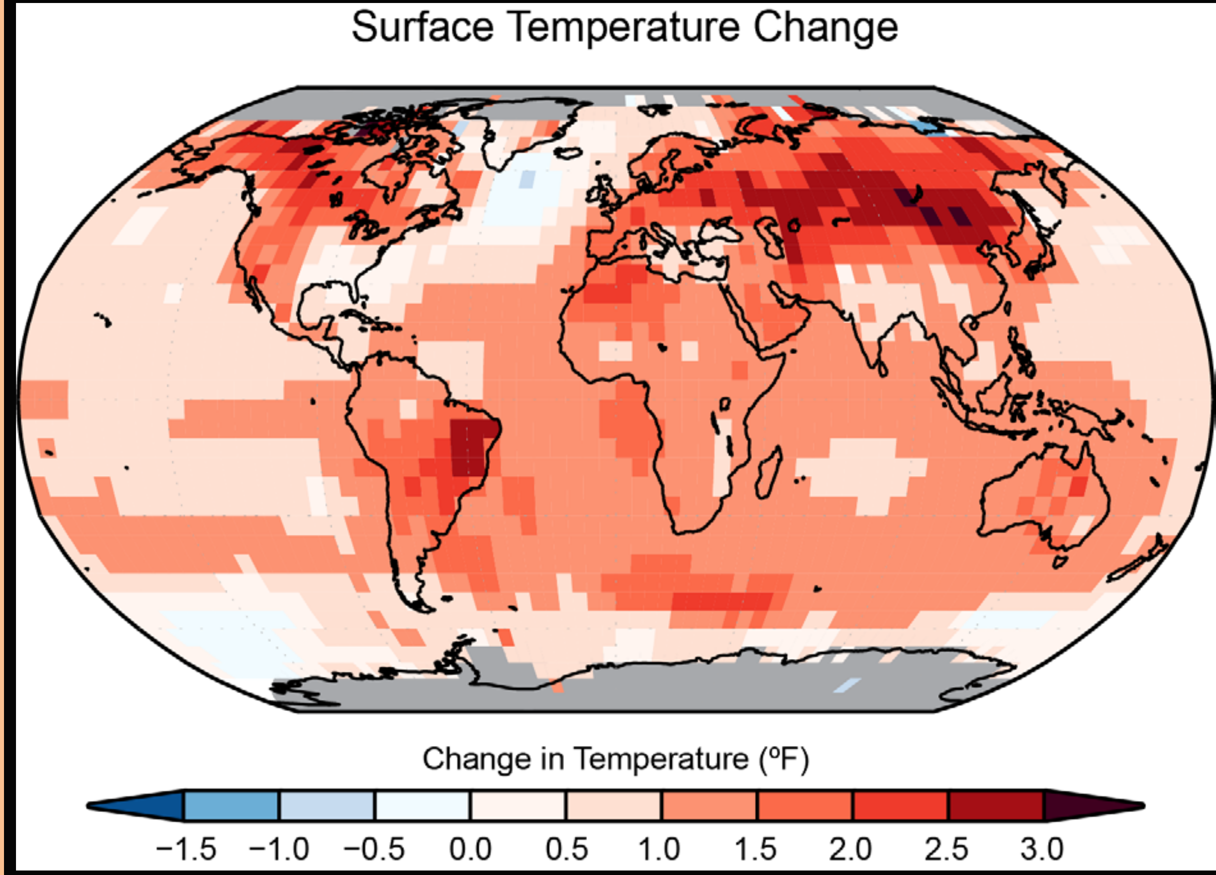
Relative to 1901-1960

Our climate continues to change rapidly

The global long-term warming trend is continuing.

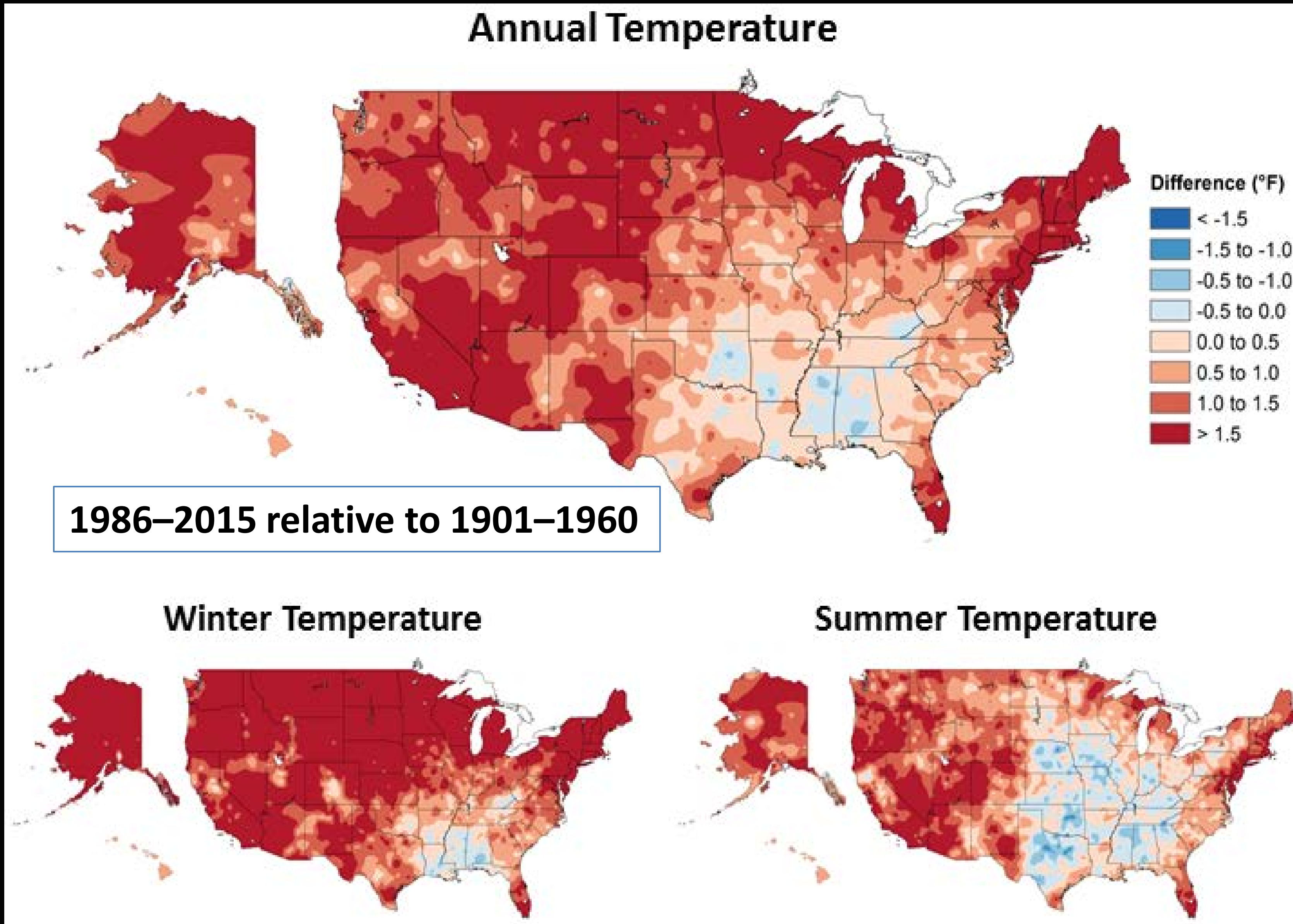
2016 was the warmest year on record, 2015 is 2nd and far surpassed 2014, which is 3rd.

Sixteen of the last 17 years are the warmest years on record for the globe.

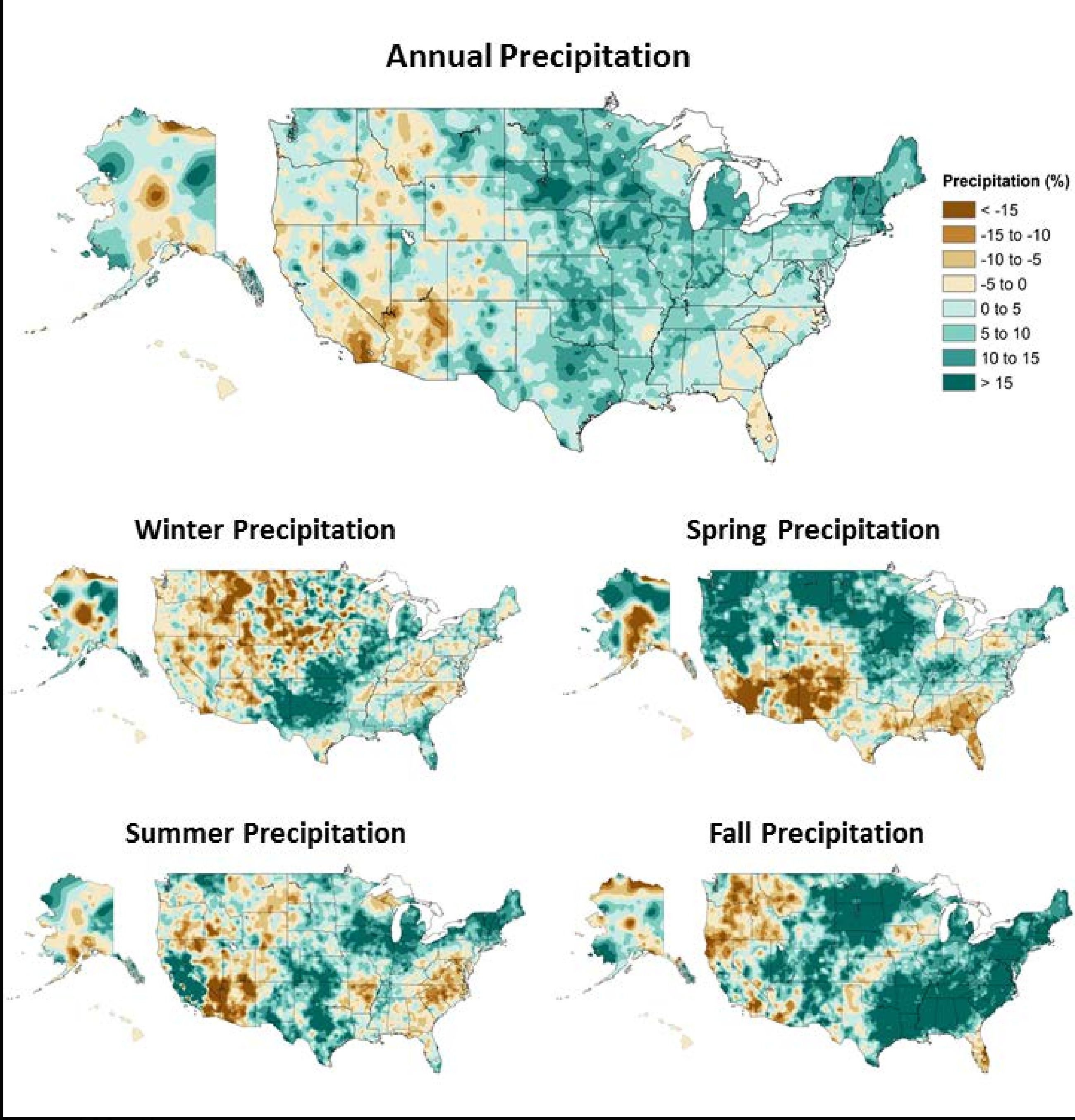


Temperature trends (change in ˚ F) for the period 1986-2015 relative to 1901-1960

Observed U.S. Temperature Change



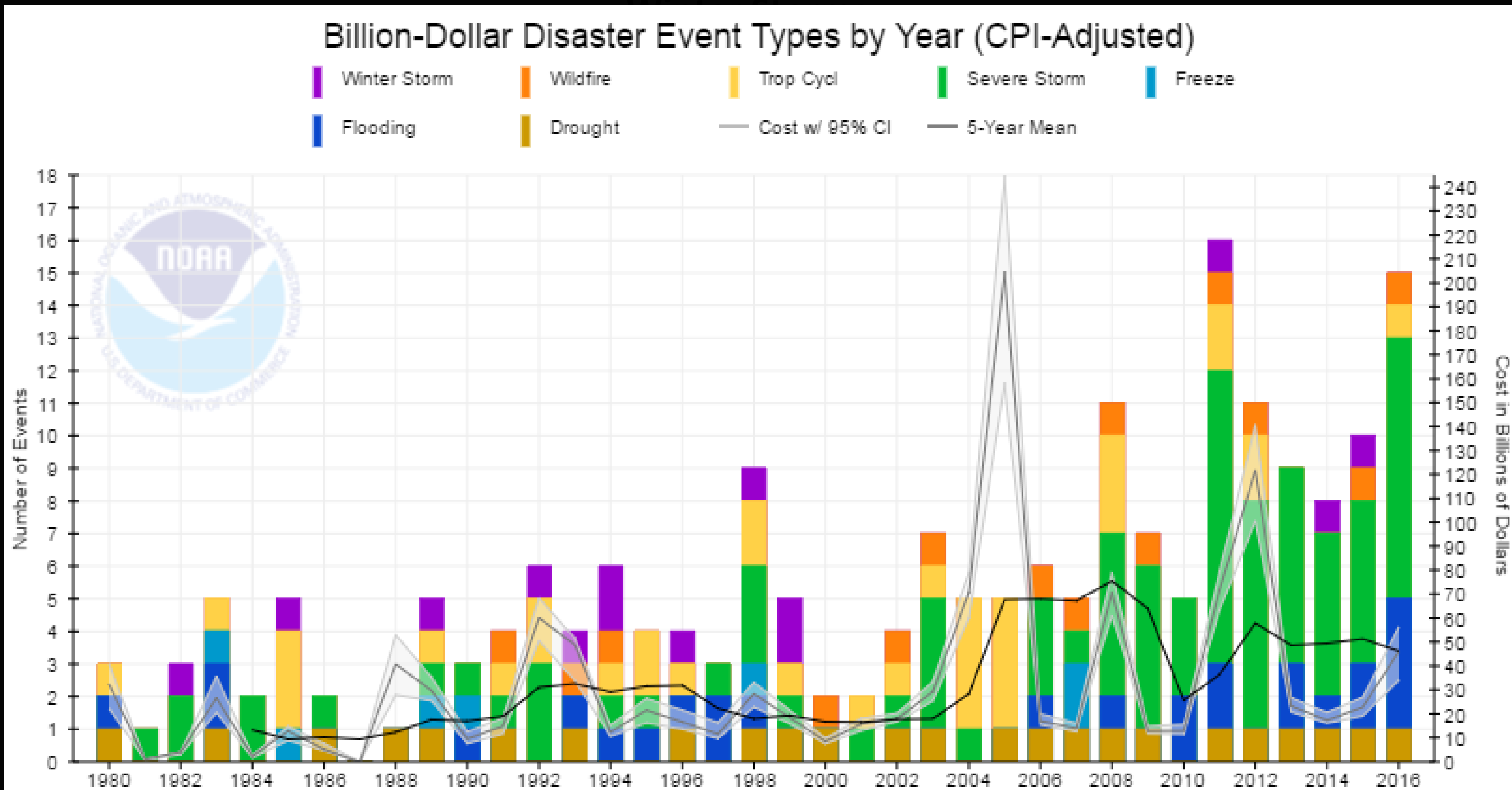
Observed U.S. Precipitation Change



We are seeing changing trends in extreme weather and climate events

The Nation is Climate Conscious… for Good Reason

NOAA Analyses of Billion-dollar weather / climate disasters frequency : 1980-2016*



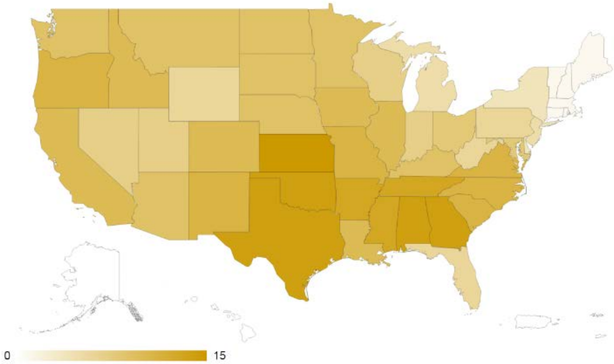
*203 weather and climate disasters reached or exceeded $1 billion during this period (CPI-adjusted)

Please note that the map reflects a summation of billion-dollar events for each state affected (i.e., it does not mean that each state shown suffered at least $1 billion in losses for each event).

