Regional Climate Change Projections: Potential Impacts to Nuclear Facilities

L. Ruby Leung and Rajiv Prasad
Pacific Northwest National Laboratory

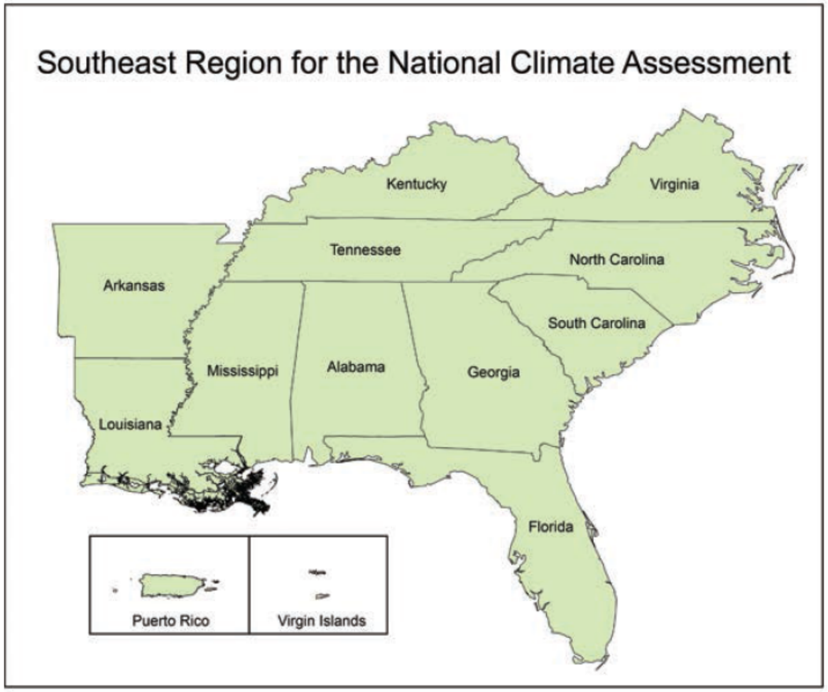
2nd Annual Probabilistic Flood Hazard Assessment Workshop
U.S. NRC Headquarters, Rockville, Maryland
January 23-25, 2017

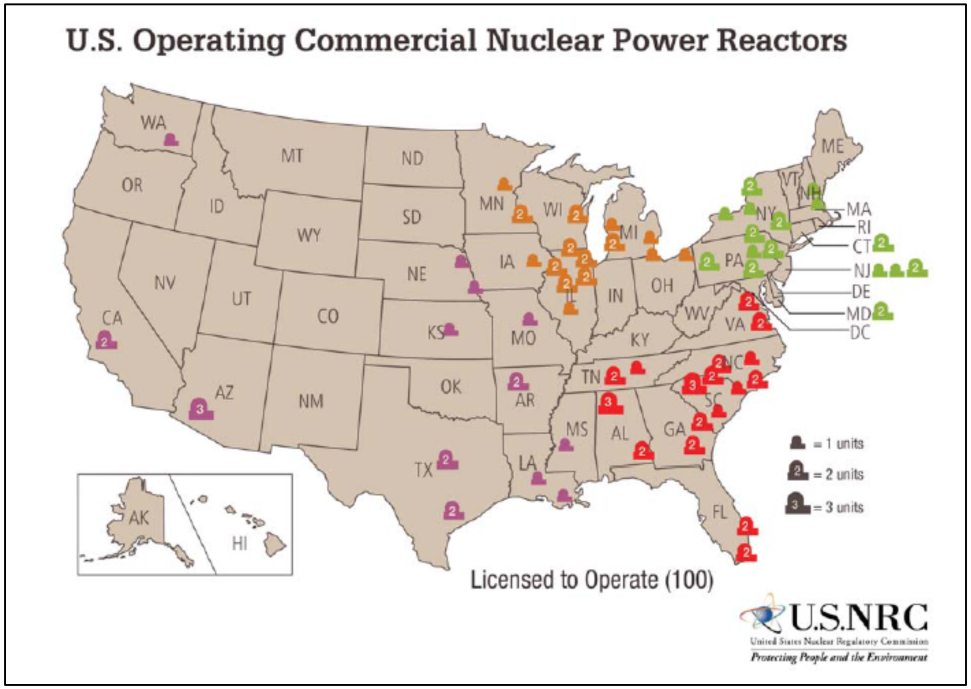
Project overview

- Objective: develop documents to summarize
  - Recent scientific findings on climate change and its impacts
  - Activities of federal agencies with direct responsibility on climate change science
  - Quality assessment of the above relevant to NRC concerns on regional level
- Progress:
  - Delivered first annual letter report focusing on recent scientific findings on climate change and regional impacts in the US - "Potential Impacts of climate change to NPPs" available in ADAMS (#ML16208A282)
  - Second year efforts focus on climate change and hydrologic impacts in southeastern US
  - Major sources of information:
    - Governmental reports (e.g., IPCC AR5, Third National Climate Assessment (NCA3) (Melilo et al. 2014); Regional Technical Input Report Series for the Southeast United States (Ingram et al. 2013); NOAA Technical Report NESDIS 142-2 (Kunkel et al. 2013); U.S. GCRP Climate Science Special Report (CSSR) (Wuebbles et al. 2017))
    - Literature in peer-reviewed journals
    - Websites (e.g., NOAA, National Hurricane Center, Southeast Regional Climate Center)

Background and context

- All Southeast states except for Kentucky, Puerto Rico, and the Virgin Islands have operating nuclear power plants
- Permit and license applications for new reactors applications proposed sites in Virginia, North Carolina, South Carolina, and Florida

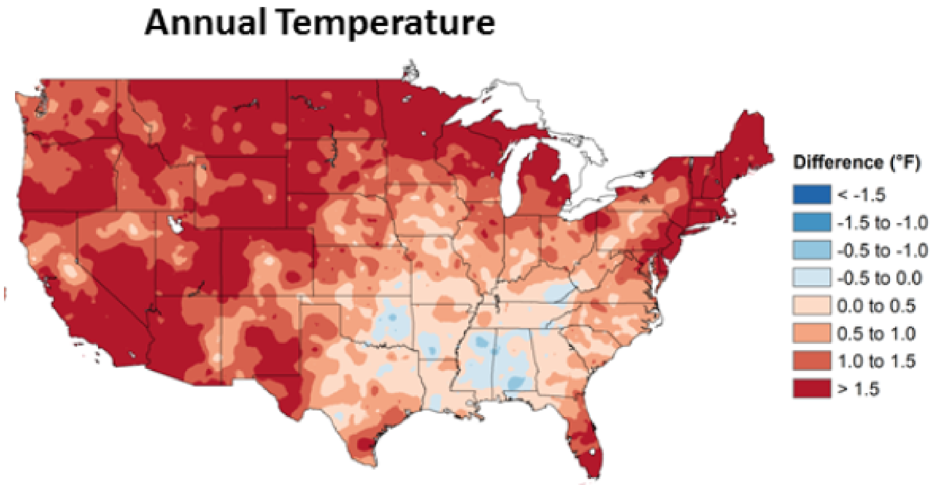




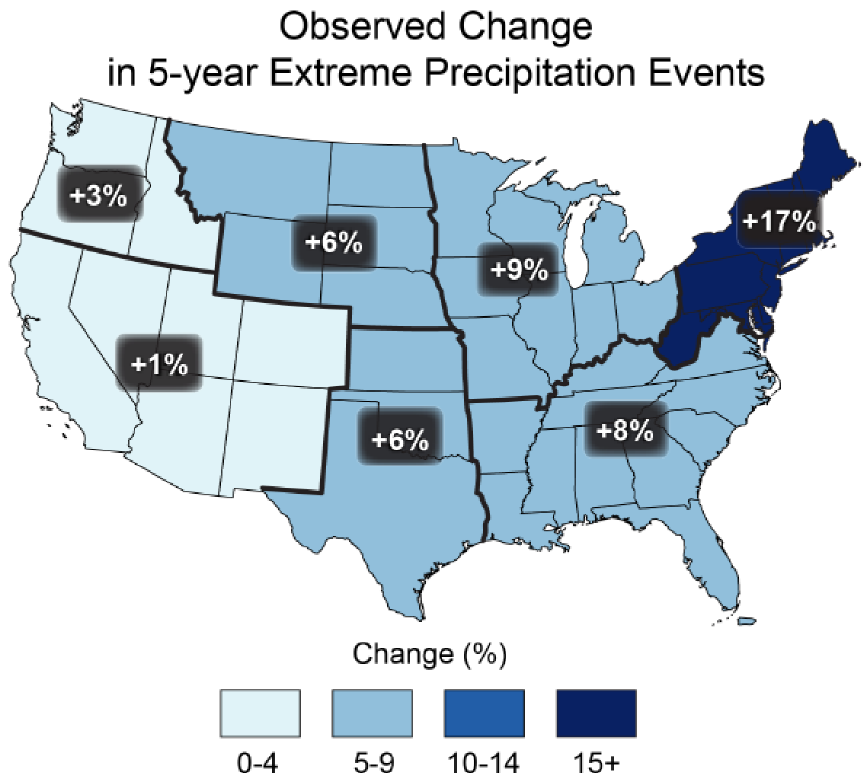
Past changes in temperature and precipitation (1986-2015 minus 1901-1960)

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

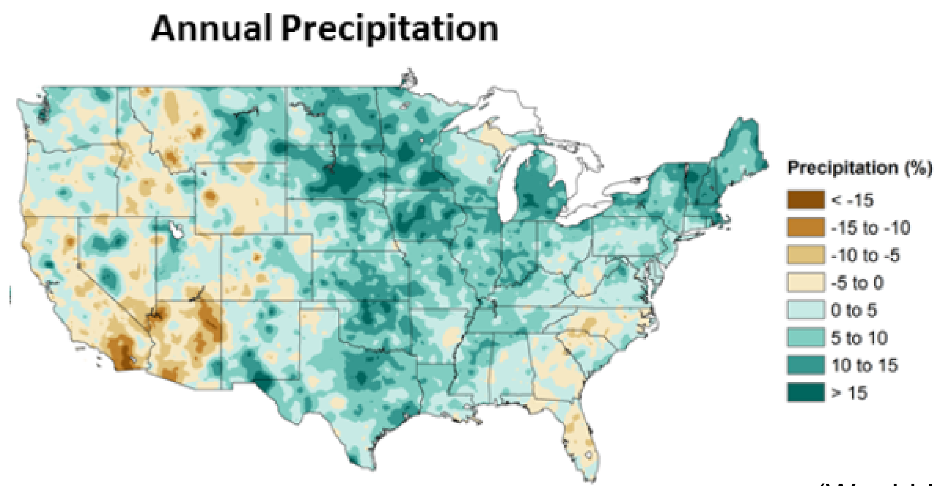
The Southeast is part of a "warming hole"



8% increase in 5-year extreme precipitation



Insignificant change in mean precipitation

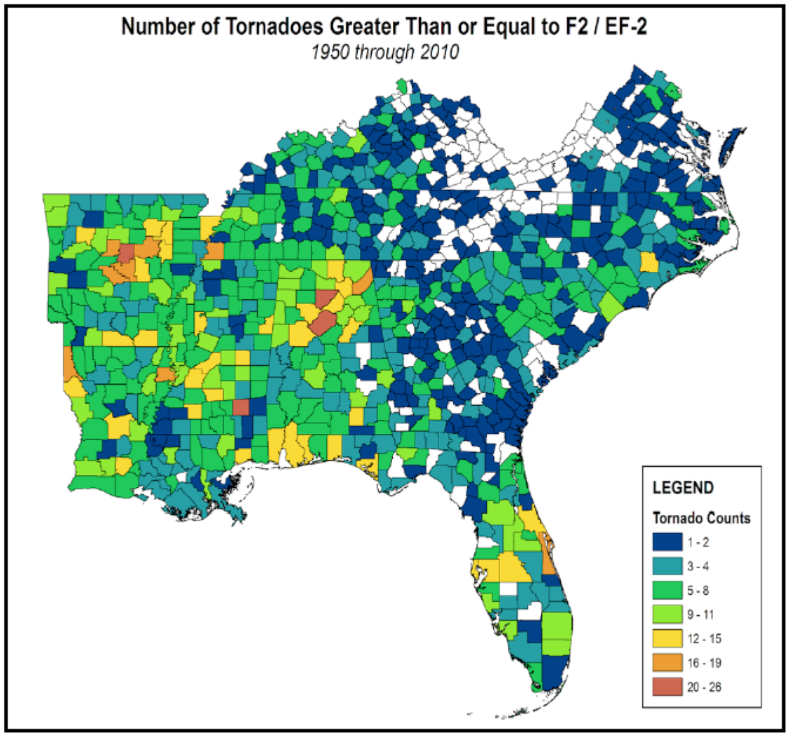


(Wuebbles et al. 2017 CSSR)

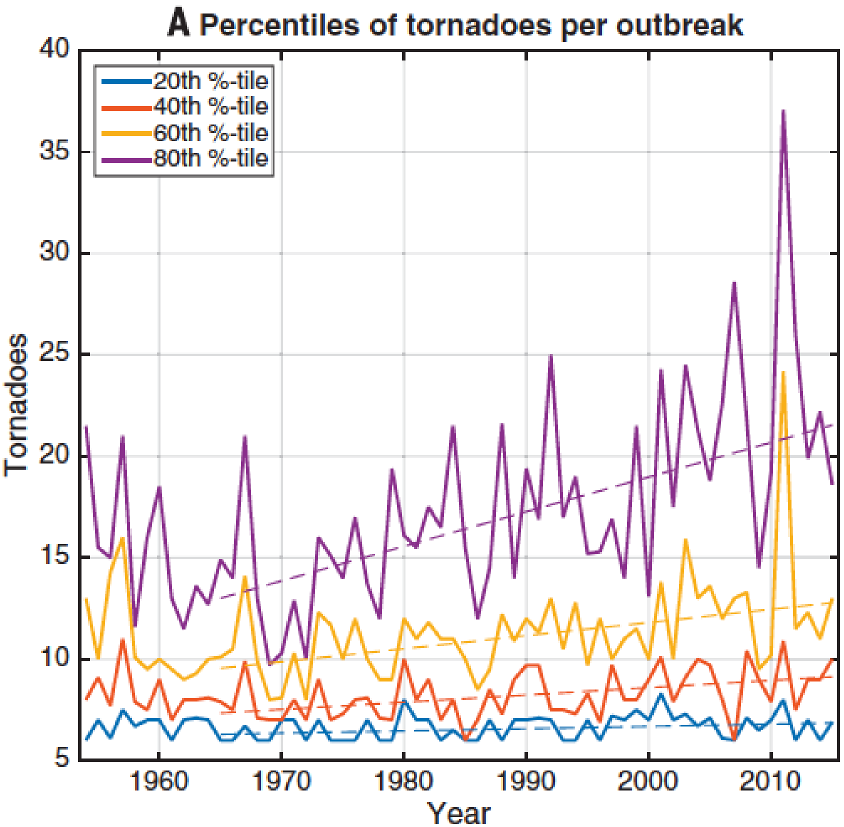
High percentile of tornadoes per outbreak has increased over time

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

- Frequency of tornado outbreaks (sequences of six or more tornadoes rated F1 and greater) has increased in the past decades



(Kunkel et al. 2013 NOAA Technical Report)



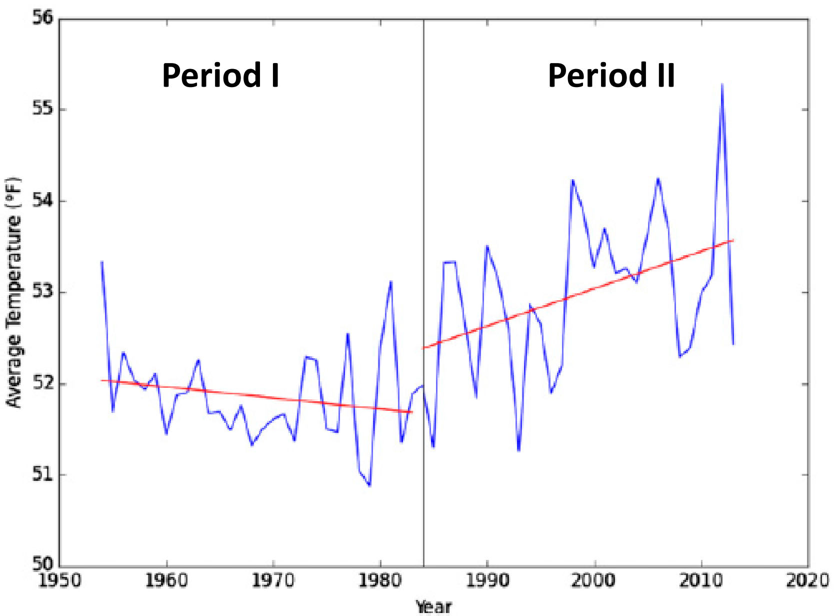
(Tippet et al. 2016 Nature Climate Change)

Spatial redistribution of tornado activity in the last 50 years

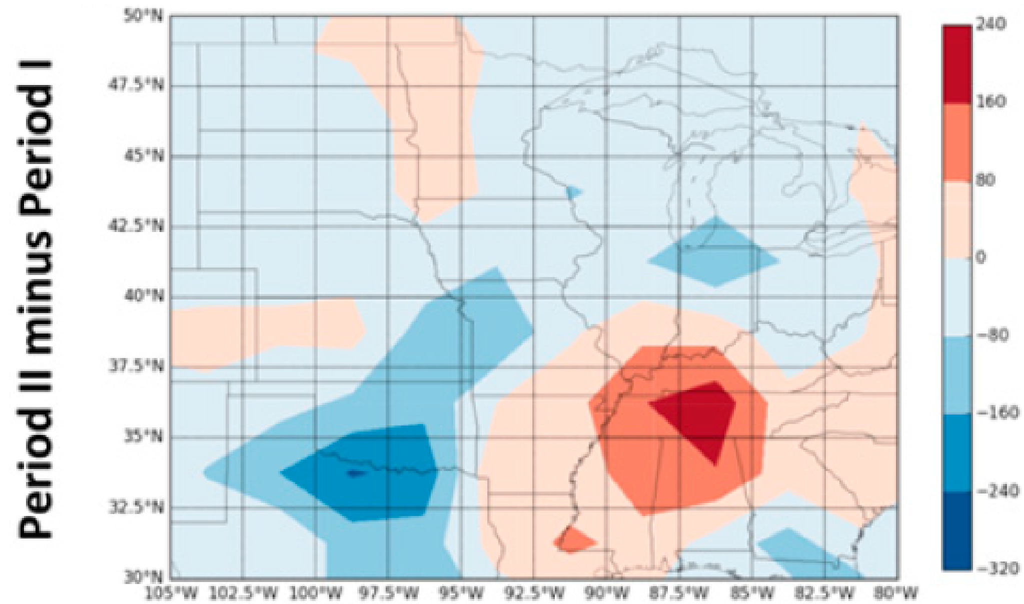
Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