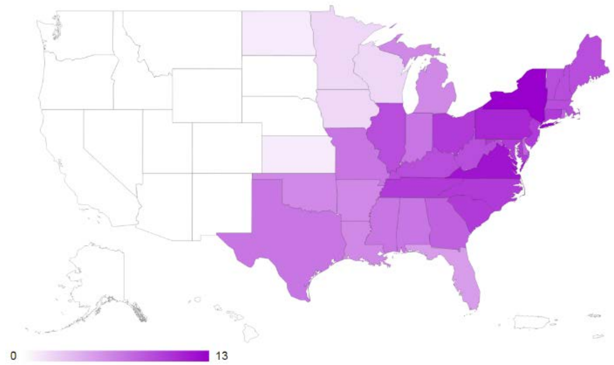
The Nation is Climate Conscious… for Good Reason

Billion-dollar weather and climate disasters frequency mapping: 1980-2016*

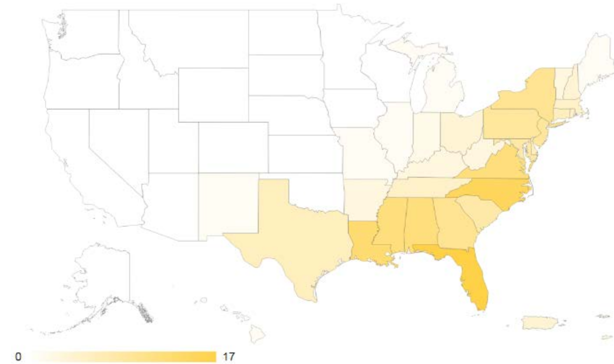
Droughts and Heat Waves



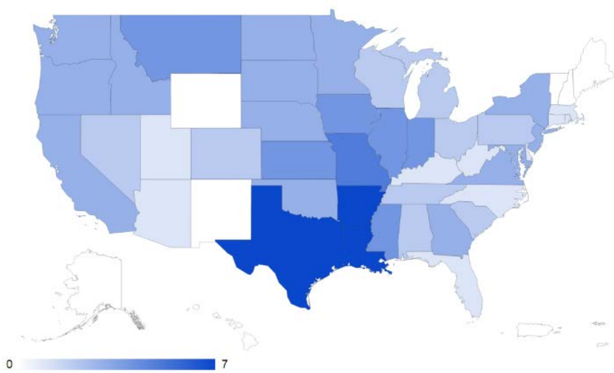
Winter Storms



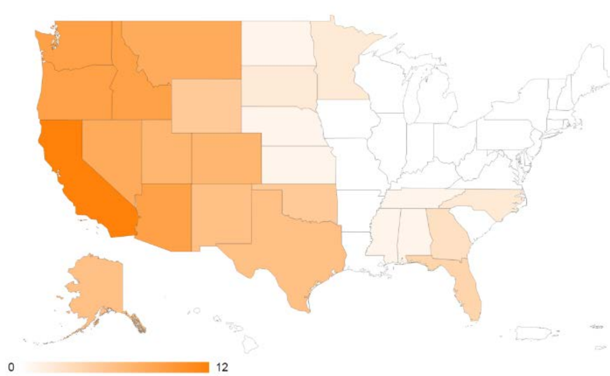
Tropical Cyclones



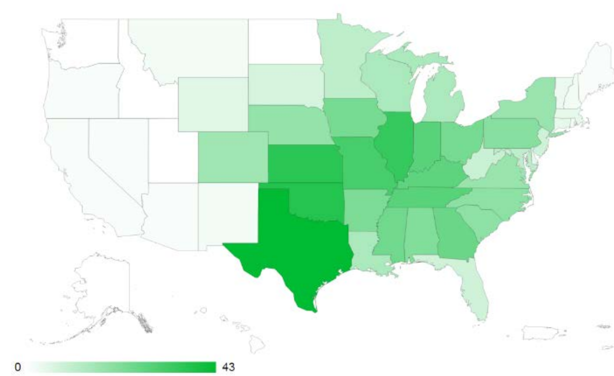
Flooding



Wildfires



Severe Local Storms



*203 weather and climate disasters reached or exceeded $1 billion during this period (CPI-adjusted)

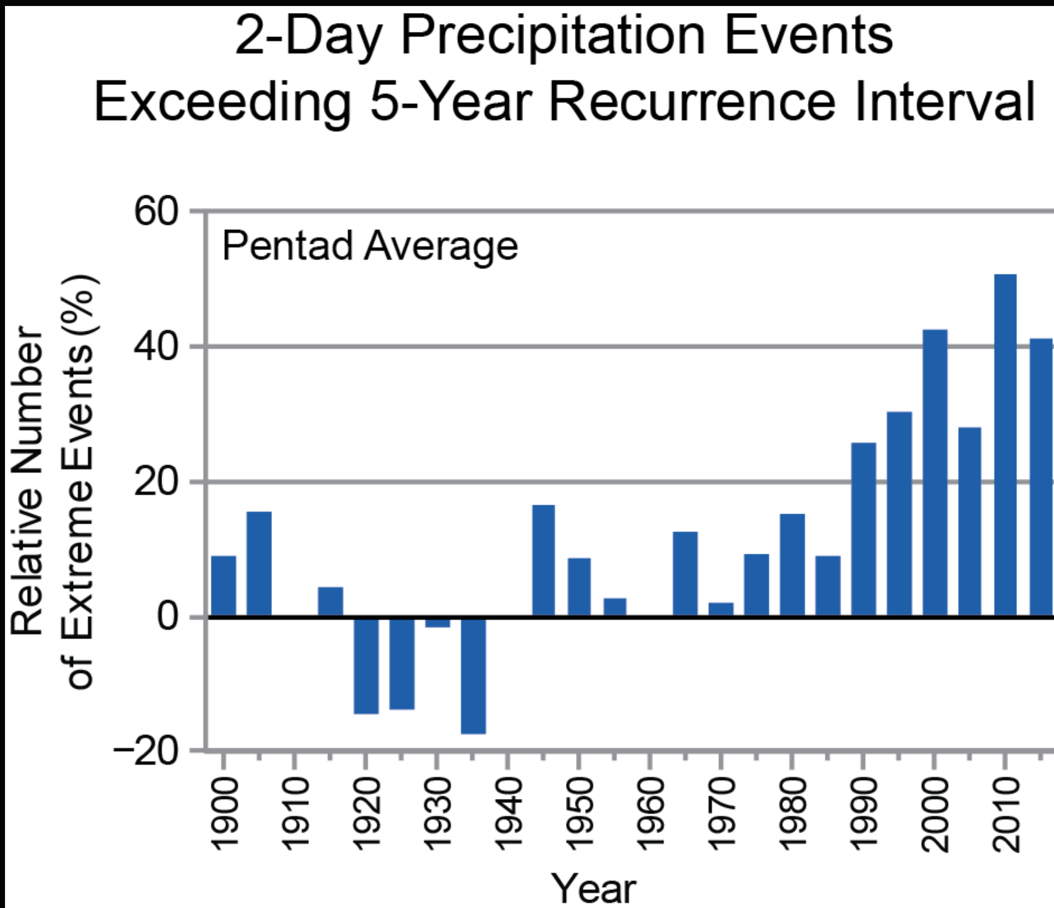
Please note that the map reflects a summation of billion-dollar events for each state affected (i.e., it does not mean that each state shown suffered at least $1 billion in losses for each event).

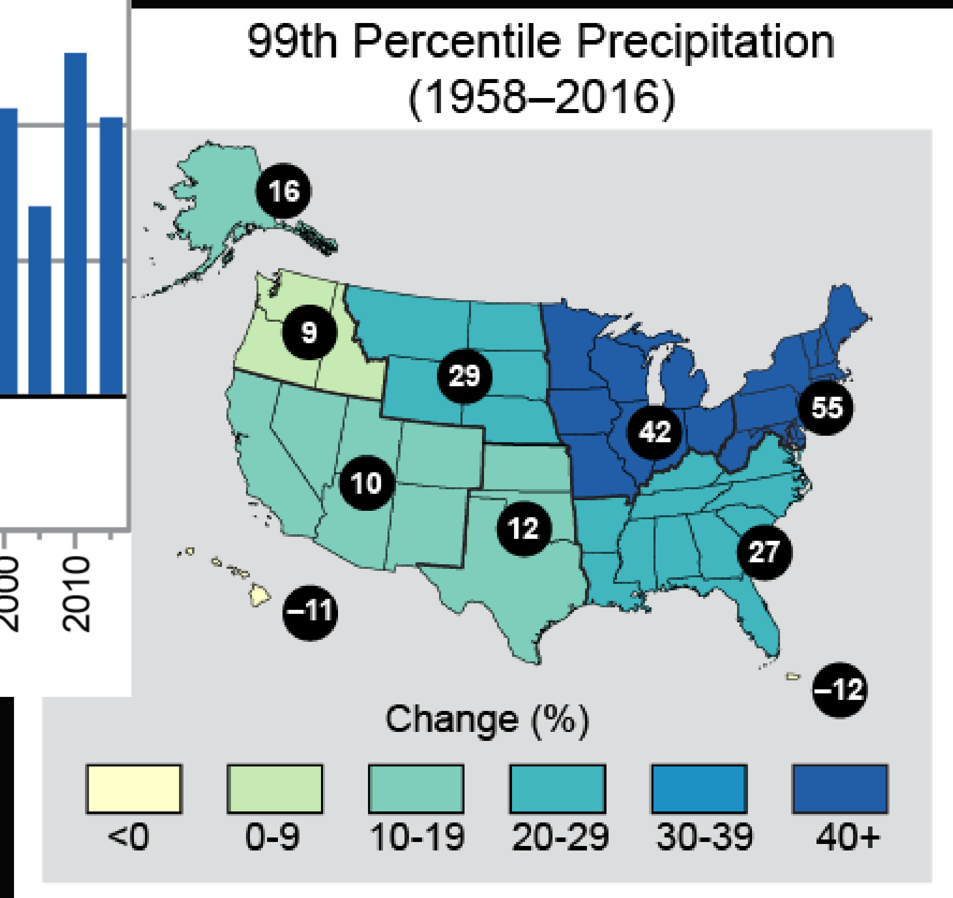
Certain Types of Extreme Events Show Important Trends

- **Heat waves are generally increasing in number and intensity; likely to become longer and more severe.**
- **Cold waves are decreasing.**
- **More precipitation coming as larger events.**
- **Increasing risk of floods in some regions (NE, MW).**
- **Droughts increasing in some regions (SW, SE).**
- **Increasing intensity of Atlantic hurricanes.**
- **Current analyses suggest tornadoes could become more intense. Hail also but more uncertain.**

These trends are expected to continue.