- Annual tornado counts have shifted from the traditional “Tornado Alley” near Oklahoma to the “Dixie Alley” near Tennessee

Two periods of contrasting temperature trends



Difference in tornado counts [E(F1) – E(F5)] between Period II and Period I

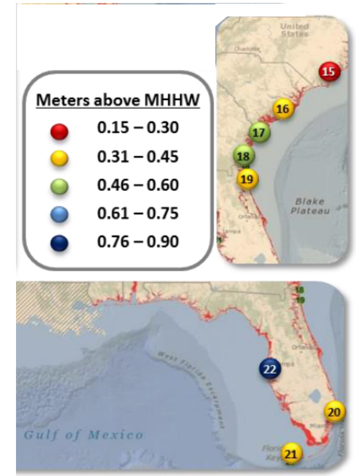


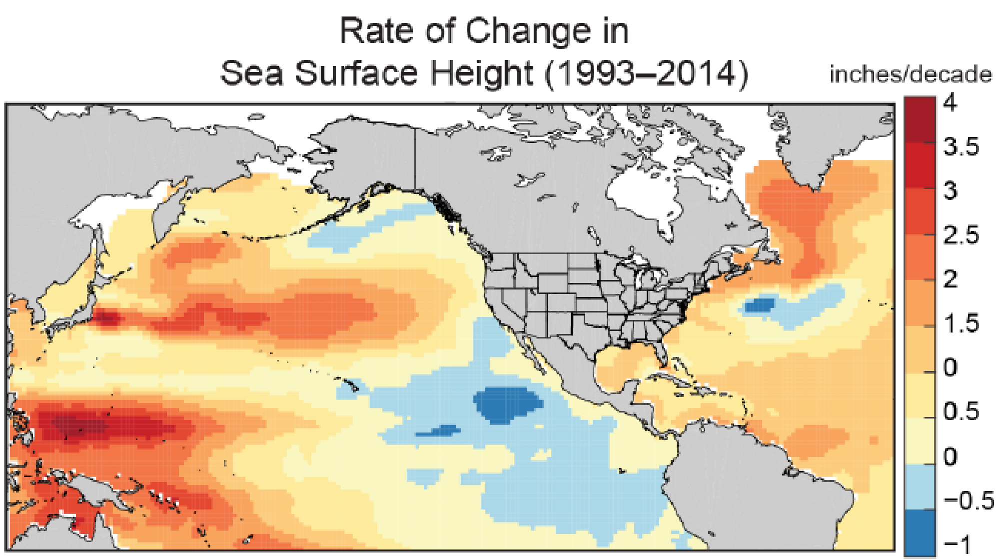
(Agee et al. 2016 J. Appl. Meteor. Climatol.)

Sea level and nuisance tidal floods have increased in the past

- The rate of sea level height increase has accelerated in the last two decades
- "Sunny day floods" or nuisance tidal floods have increased in the past
- Nuisance flooding is defined as a water level above the local NOAA NWS threshold for minor impacts established for emergency preparedness

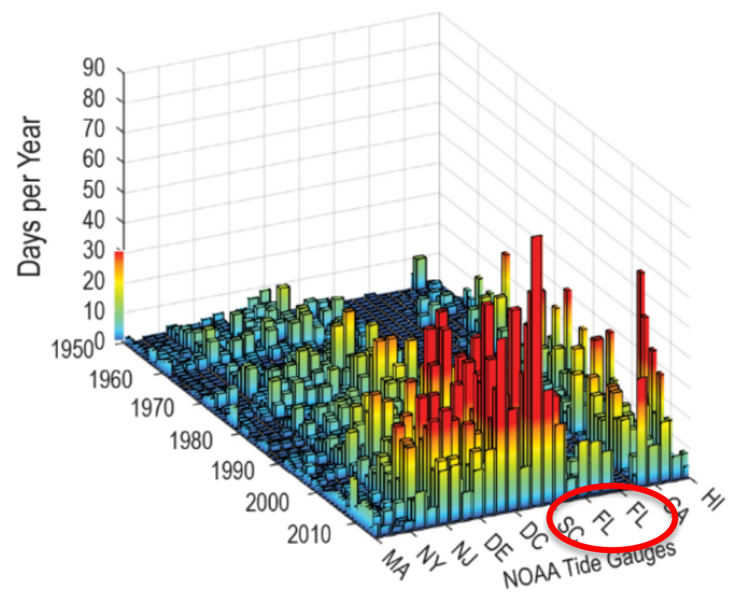
Nuisance elevation thresholds relative to mean higher high water (MHHW)





(Wuebbles et al. 2017 CSSR)

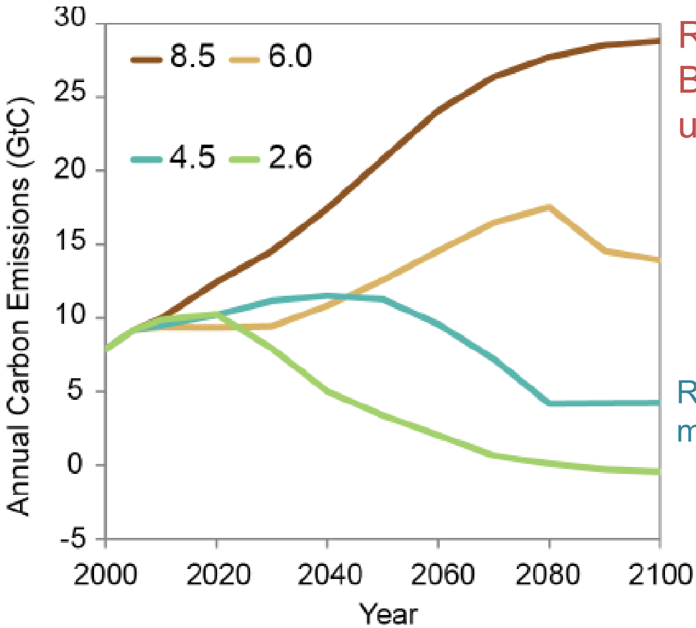
Nuisance Tidal Floods



Scenarios for climate projections

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*

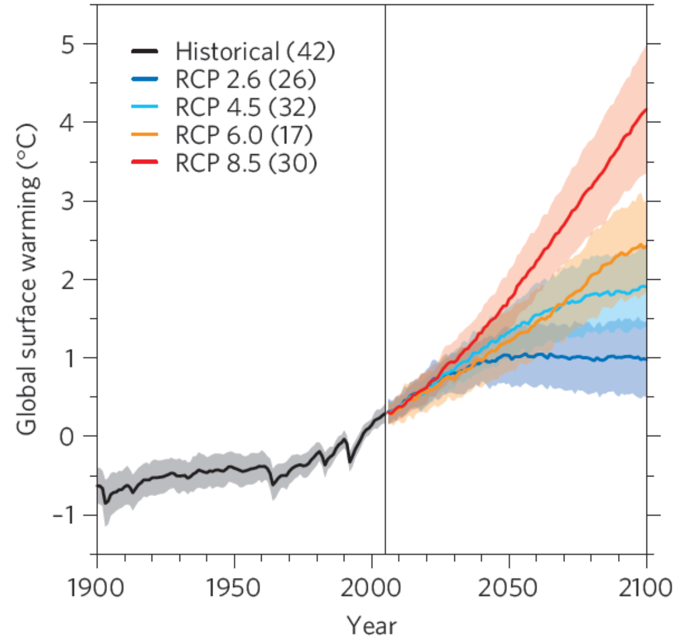
Representative Concentration Pathway (RCP) carbon emission scenarios



RCP8.5: Business-as-usual

RCP4.5: Climate mitigation

Global surface warming simulated by CMIP5 models



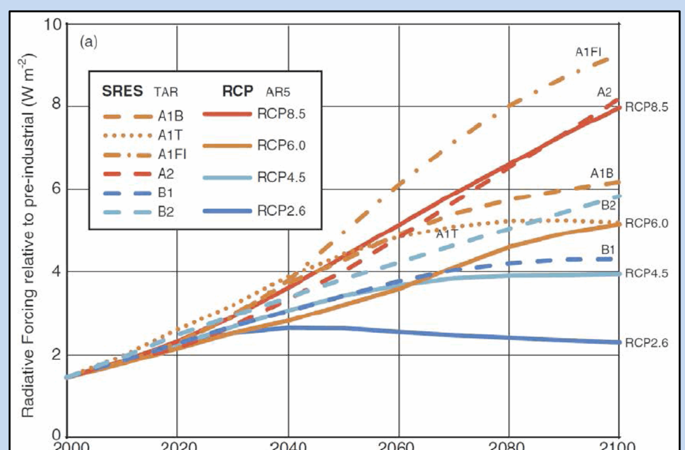
RCP8.5

RCP4.5

Comparison of scenarios used in IPCC AR4 and AR5:

Business-as-usual: A2 – RCP8.5

Climate mitigation: B1 – RCP4.5



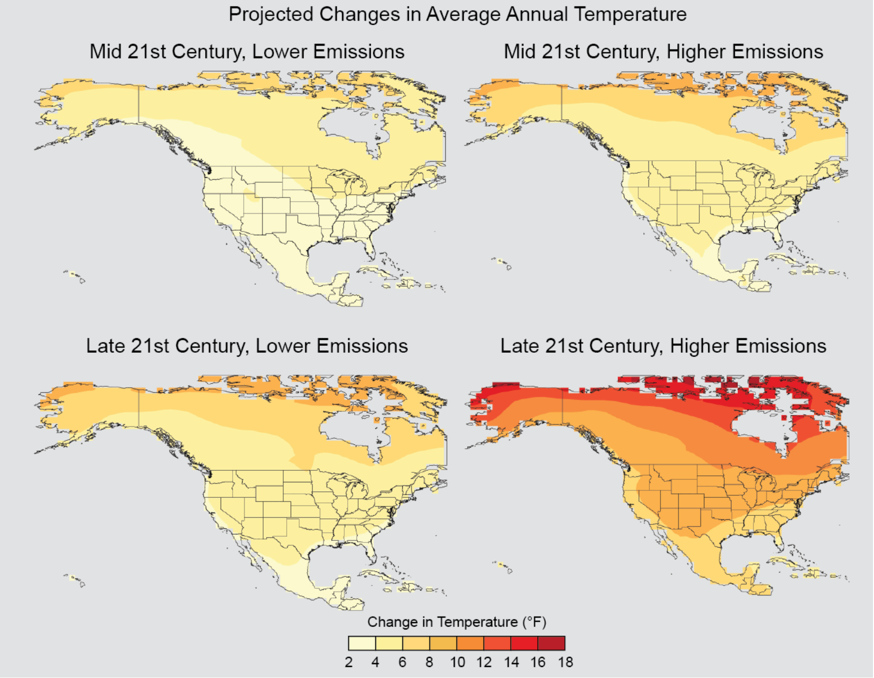
A2 ~ RCP8.5

B1 ~ RCP4.5

Frequency of high temperature projected to increase

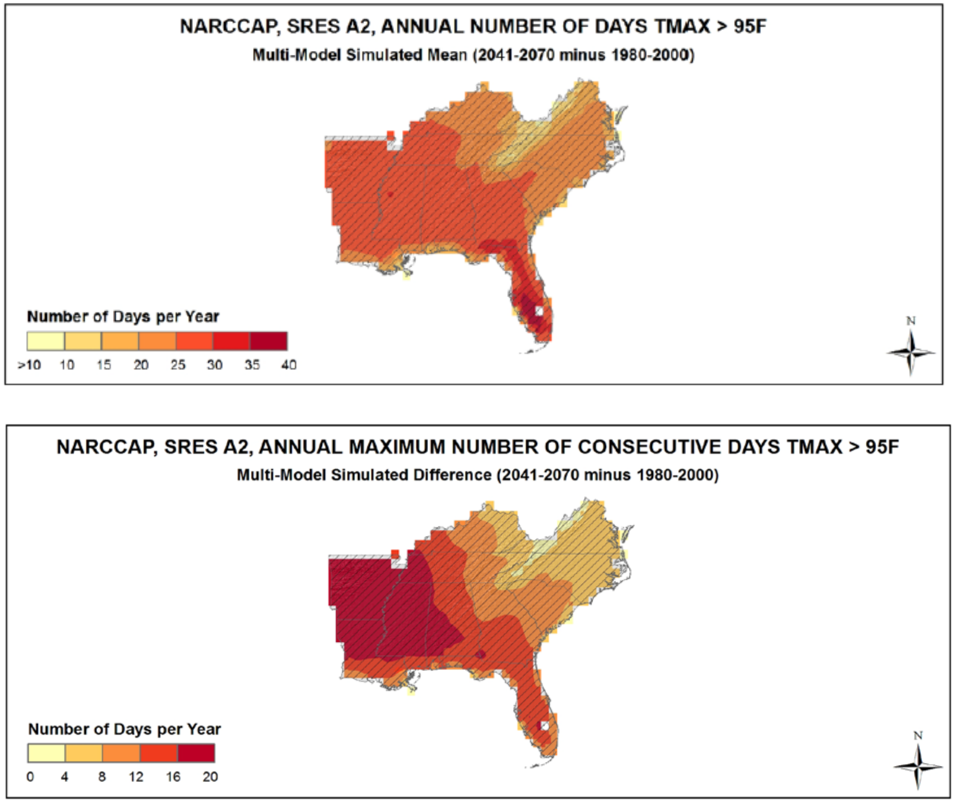
Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

No "warming hole" in future projections
Milder warming along the coast compared to inland



(Wuebbles et al. 2017 CSSR)

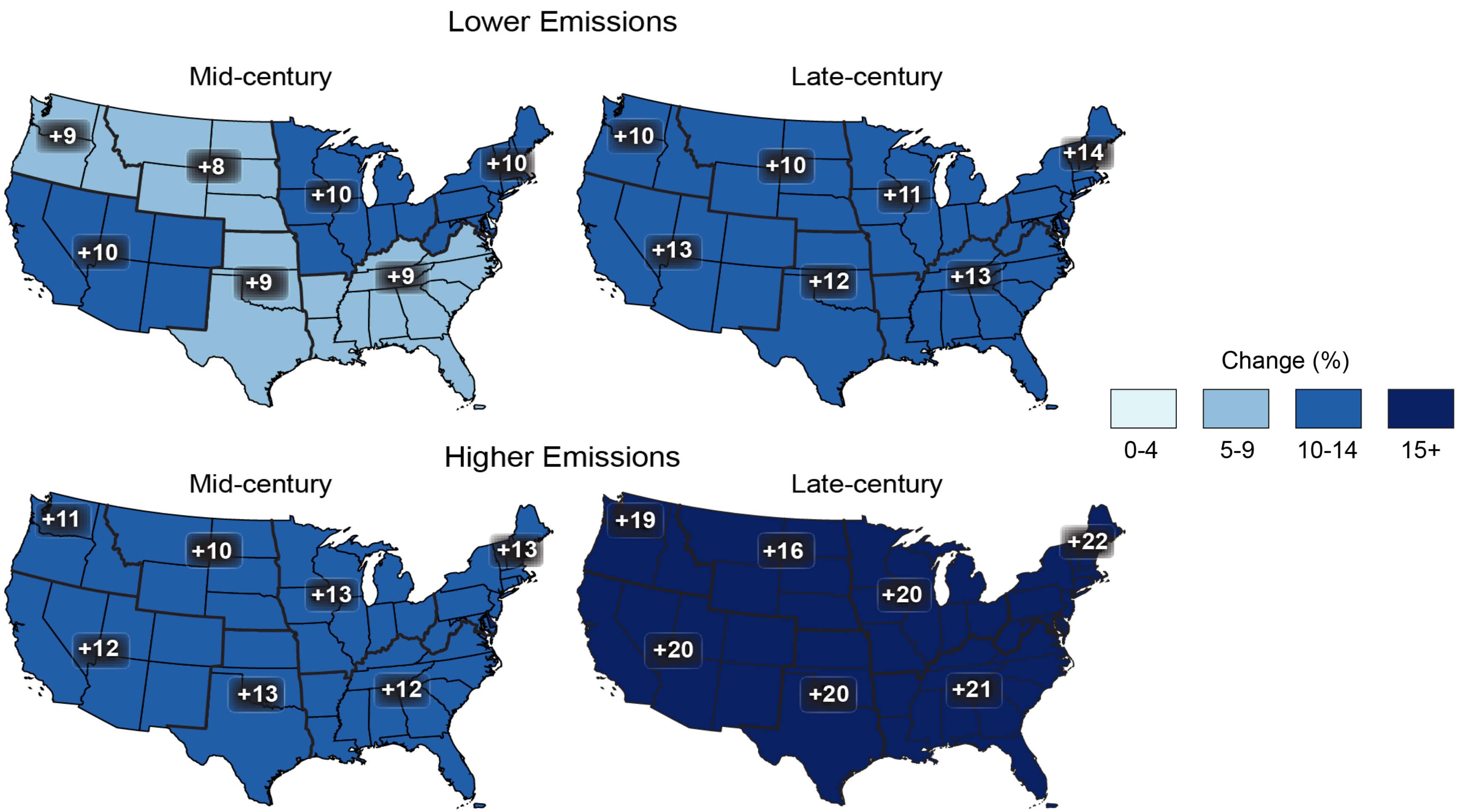
Multi-model mean changes from 8 NARCCAP simulations for A2 scenario



(NOAA NESDIS Technical Report 2013)

Extreme precipitation projected to increase in the future

Projected change in daily, 20-year extreme precipitation: scales with the magnitude of warming