Extreme Precipitation Events are Increasing in Frequency and Intensity



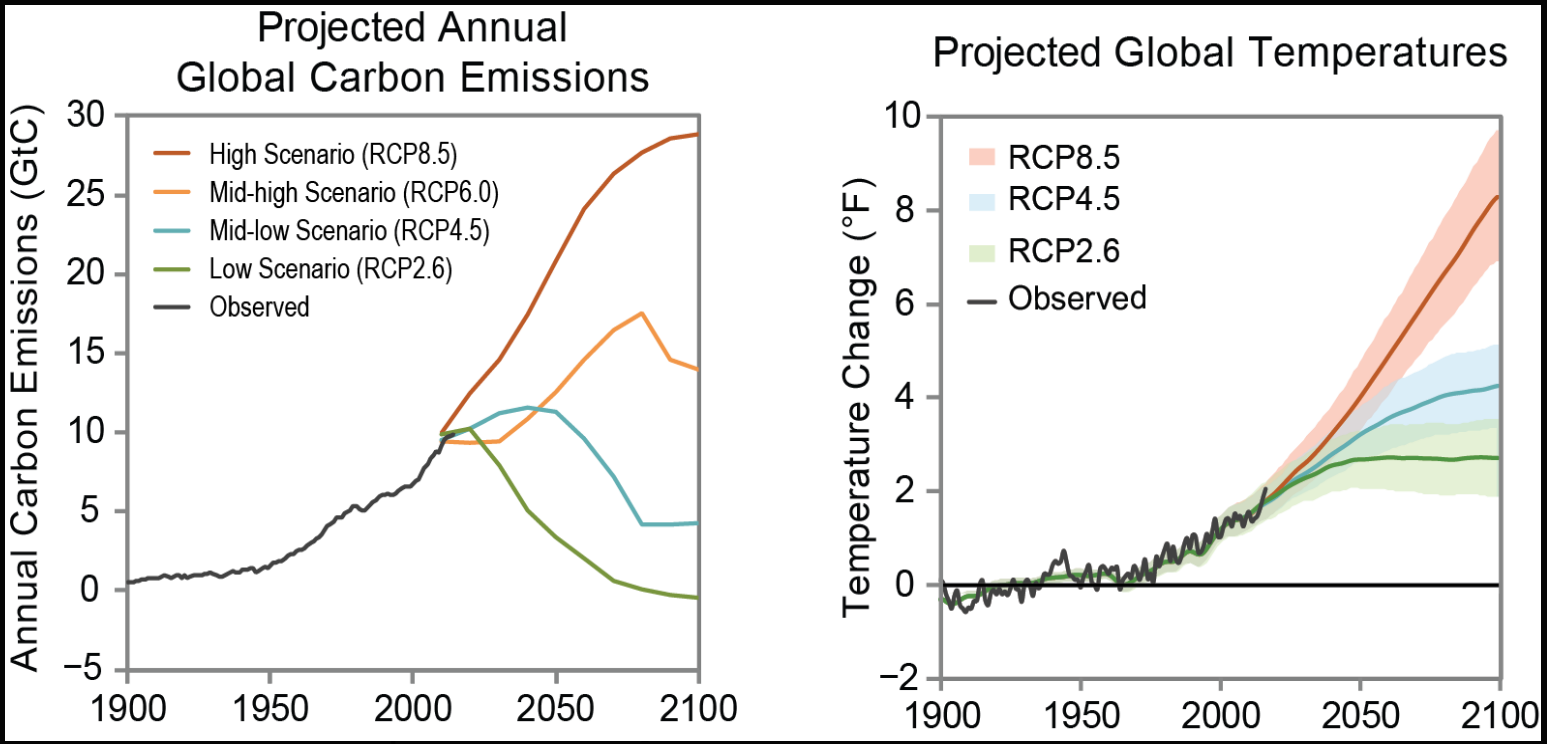


What is Causing the Observed Changes in Climate

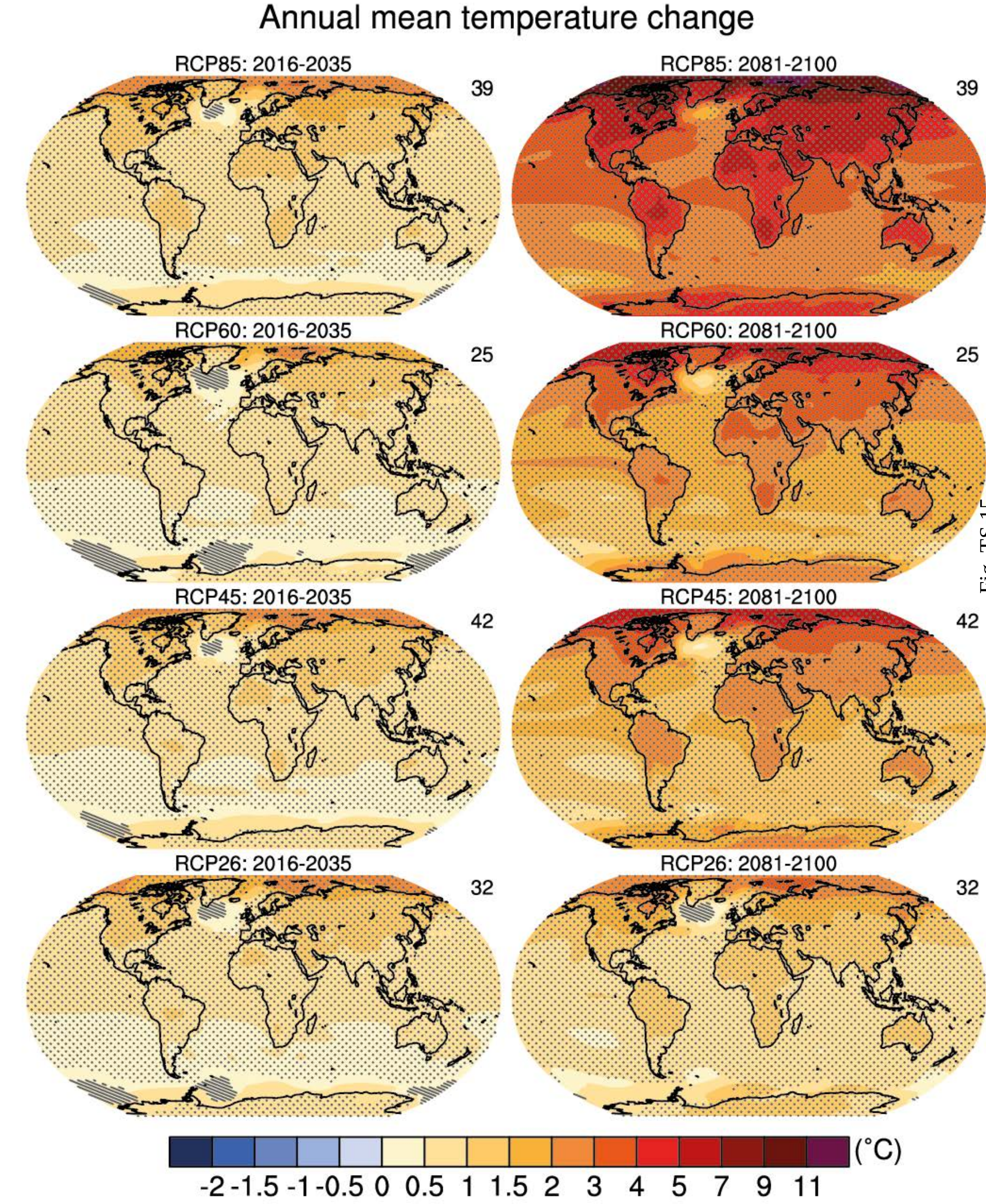
- **Many lines of evidence demonstrate that human activities, especially emissions of greenhouse gases, are primarily responsible for the observed climate changes.**
- **For the period extending over the last century, there are <u>no credible alternative explanations</u> supported by the extent of the observational evidence.**
  - Solar output changes and natural variability can only contribute marginally to the observed changes in climate over this time period.
  - No natural cycles are found in the observational record that can explain the observed changes in climate.

Climate will Continue to Change

- Globally climate is expected to continue to change over this century and beyond.
- The magnitude of climate change depends primarily on the additional amount of greenhouse gases emitted globally, and on the sensitivity of Earth's climate to those emissions.



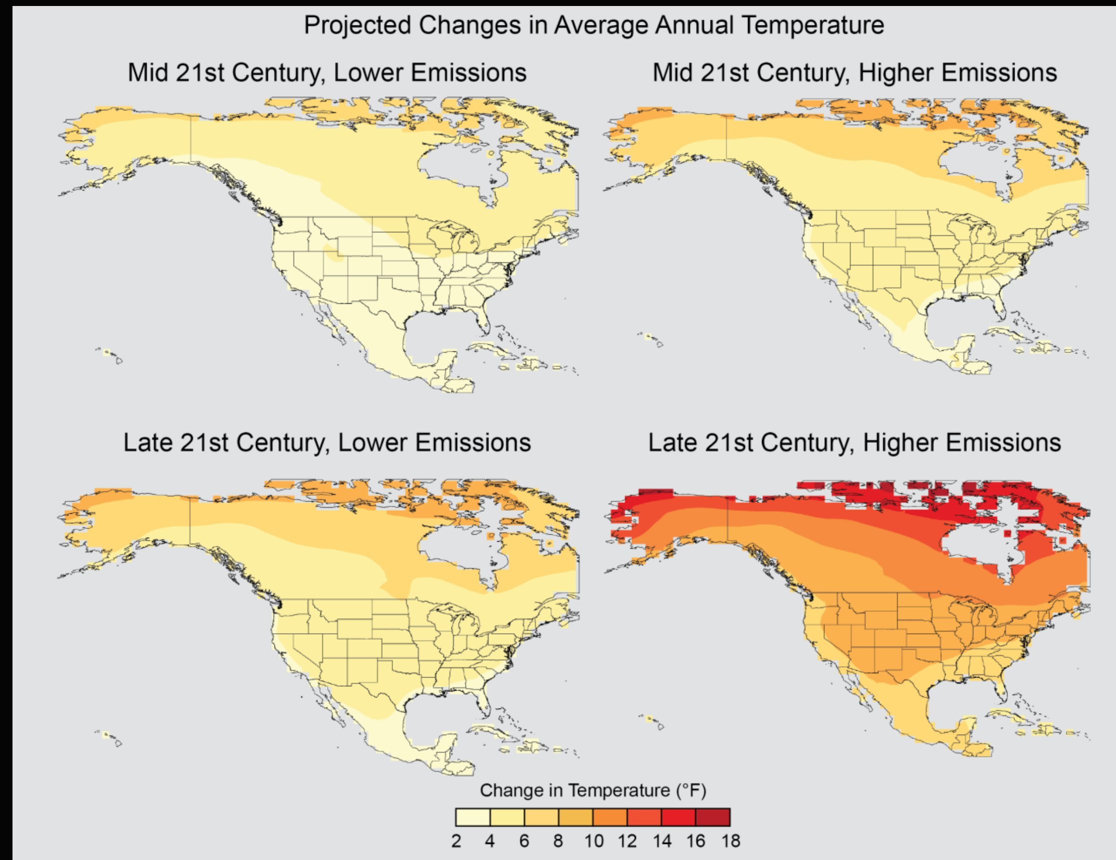
Global Temperature and Other Changes in Climate Depend on Future Emissions



Temperature Projections for United States

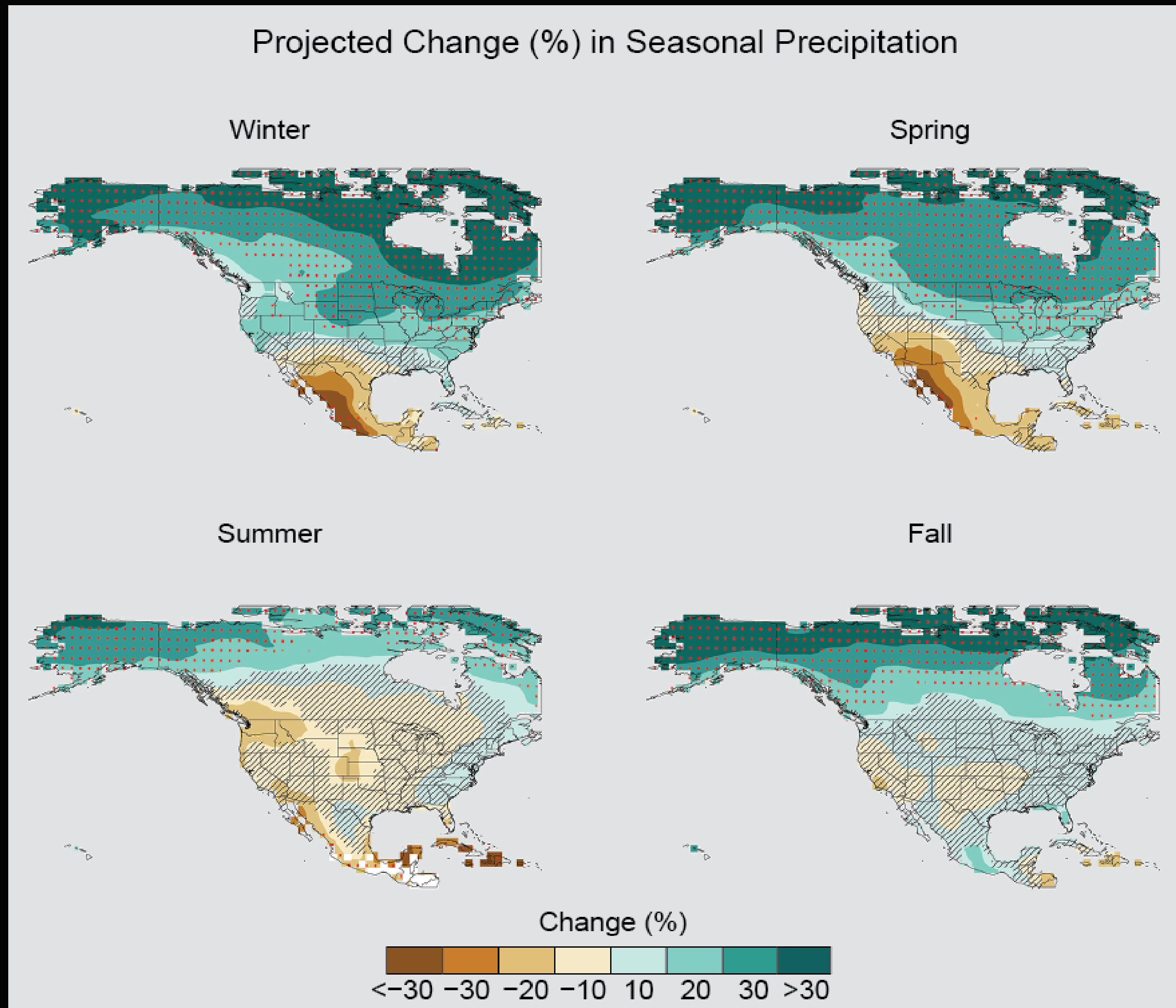
Increases of at least 2.5°F (1.4°C) are projected over the next few decades even under significantly reduced future emissions, meaning that the temperatures of recent record-setting years will become relatively common in near future.

Increases much larger by late century: 5.0°F [2.8°C] under a scenario with lower emissions and 8.7°F [4.8°C] under a higher scenario.