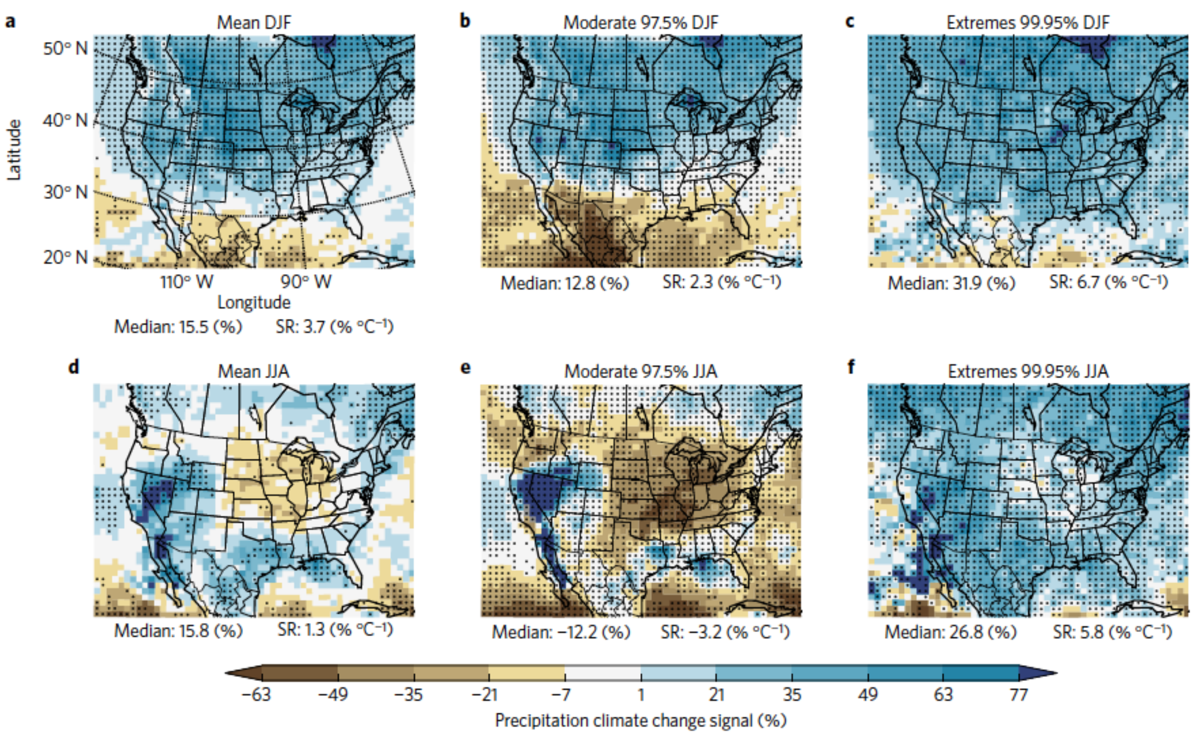
(Wuebbles et al. 2017 CSSR)

Exceedance probability of 99.95% hourly precipitation may increase by fourfold

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*

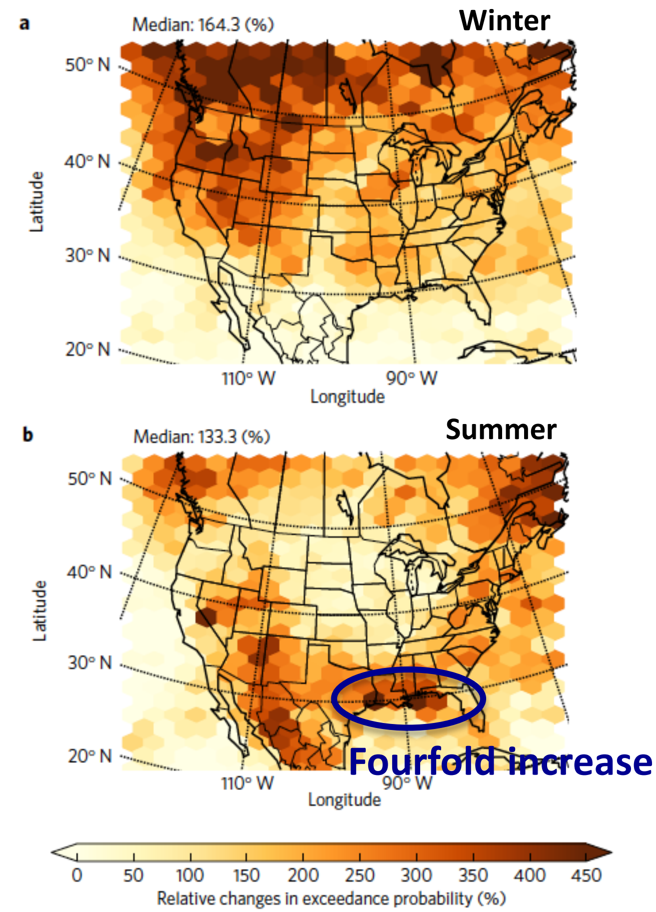
- Convection permitting modeling shows dominant increases in 99.95% extreme hourly precipitation across the US

Precipitation change (%) for 2071-2100 relative to 1976-2005: increase in 99.95% everywhere



(Prein et al. 2016 Nature Climate Change)

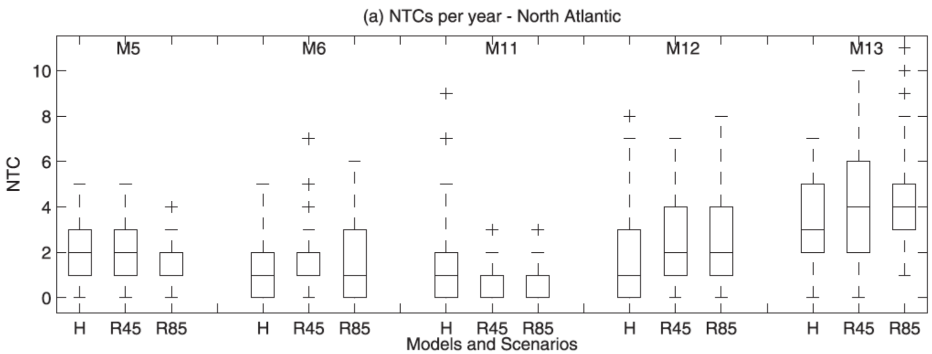
Relative change in exceedance probability of the present day 99.95% hourly precipitation



Frequency of intense tropical cyclones is projected to increase

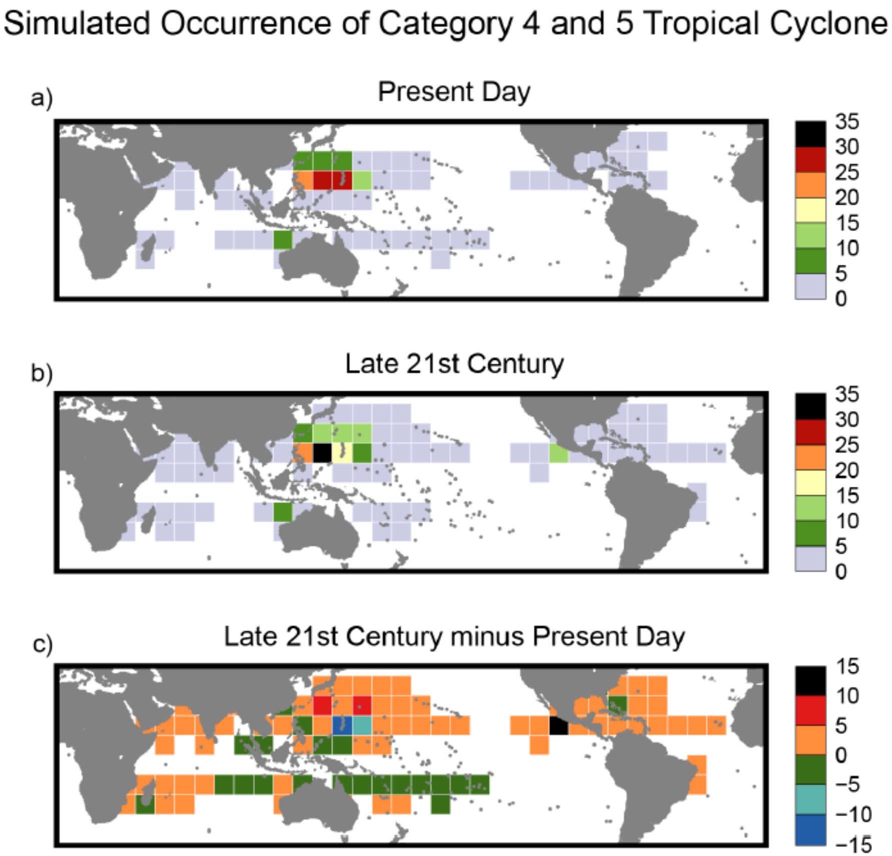
Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*

No consistent change in Atlantic TC number across models
(unit: TC number per year)



(Camargo et al. 2013 J. Climate)

High resolution modeling shows increasing frequency of category 4 and 5 TCs
(unit: storms per decade)