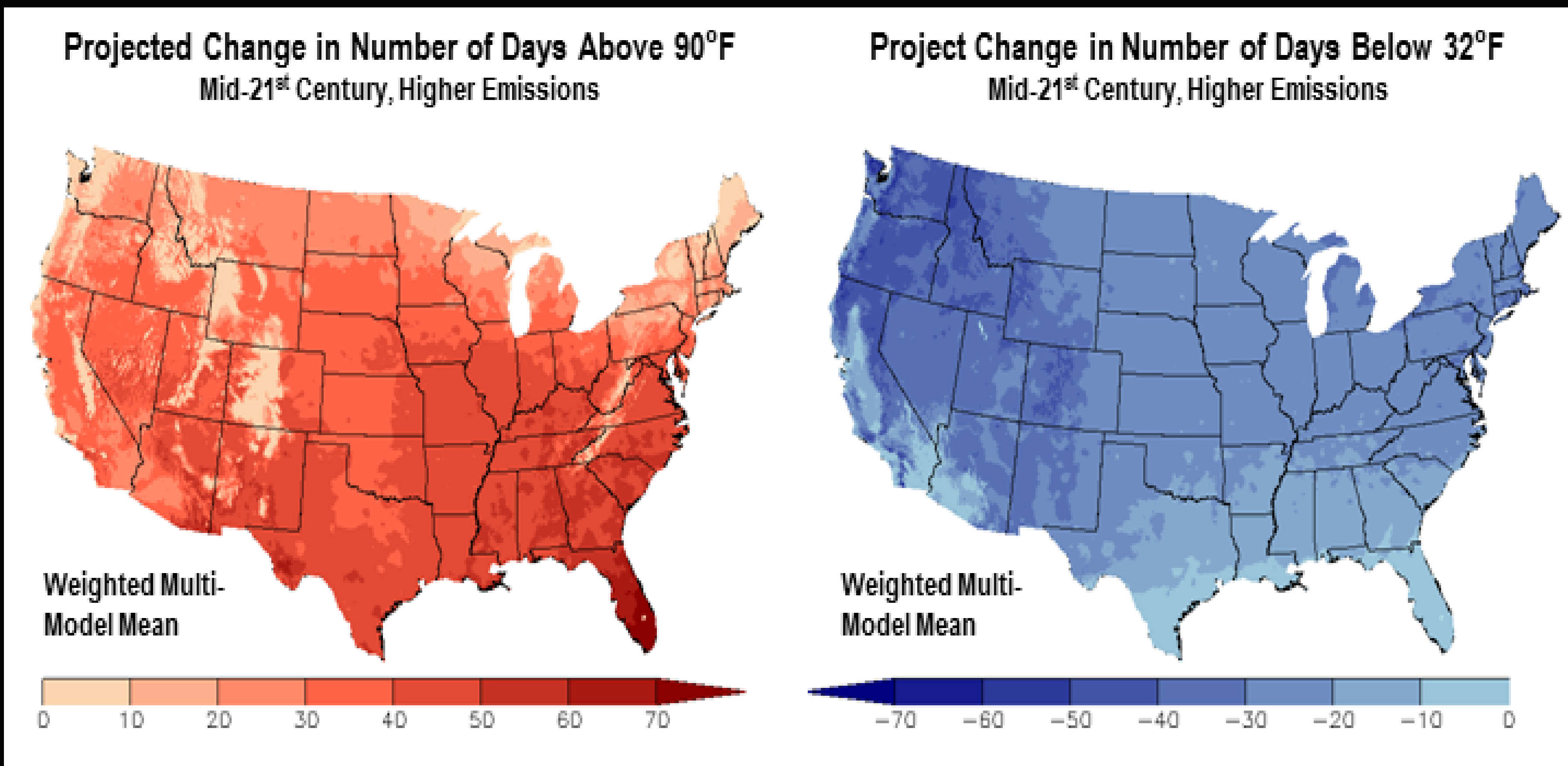
Projected changes in annual average temperature for mid- and late-21st century for various future pathways. Changes are the difference between the average for mid-century (2036–2065; top), late-century (2071–2100; bottom), and 1976–2005.

U.S. Precipitation Projections (% change 2070-2099, High scenario)

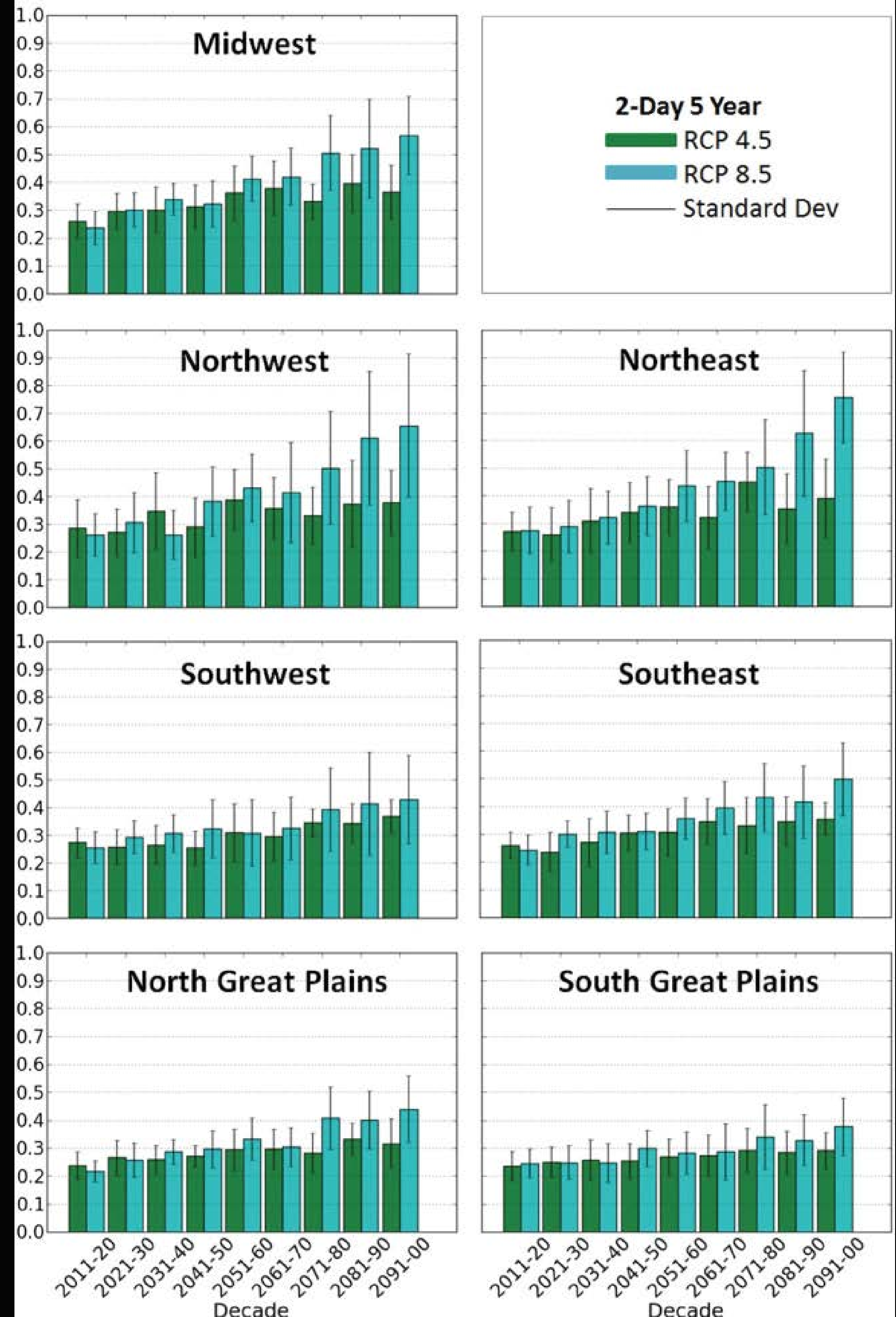


Relative to 1976–2005

Projected Changes in Number of Days with >90°F and <32°F for 2036-2065 relative to 1976-2005 for a High Emissions Scenario

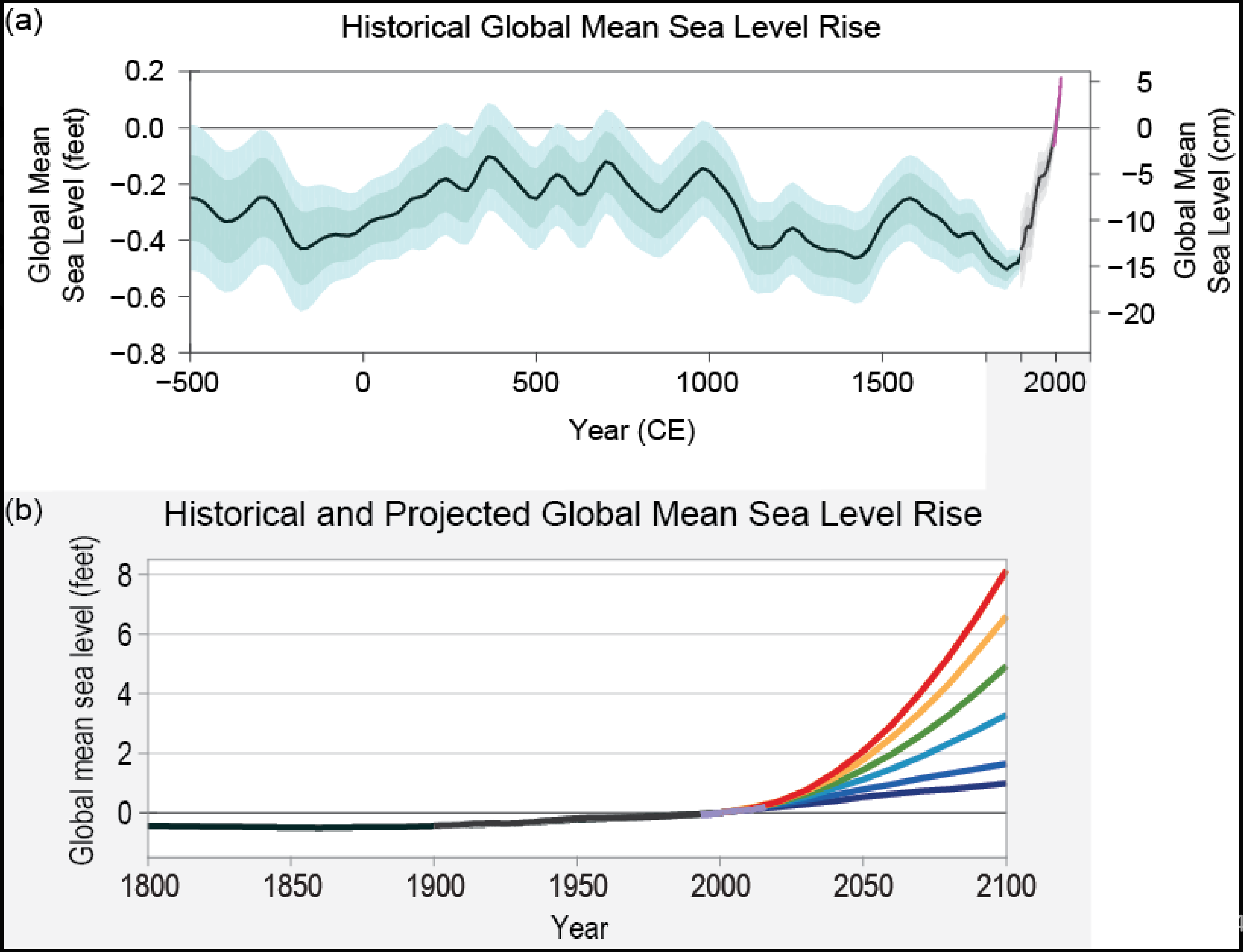


Extreme Precipitation Event Frequency for events of 2-day duration and 5-year return (for high and intermediate scenarios)



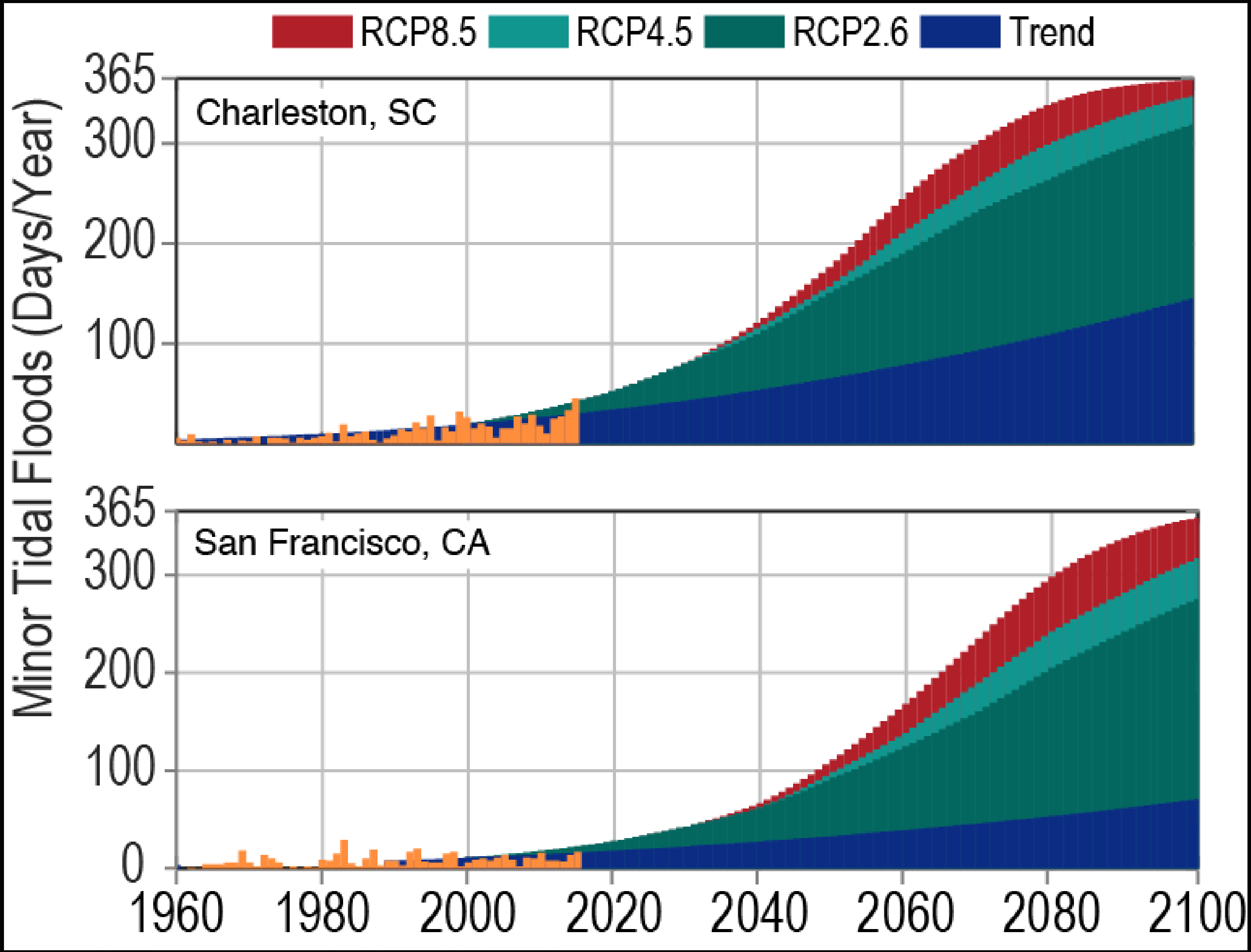
Extreme rainfall can lead to flash floods