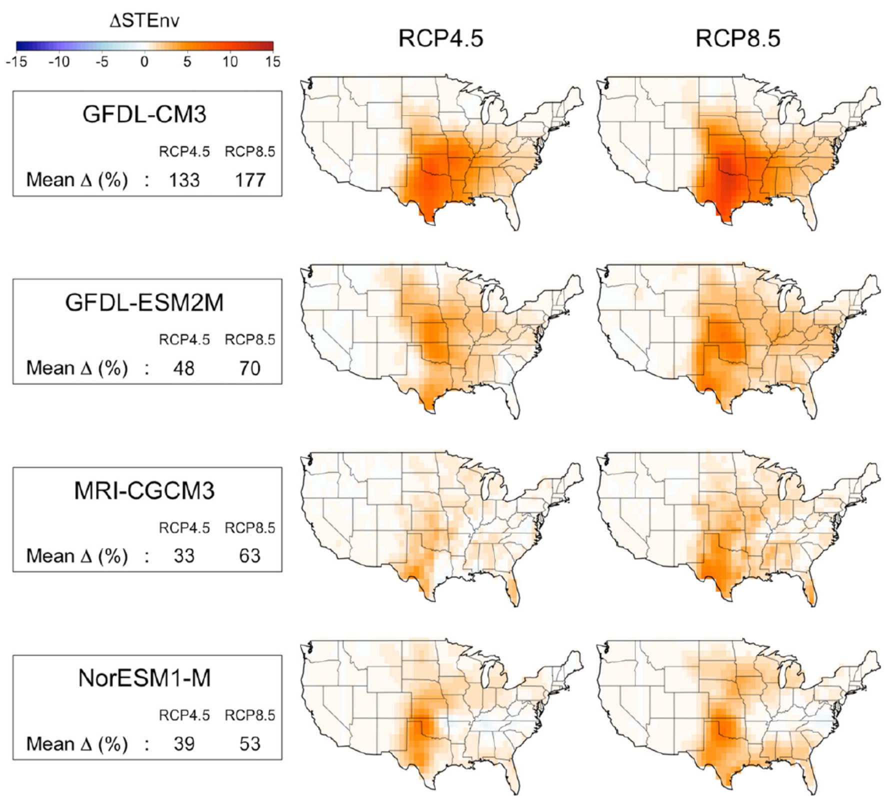
(Wuebbles et al. 2017 CSSR; from Knutson et al. 2015 J. Climate)

Severe thunderstorm environment more favorable in future springtime

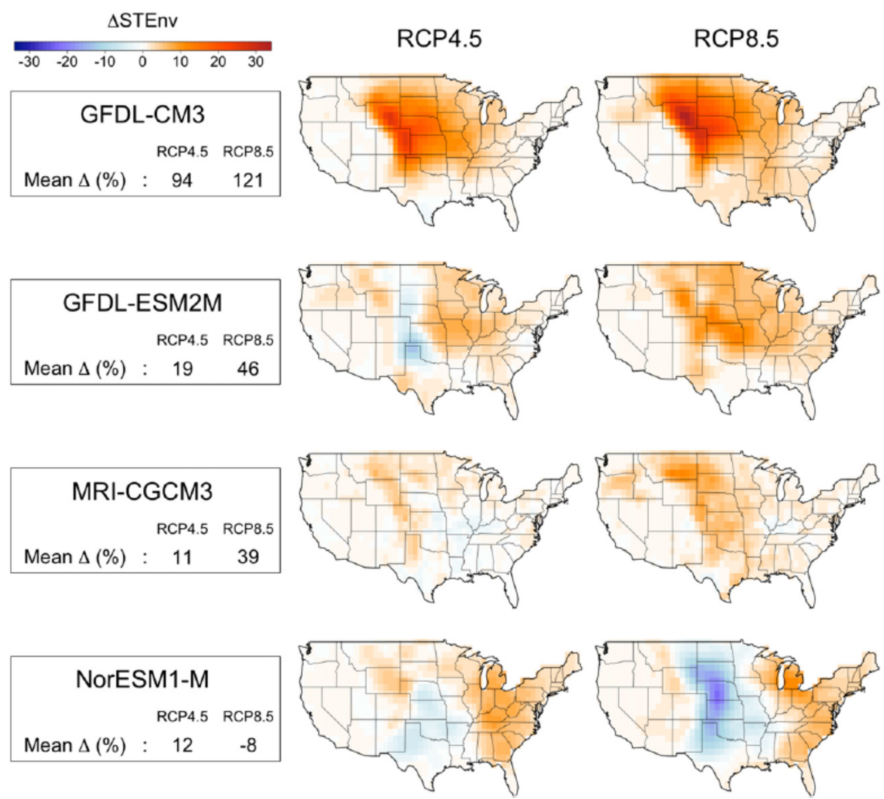
Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- Severe thunderstorm environment (STEnv) is defined based on Convective Available Potential Energy (CAPE) and vertical wind shear

Consistent increases in STEnv projected for spring across models and scenarios

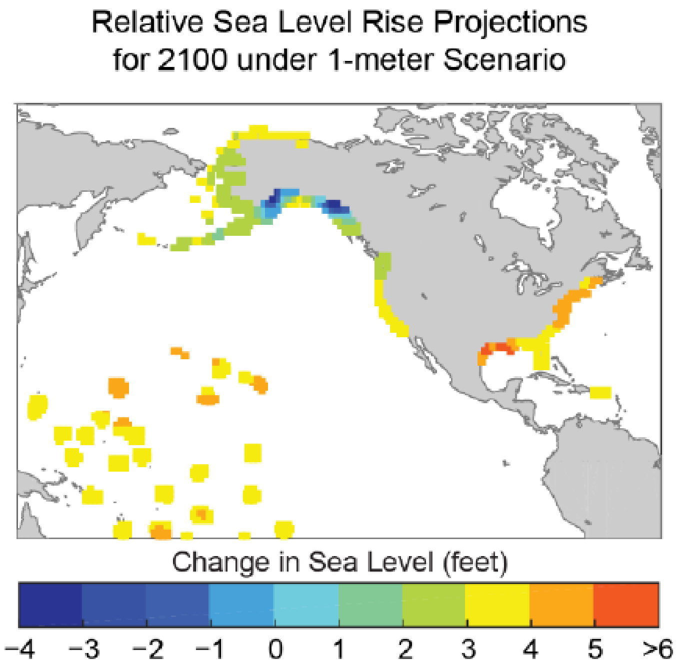


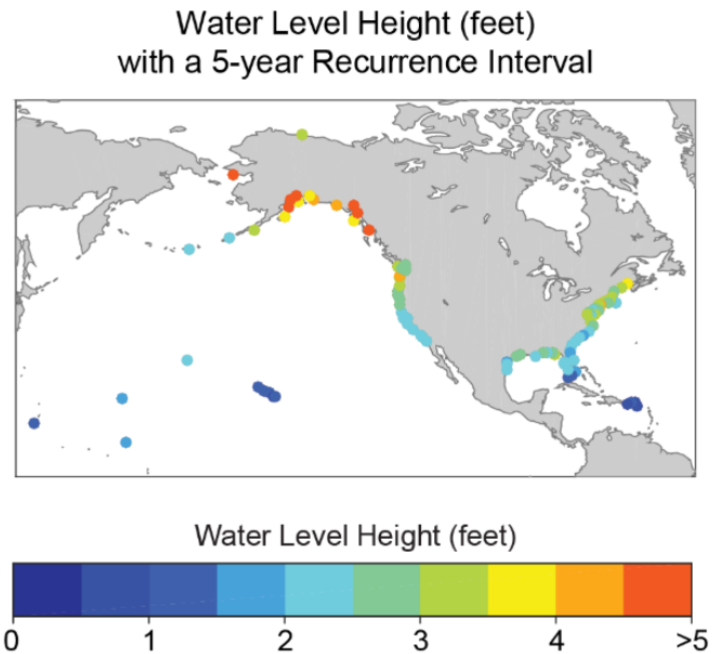
Inconsistent changes in STEnv projected for summer due to diverging changes in boundary layer humidity

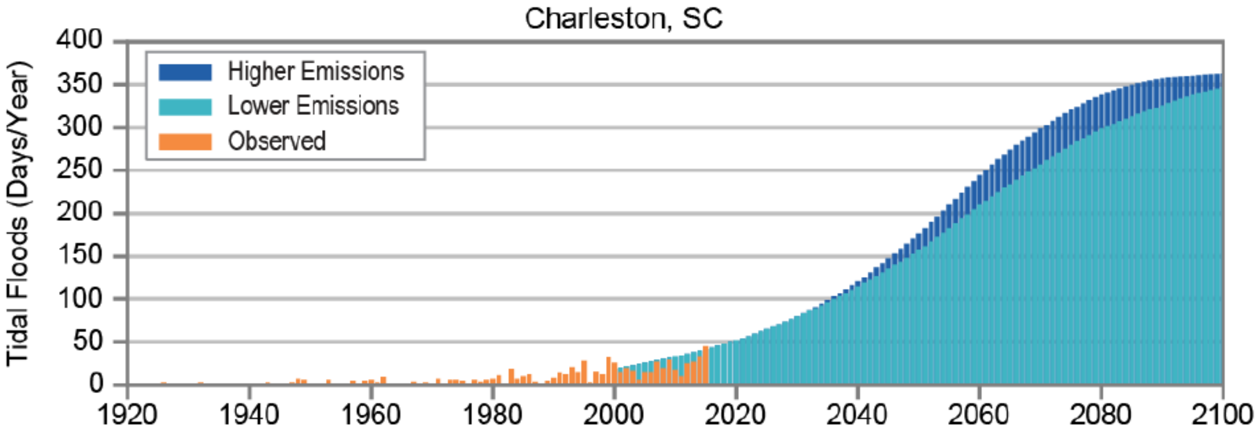


(Seeley and Romps 2015 J. Climate)