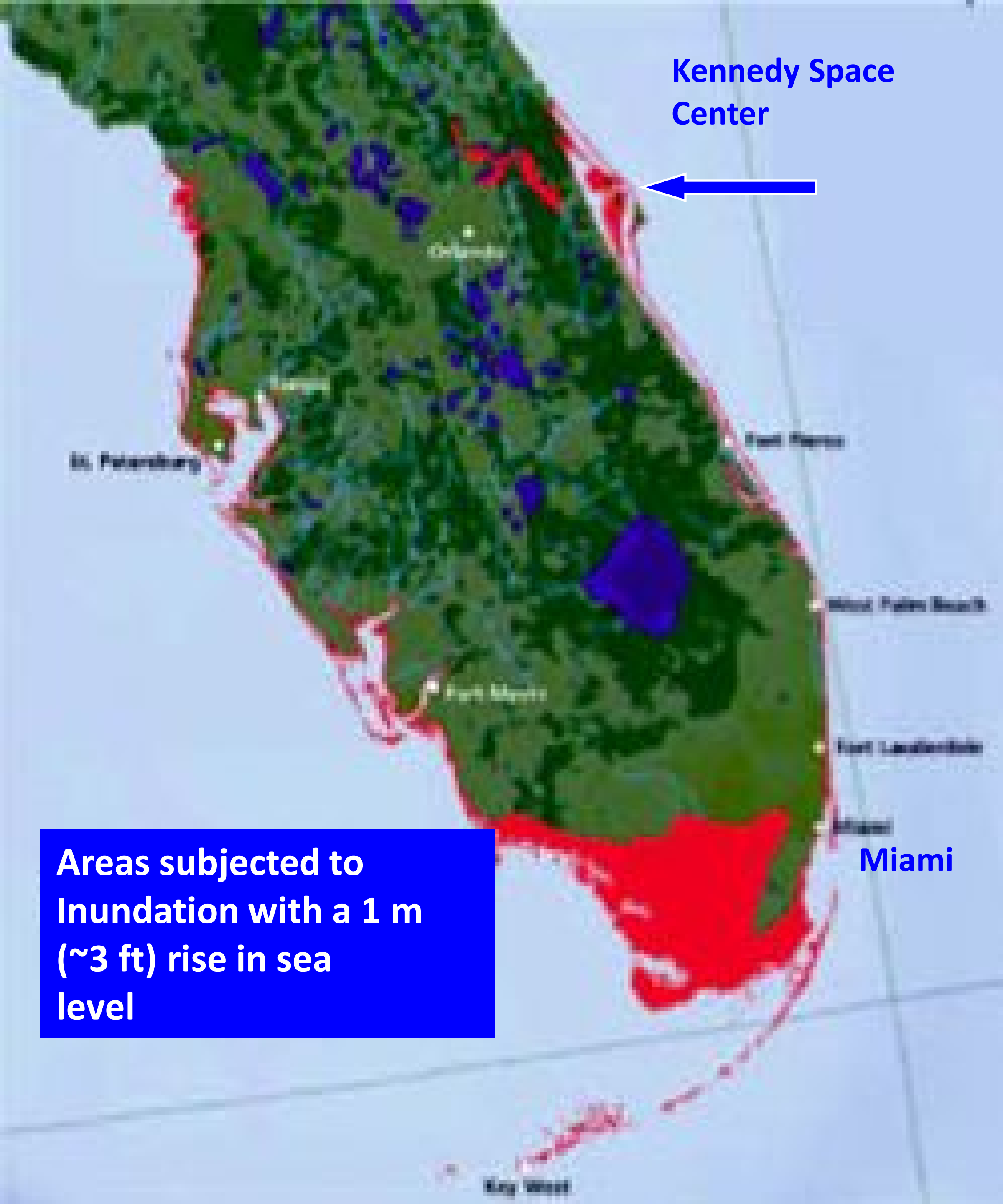
Past and Projected Changes in Global Sea Level



Best estimate of SLR is 1-4 feet by 2100

“Nuisance Flooding” is Increasing Across the United States



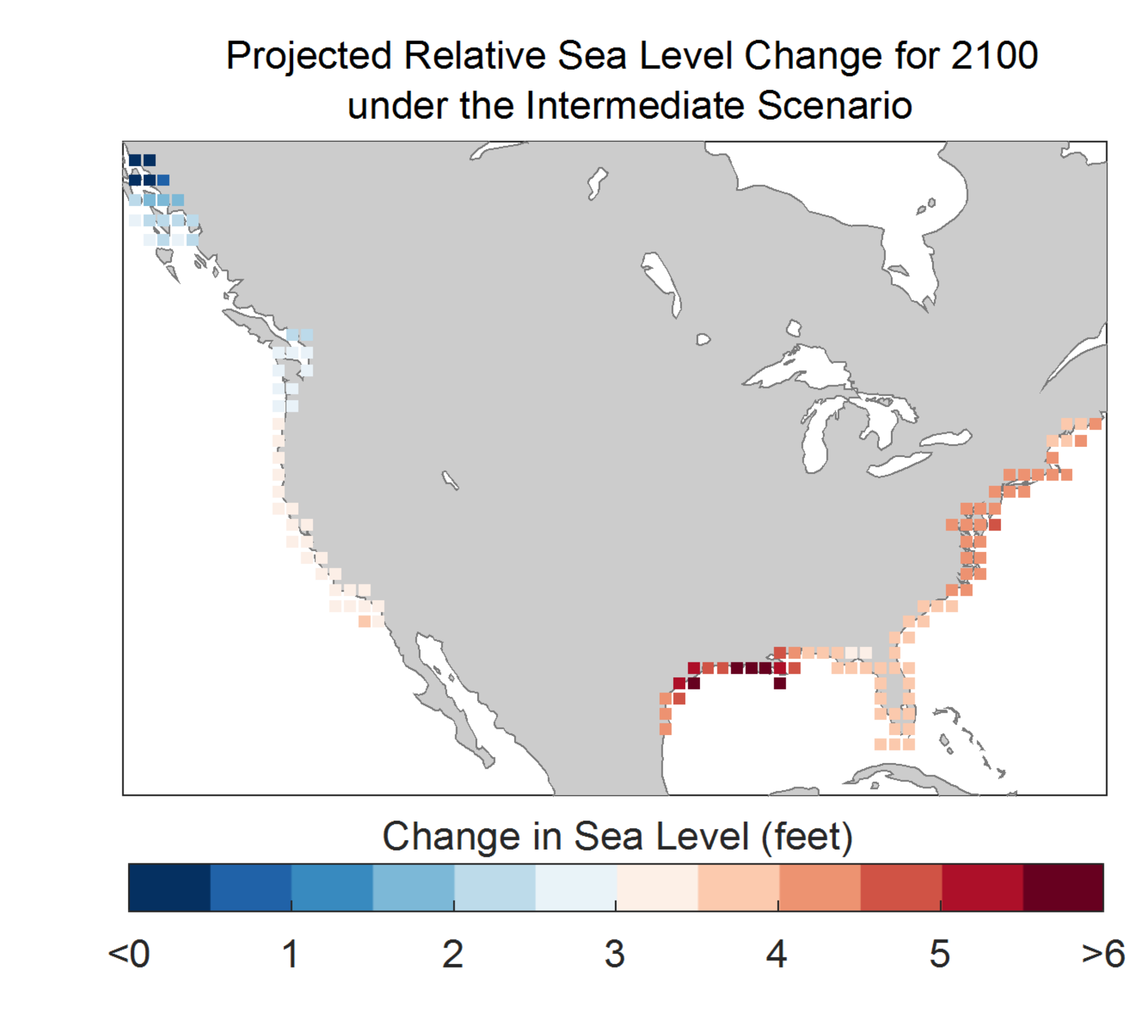


Impact of a 1-m rise in sea level on low-lying areas

Source:

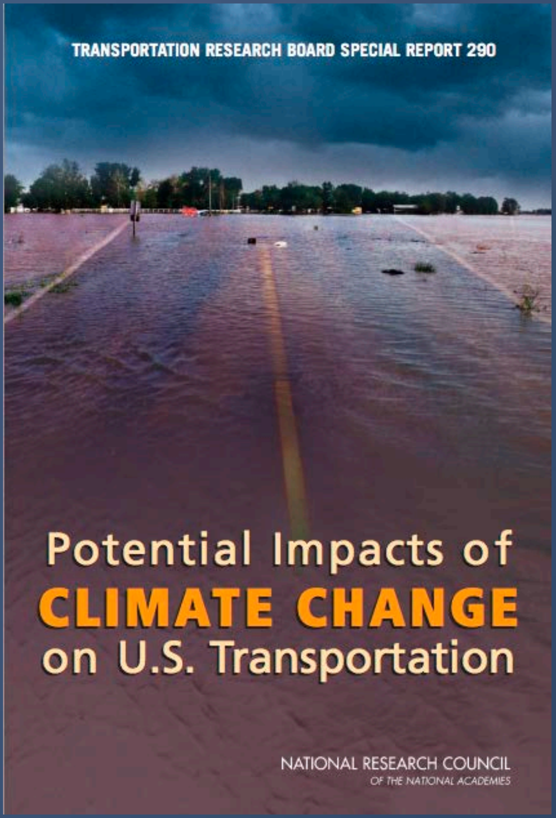
Corell, R. W., 2004: Impacts of a warming Arctic. *Arctic Climate Impact Assessment* (www.acia.uaf.edu) Cambridge University Press (www.cambridge.org).

Regional SLR in 2100 projected for the Intermediate Scenario (3.3 feet] GMSL

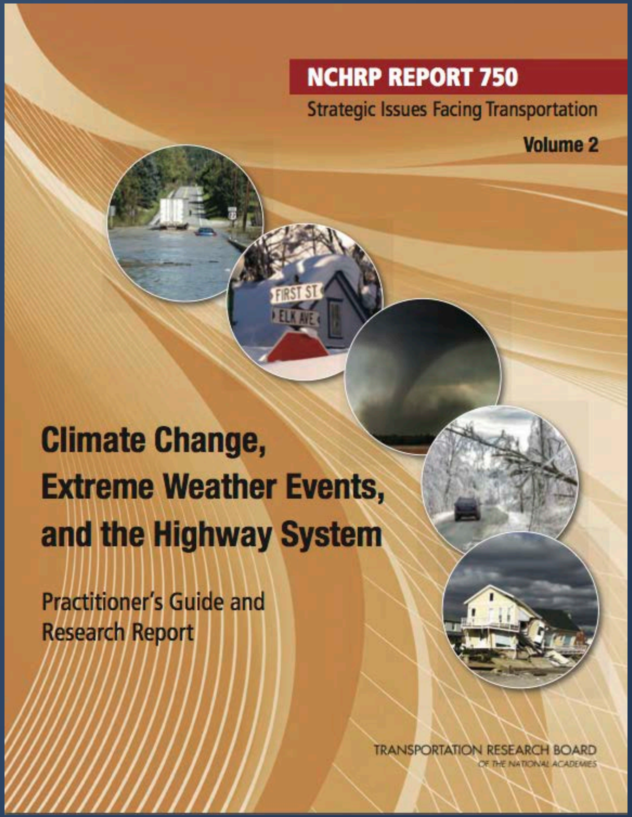


Effects of Projected Future Climate on the Interstate Highway System

Climate variability and change affect DOT's strategic goals of safety, state of good repair and environmental sustainability



TRB Special Report 290, 2008



NCHRP, 2014: http://www.trb.org/Main/Blurbs/169781.aspx

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Notable impacts identified by the USDOT are wide-ranging and not limited to the IHS

Notable Potential Impacts to the IHS

- More frequent/severe flooding of underground tunnels and low-lying infrastructure
- Increased storm surges and sea level rise shorten infrastructure life.
- Increased thermal expansion of pavement due to higher temperatures
- Higher maintenance/construction costs for roads and bridges
- Increased asphalt degradation due to higher temperatures.
- Culvert and drainage infrastructure damage due to changes in precipitation intensity
- Decreased driver/operator performance due to adverse weather.
- Increased risk of vehicle crashes in severe weather.

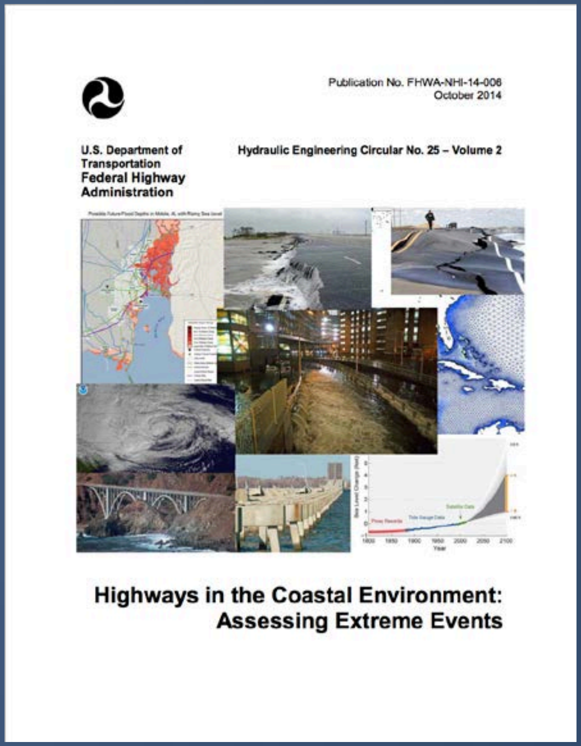
Notable Potential Imports to Alternative Transport Modes

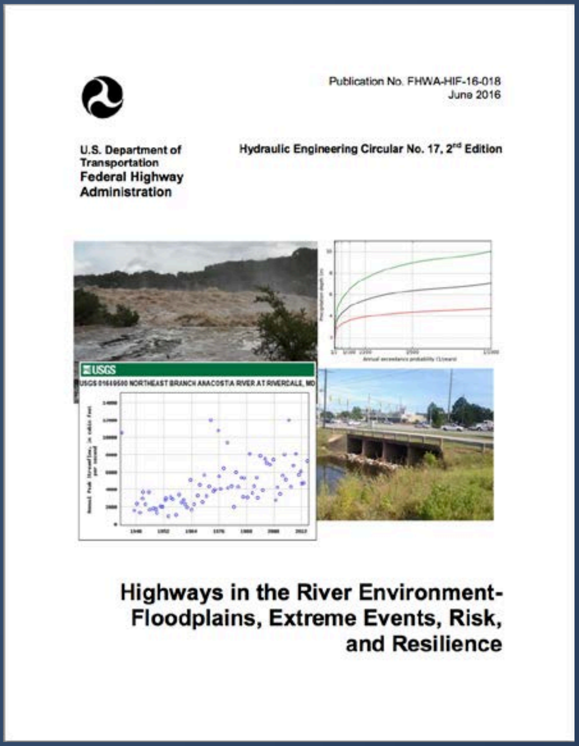
- Rail buckling during extremely hot days.
- Reduced aircraft performance leading to reduced payloads.
- Air traffic disruptions, due to severe weather and precipitation
- Reduced shipping access to docks and shore equipment.
- Restricted access to local economies and public transportation.