Increase in regional sea level and tidal floods





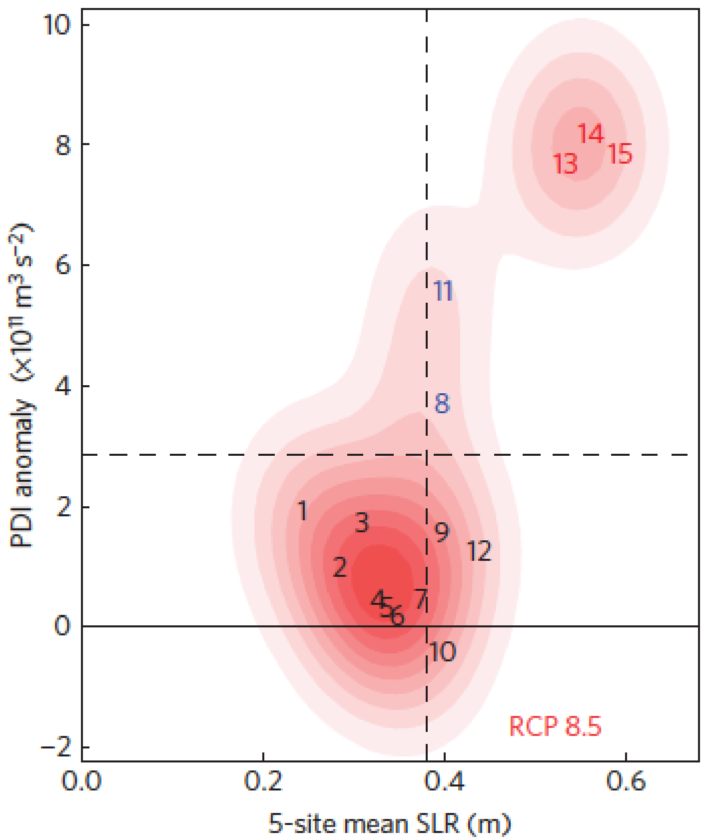


(Wuebbles et al. 2017 CSSR)

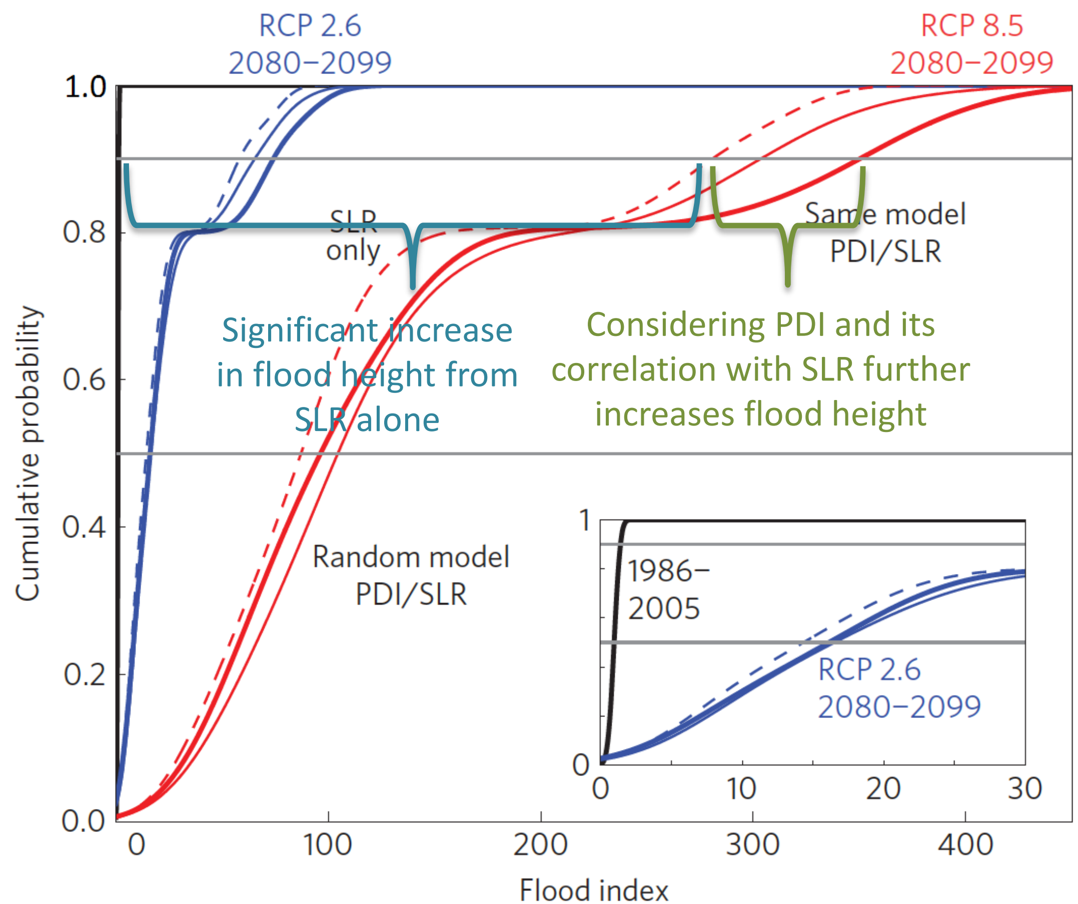
Joint projections of sea level and storm surge

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

Joint probability density function of sea level rise (SLR) and power dissipation index (DPI) from 15 climate models



Cumulative distribution functions for the 1986–2005 (black) and 2080–2099 flood index under RCP2.6 (blue) and RCP8.5 (red)



(Little et al. 2015 Nature Climate Change)

Hydrologic characteristics of the Southeast region

- Floods in the southeast region can be produced by
  - locally heavy precipitation
  - slow-moving extratropical cyclones during the cool season
  - tropical cyclones during summer and fall
  - late spring rainfall on snowpack
  - storm surge near coastal areas from hurricanes, and
  - occasional large releases from upstream dams.
- Examples of recent floods
  - The August 2016 Louisiana floods
  - The March 2016 southern floods
  - The October 2016 Hurricane Matthew floods
- Droughts in the southeast region
  - relatively short duration (one to three years)
  - recent episodes: 1998-2002 and 2007-2008
- Projected changes in soil moisture and runoff in the southeast region are not statistically significant

Hydrologic impacts to Southeast region

- Several studies
  - Effects of urbanization and climate change on freshwater resources
    - Hay et al. (2011), Viger et al. (2011), Bastola (2013), Sun et al. (2015)
- Bastola (2013)
  - Assessed 28 southeast US watersheds