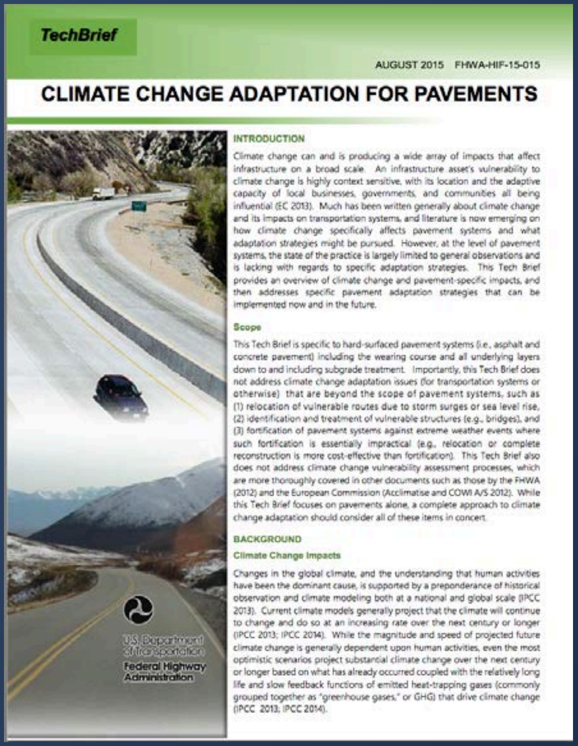
Transportation Sector Vulnerability Studies

Georgetown Climate Center

New strategies to incorporate future climate in infrastructure planning and design processes are now emerging.







TechBrief

AUGUST 2015 FHWA-HIF-15-015

CLIMATE CHANGE ADAPTATION FOR PAVEMENTS

INTRODUCTION

Climate change can and is producing a wide array of impacts that affect infrastructure on a broad scale. An infrastructure asset's vulnerability to climate change is highly context sensitive, with its location and the adaptive capacity of local businesses, governments, and communities all being influential (EC 2013). Much has been written generally about climate change and its impacts on transportation systems, and literature is now emerging on how climate change specifically affects pavement systems and what adaptation strategies might be pursued. However, at the level of pavement systems, the state of the practice is largely limited to general observations and is lacking with regards to specific adaptation strategies. This Tech Brief provides an overview of climate change and pavement-specific impacts, and then addresses specific pavement adaptation strategies that can be implemented now and in the future.

Scope

This Tech Brief is specific to hard-surfaced pavement systems (i.e., asphalt and concrete pavement) including the wearing course and all underlying layers down to and including subgrade treatment. Importantly, this Tech Brief does not address climate change adaptation issues (for transportation systems or otherwise) that are beyond the scope of pavement systems, such as (1) relocation of vulnerable routes due to storm surges or sea level rise, (2) identification and treatment of vulnerable structures (e.g., bridges), and (3) fortification of pavement systems against extreme weather events where such fortification is essentially impractical (e.g., relocation or complete reconstruction is more cost-effective than fortification). This Tech Brief also does not address climate change vulnerability assessment processes, which are more thoroughly covered in other documents such as those by the FHWA (2012) and the European Commission (Acclimatise and COWI A/S 2012). While this Tech Brief focuses on pavements alone, a complete approach to climate change adaptation should consider all of these items in concert.

BACKGROUND

Climate Change Impacts

Changes in the global climate, and the understanding that human activities have been the dominant cause, is supported by a preponderance of historical observation and climate modeling both at a national and global scale (IPCC 2013). Current climate models generally project that the climate will continue to change and do so at an increasing rate over the next century or longer (IPCC 2013; IPCC 2014). While the magnitude and speed of projected future climate change is generally dependent upon human activities, even the most optimistic scenarios project substancial climate change over the next century or longer based on what has already occurred coupled with the relatively long life and slow feedback functions of emitted heat-trapping gases (commonly grouped together as "greenhouse gases," or GHG) that drive climate change (IPCC 2013; IPCC 2014).

U.S. Department of Transportation
Federal Highway Administration

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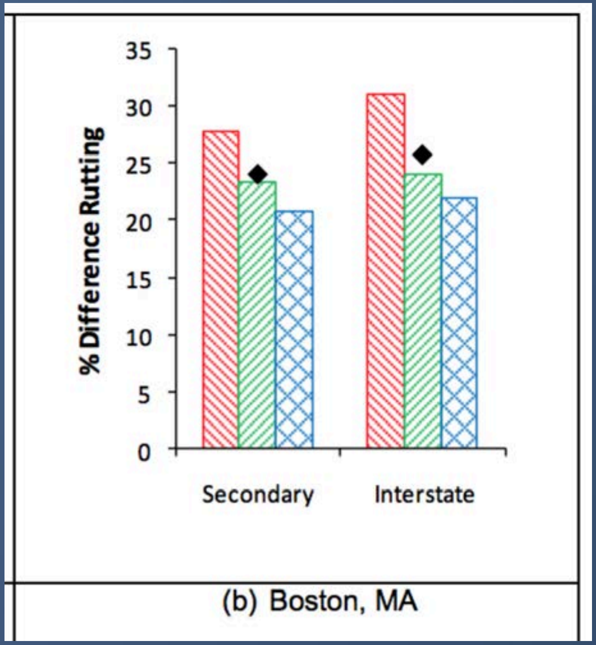
IHS and Temperature Changes

Warming average temperatures, heat waves, and record setting summer temperatures

Rutting



Percent difference in asphalt concrete rutting between baseline and future periods for Boston, MA [Adaptation of Figure 7 in Meagher et al. (2012)].

Buckling

Buckled pavement on Interstate 84 in Box Elder County, June 30, 2015. Photo Courtesy of Utah Highway Patrol

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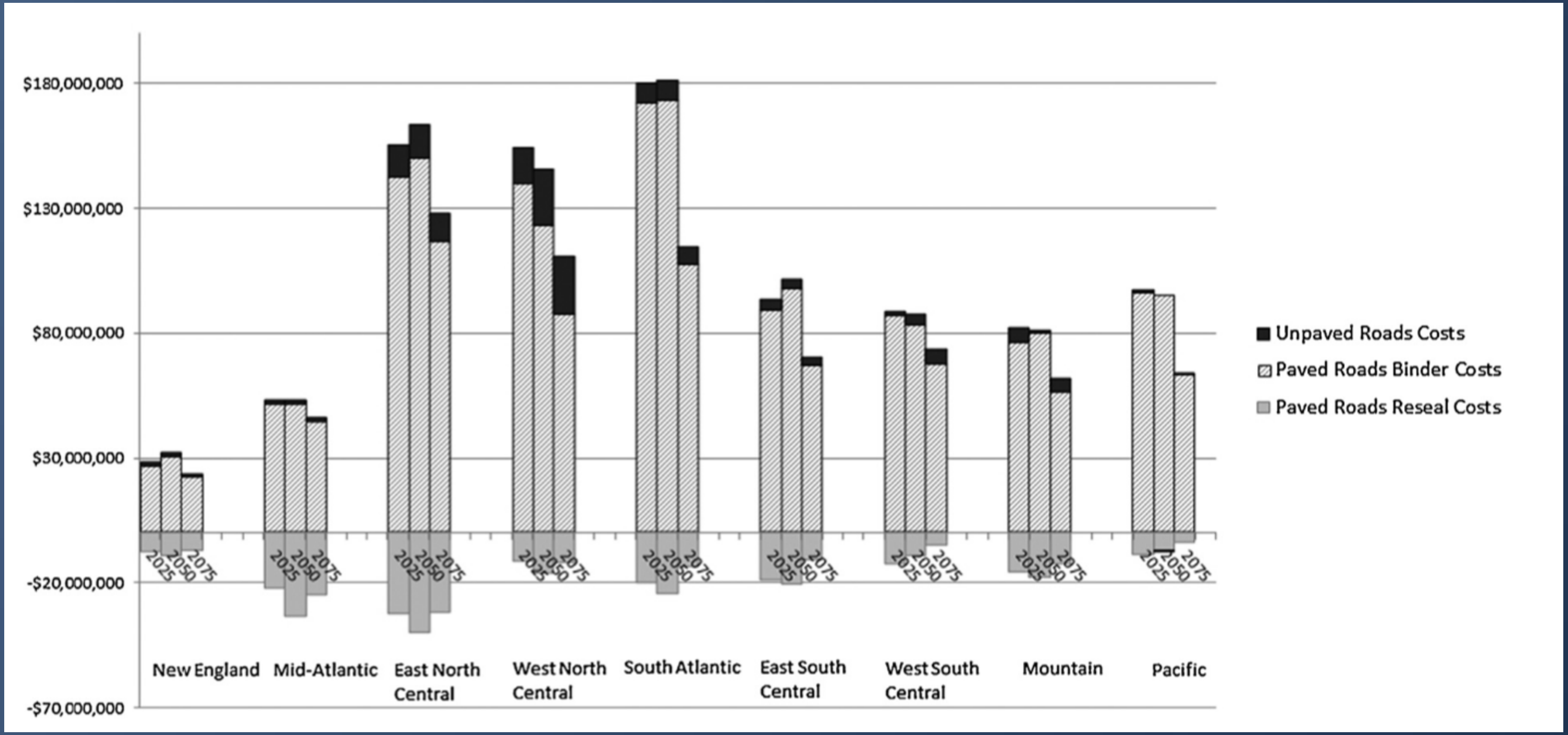
IHS and Temperature Changes

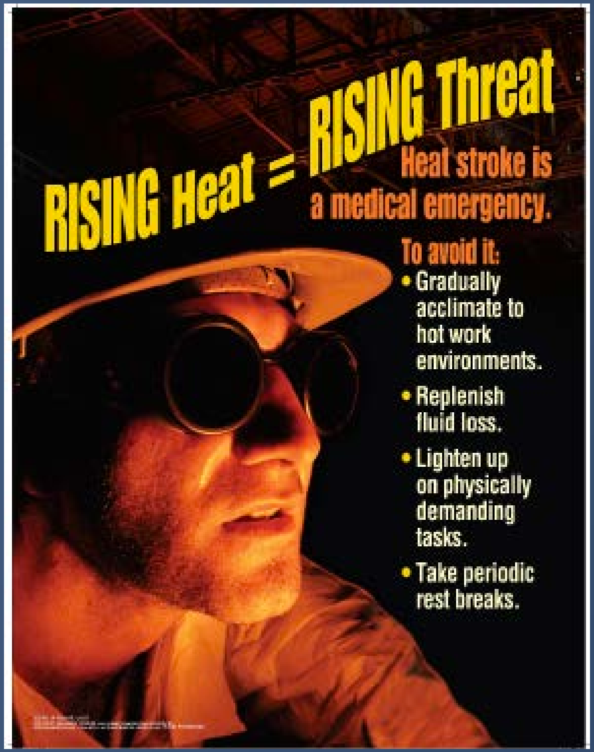
Warming average temperatures, heat waves, and record setting summer temperatures



Annual adaptation costs for the U.S road network by region, year, and cost type. Estimates are expressed in year 2010 dollars using a 3% discount rate. [Adaptation of Figure 4 in Chinowksy et al. (2013)].

IHS and Temperature Changes

Other Impacts



Construction Activities

Electrical Support Equipment Malfunction

IHS and Changes to Rainfall
Flooding and Mudslides

I-80 January 2017

https://www.accuweather.com/en/weather-news/flooding-problems-to-mount-as-storm-train-aims-for-california/70000496

I-44 St. Louis County, MO; May 2017

http://www.cnn.com/2017/05/04/weather/missouri-flooding-images/index.html

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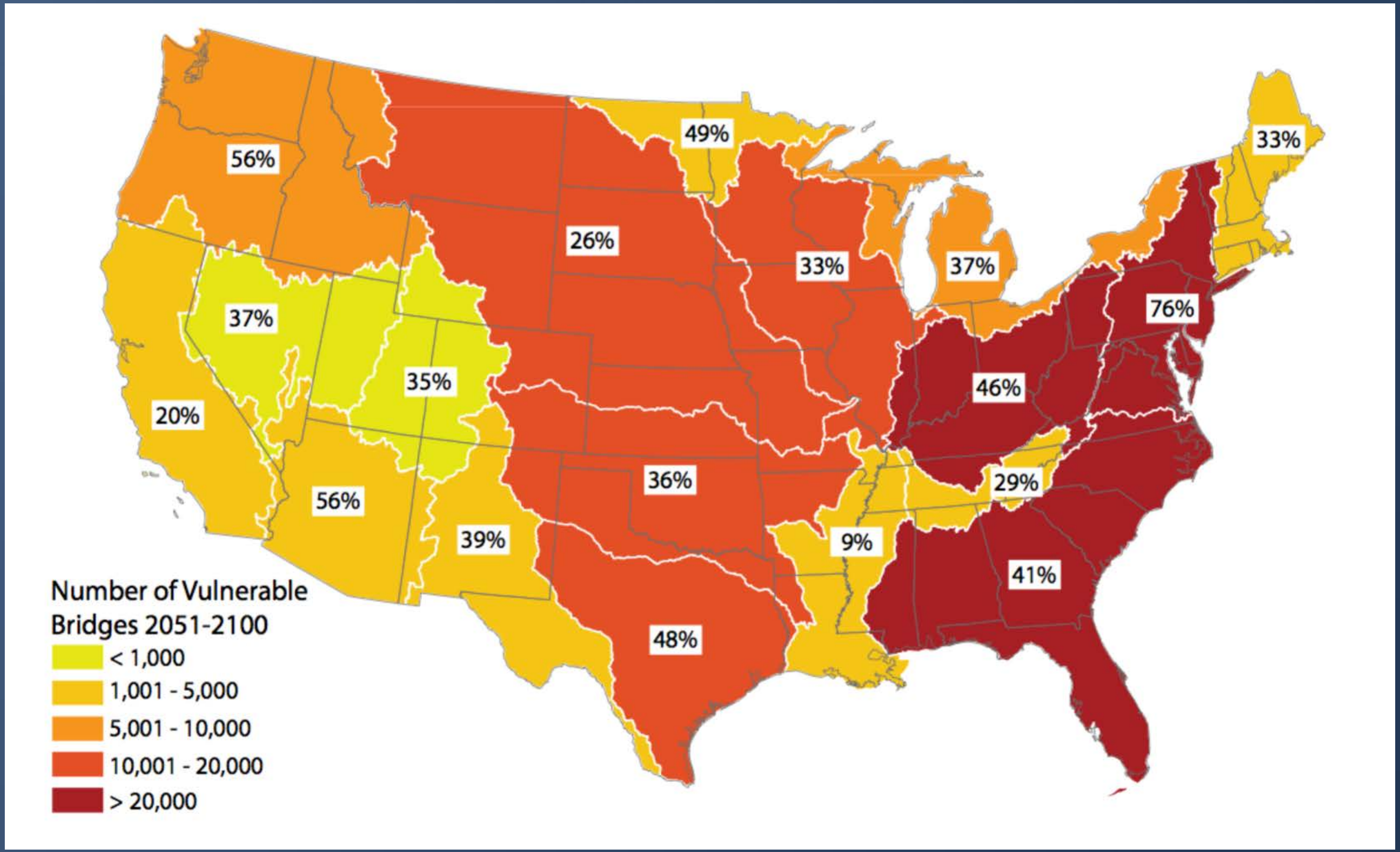
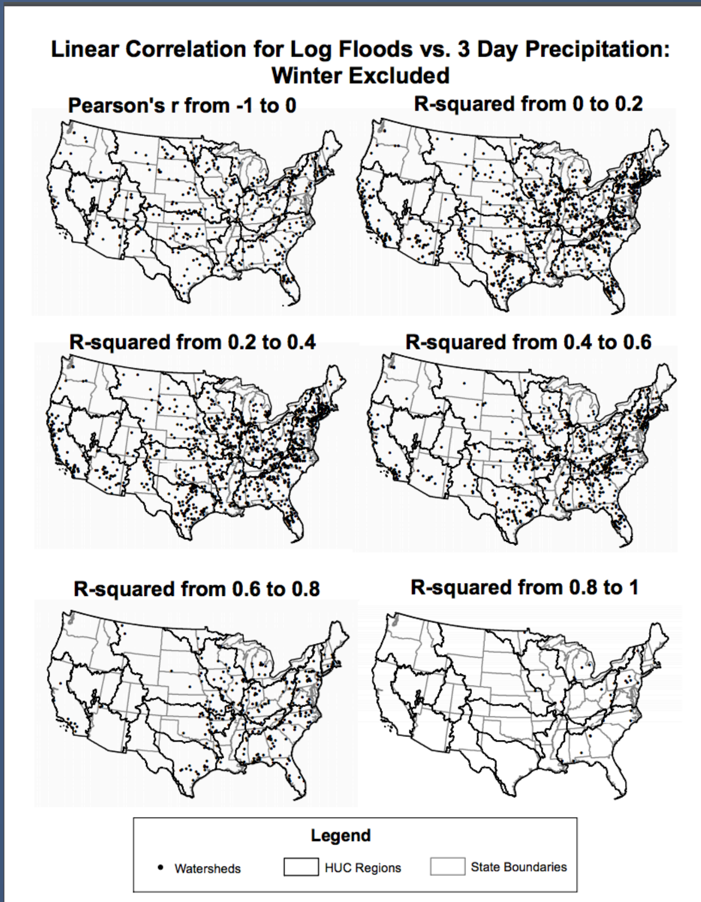
IHS and Changes to Rainfall
Vulnerable Bridges



Inland bridges identified as vulnerable in the second half of the 21st century due to climate change [Adaptation of Figure 1 p. 34 in EPA (2015)]. From Wright et al. 2012

IHS and Changes to Intense Rainfall

Precipitation, Flooding and Impacts



Miller et al., 2017

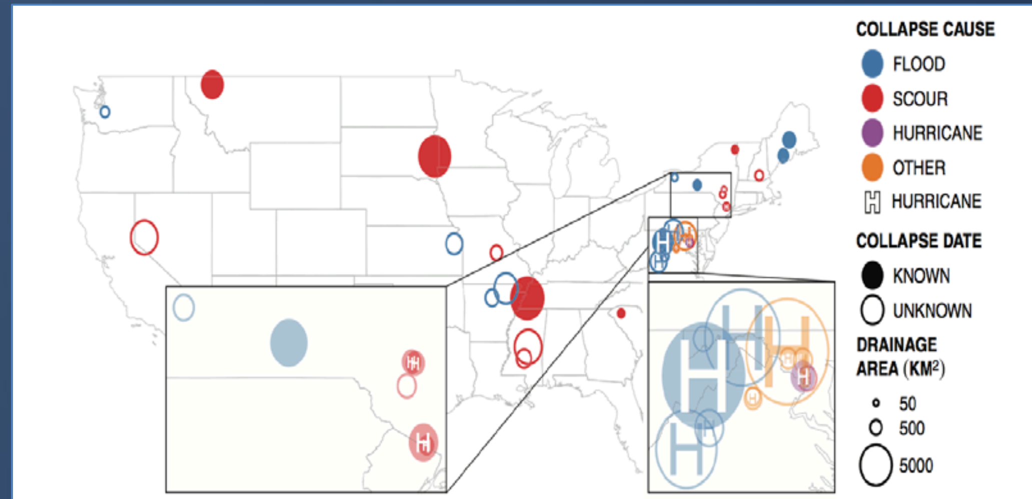


Fig. 2. (Color) Location of 35 historical bridge collapses; 13 bridges collapsed because of floods, 16 because of scour, one during Hurricane Agnes, and five from other causes (four were coded "hydraulic," and one was coded "hydraulic debris"); superimposed H denotes sites where a hurricane or tropical storm occurred in the region of the collapsed bridge and may have influenced the flow on the collapse date (14 bridges); the collapse date was known or confirmed for 13 bridges; area of circles is proportional to drainage area of the bridge site (range: 46–5,920 km^2); sites are plotted as semiopaque in inset maps for visual clarification; bridge and gauge data are provided in Table 1; additional maps are available in a permanent repository (Flint et al. 2016)

Flint et al., 2017

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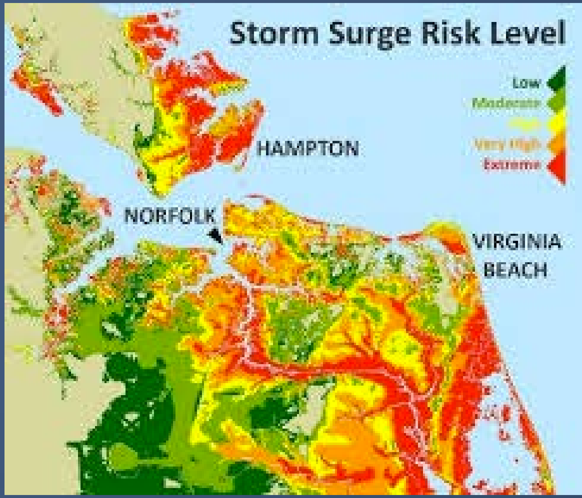
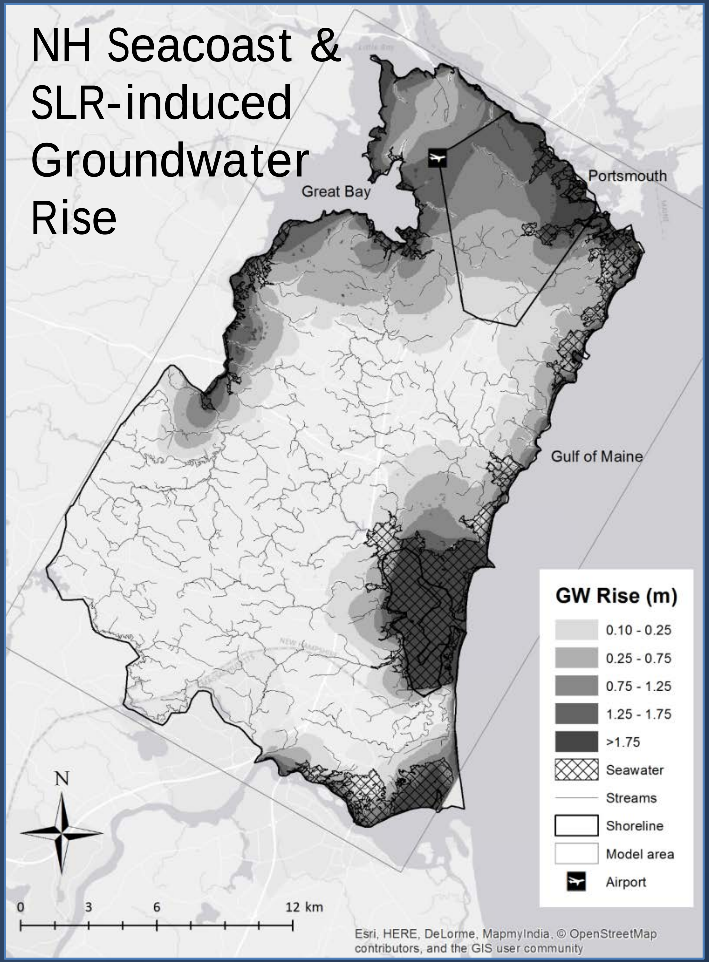
IHS and Changes to SLR & Storm Surge
High Tide and Storm Events

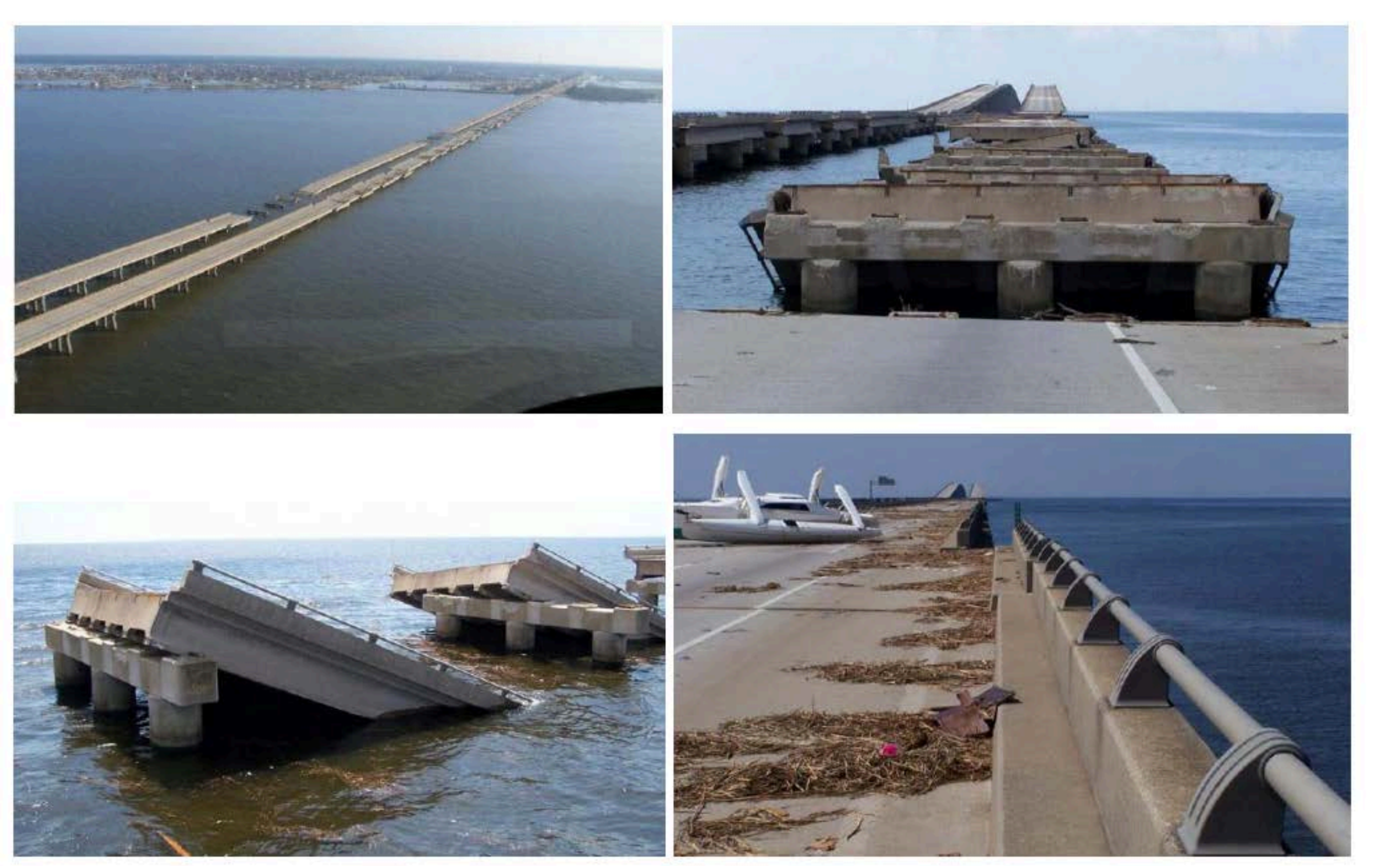




Knott et al., 2017

IHS and Changes to SLR & Storm Surge

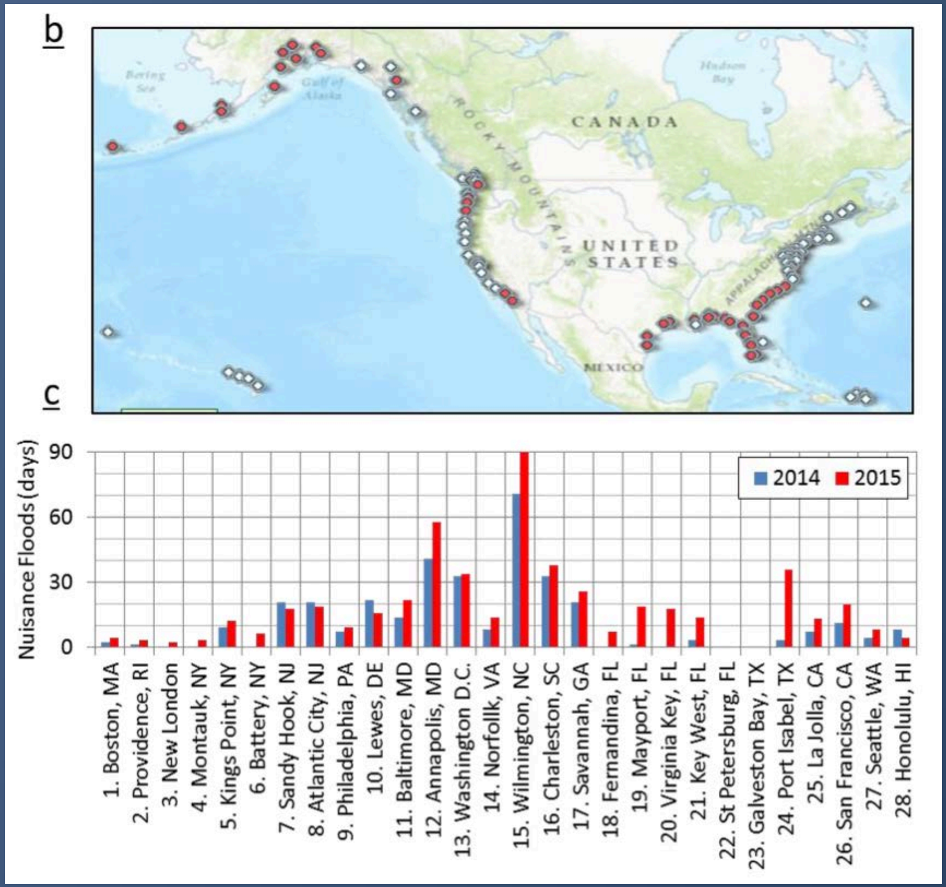
Tropical Storms



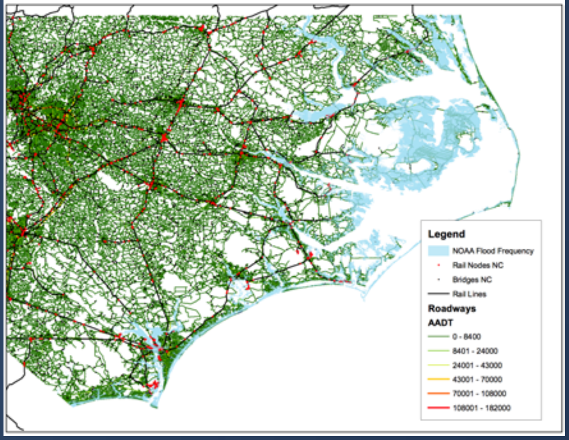
Lake Pontchartrain Bridge damage from Hurricane Katrina [Adaptation of Figure 1.3 in Xu (2015) adopted from Sheppard and Marin 2009].

IHS and Changes to SLR & Storm Surge

Nuisance Flooding or Sunny Day Flooding



In Charleston NC each event costs $12.5 M



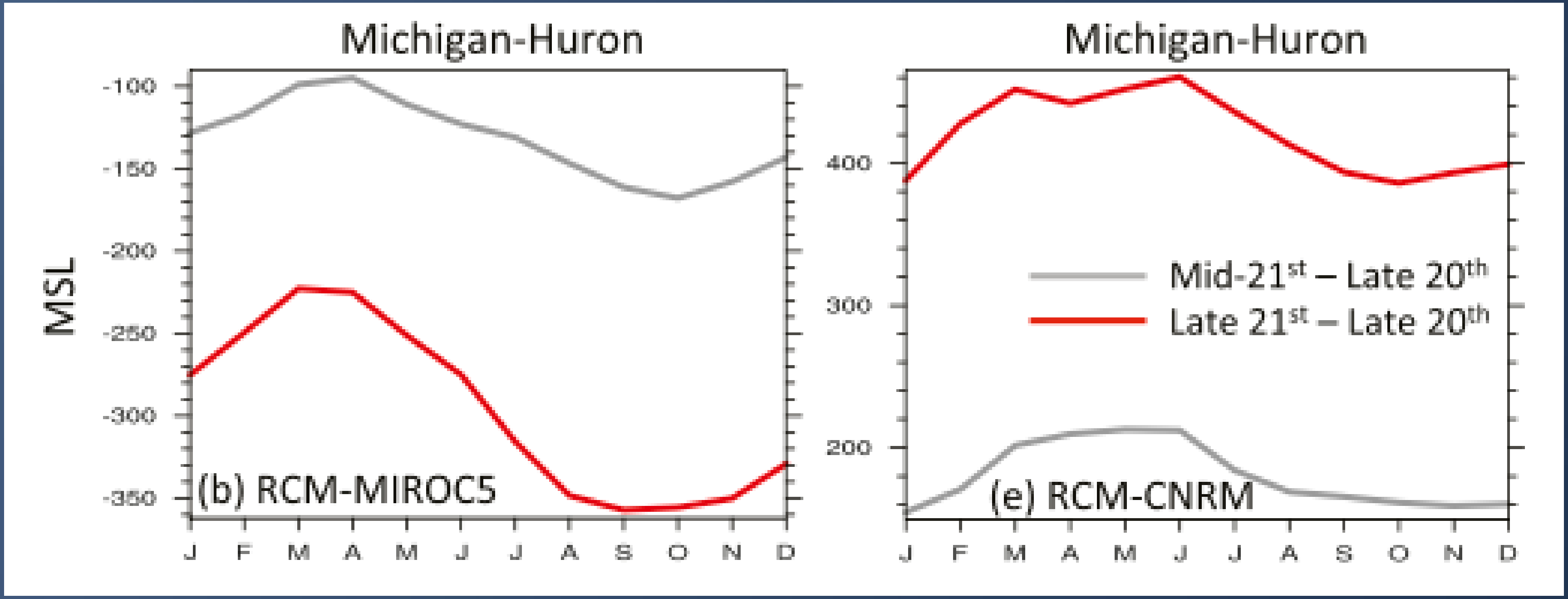
Sweet et al., 2016

Nuisance flooding in NC impacts 21 miles of functional class 1 & 2 roads

IHS and Disruption from Dust and Fire
From Drier Summer & Fall, Warmer Summer

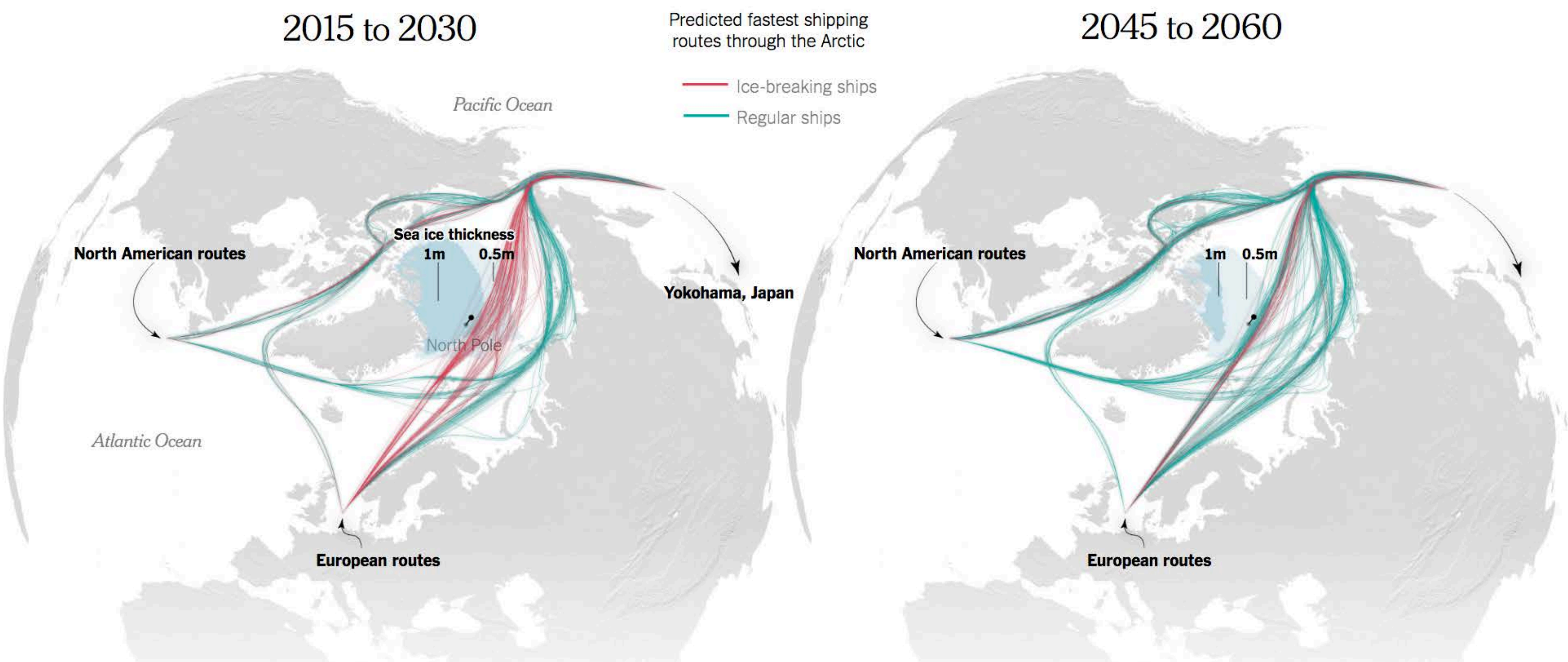
Arizona Department of Public Safety Officers and other emergency personnel make their way around a 16-car crash on Interstate 10 between Tucson and Phoenix Tuesday, Oct. 4, 2011. Photo Credit: Darryl Webb AP

IHS and Inland Navigation
From Changing Water Levels and Winters



Summary of projected lake level change (mm) from mean sea level (MSL) for Lakes Michigan by month. Gray lines are for the mid-twenty-first century (2040–59) and red lines are for late twenty-first century (2080–99) as compared to the late twentieth century (1948–2006) [Adaptation of Figure 13 in Notaro et al. (2015)].

IHS and Artic Sea Ice Opening Northern Transportation Routes



As global warming continues, by 2030 routes over the North Pole could open for **ice-breaking cargo ships** capable of operating in ice up to four feet thick.

By 2045 to 2060, the decline of Arctic sea ice under moderate warming could allow even **ordinary cargo ships** to journey directly over the North Pole.

New York Times, May 5, 2017 adapted from Melia et al., 2016

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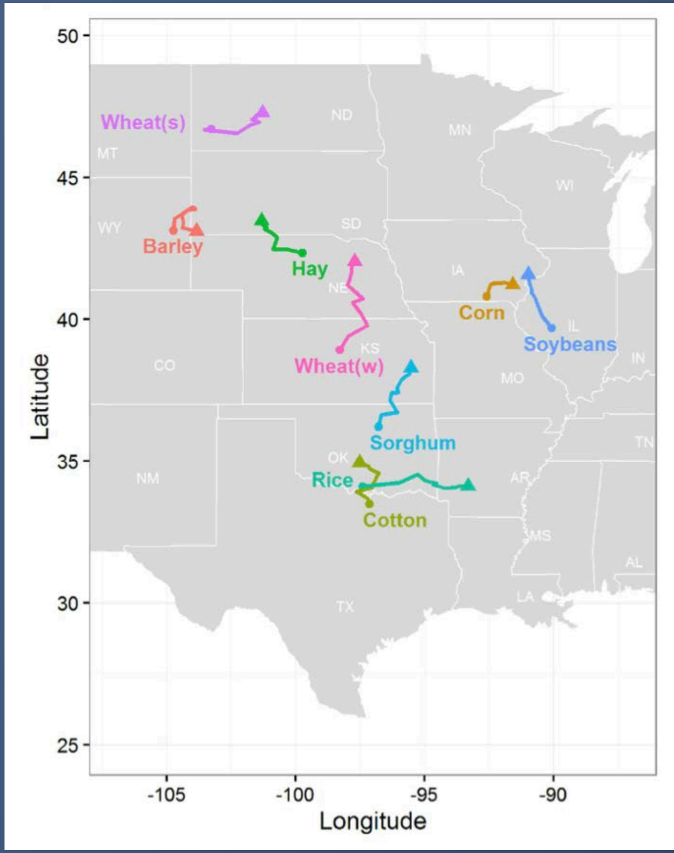
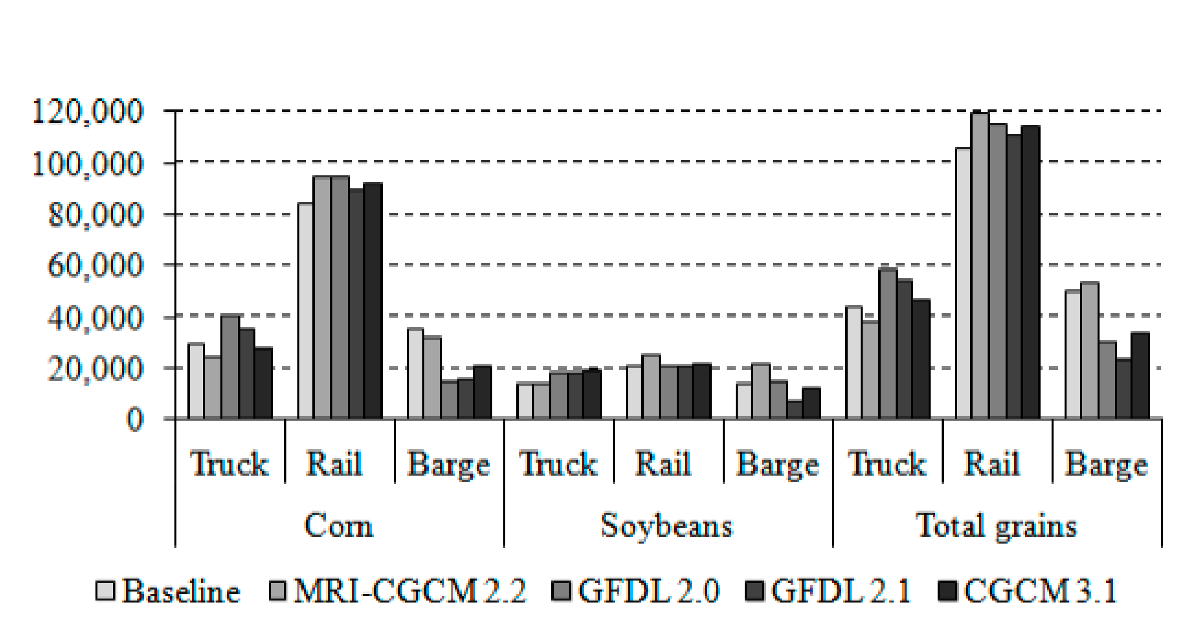
IHS and Northward Changes in Agricultural Production From Warmer Summers





Above Right: Grain shipment modes of transportation due to climate induced shifts in crop production patterns under baseline (2007/2008) conditions and future (2050) conditions using output from four different GCM models. Quantities are in 1,000 metric tons. [Figure S1 in Attavanich et al. (2013)].

Above Left: Locational shifts in production-weighted centroids and elevations by crop under the RCP 8.5 scenario by 2090. [Adaptation of Figure 2 in Cho and McCarl (2017)].

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Concluding Thoughts

- Climate change induced impacts to the IHS are happening now and impacts are anticipated to increase in the future
- Direct impacts with high confidence will result from
  - Warmer summers and new temperature extremes
  - Rising seas coupled with storm surges
- Indirect impacts will change the magnitude and location of IHS demands
- Actionable guidance on best practices are needed for IHS planning, design, operation and maintenance

Thank You

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