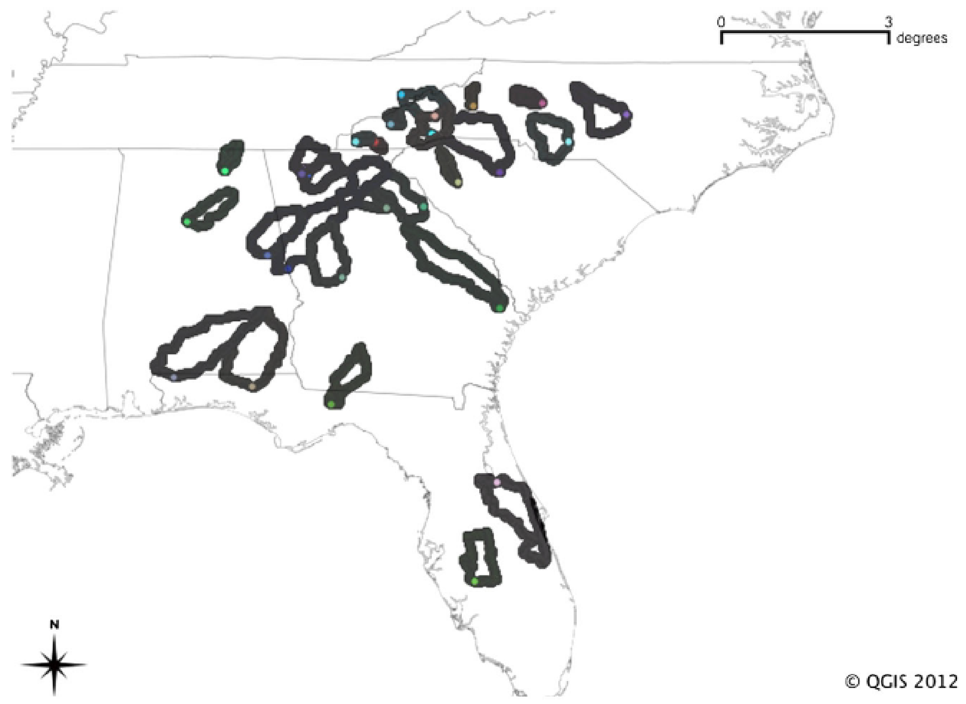
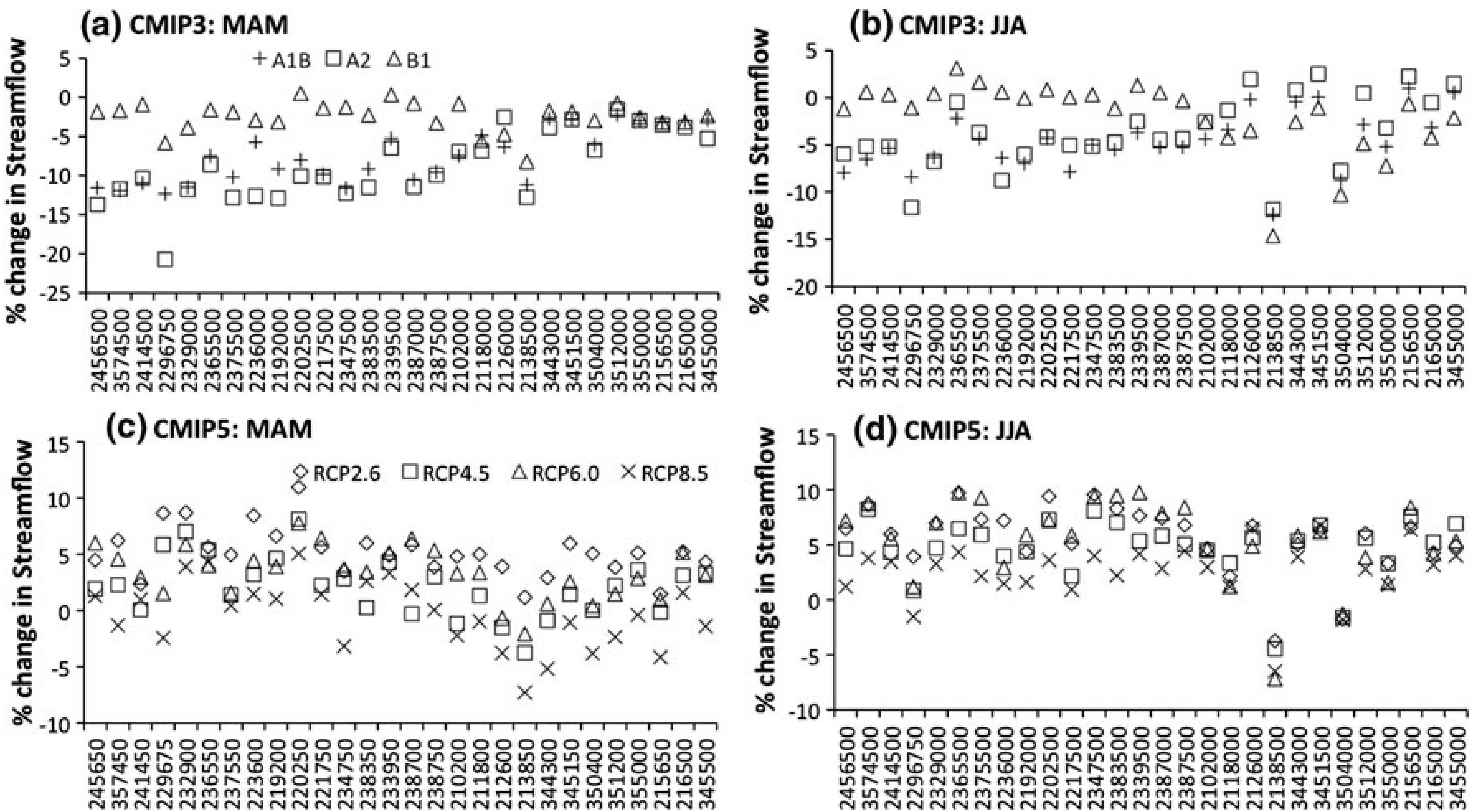


Figure 1. Location of the 28 watersheds within the southeastern United States used in this study

Hydrologic impacts to Southeast region

- Results from Bastola (2013)



Hydrologic impacts to Southeast region

- Hay et al. (2011) and Viger et al. (2011)

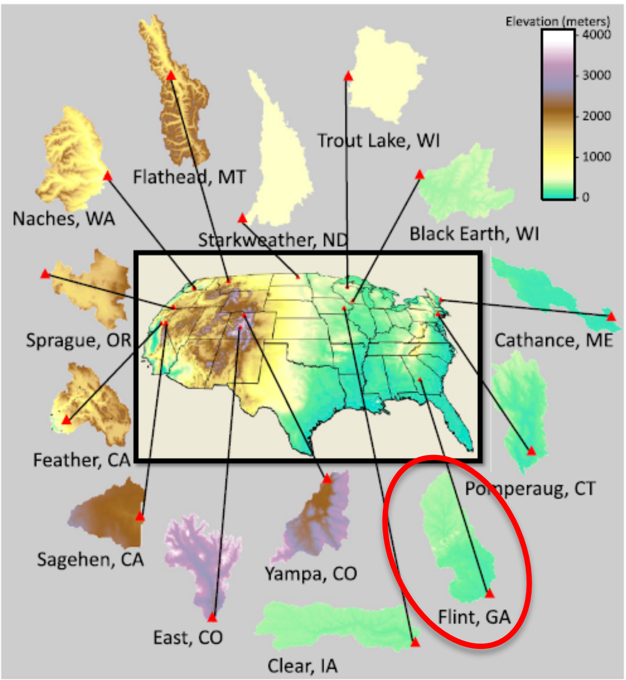


Figure 1. Location map of the United States showing the sites of the 14 selected basins. PRMS models were developed for the basin areas shown. Red triangle denotes location of stream gauge for model calibration (note that basins are not to scale; see Table 1 for relative scales).

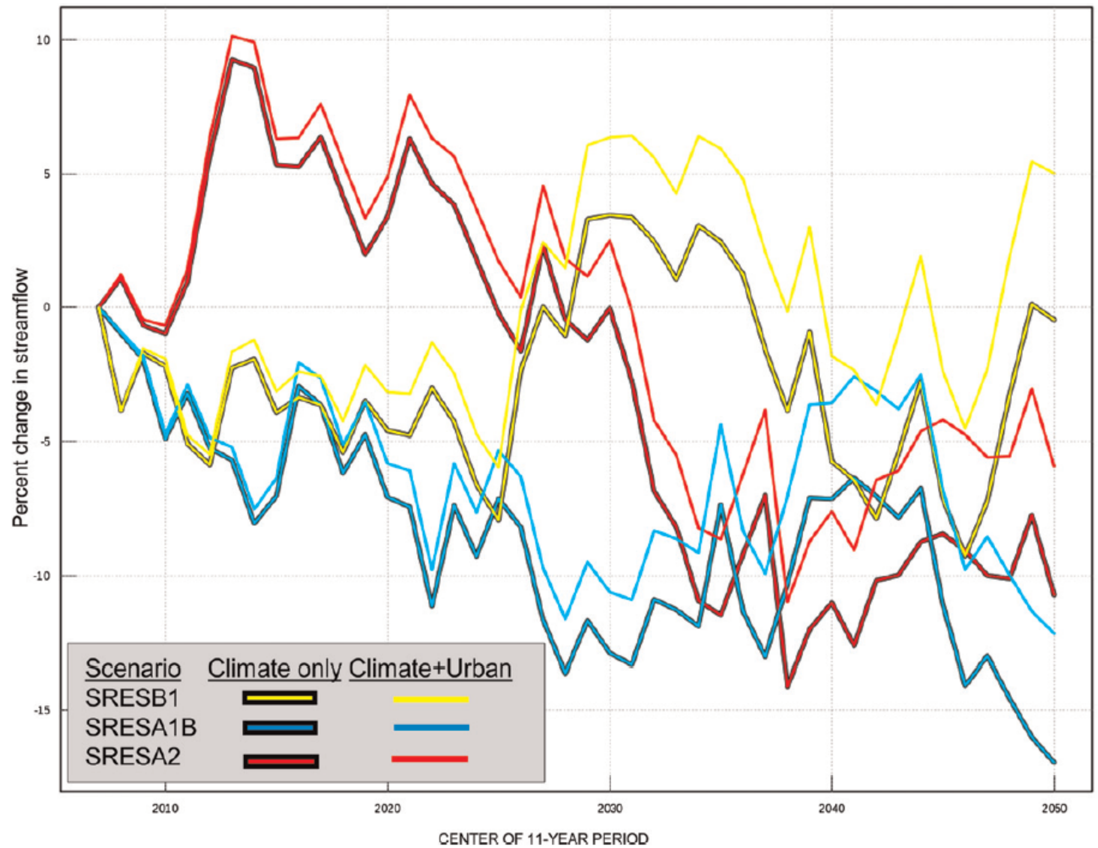


Figure 11. Percent change in 11-yr moving mean daily values of streamflow derived from the five GCMs, with (solid lines) and without (outlined in black) urbanization forecasts, grouped by climate-change scenario.

Insights for floods in Southeast region

- Many hydrometeorologic parameters that influence floods are not directly addressed in NCA3
- Studies typically investigate the impacts of climate change on runoff characteristics
  - Mean annual, seasonal, or monthly flows
- Floods of interest to the NRC, particularly for safety analysis and review
  - Significantly shorter time-scales (hours to days)
  - Almost always are in the tails of the distribution, away from the mean
  - Typically need complete hydrographs
  - With existing studies, direct conclusions are difficult to draw
- Insights of interest
  - A site -specific analysis should be performed
  - A change in the mean behavior of floods can also reflect a change in the behavior in the tails
  - Further investigations are needed to couple the outputs of GCMs to hydrologic models
  - Exploring dynamical downscaling and nesting of hydrological models
  - Significant uncertainty in predictions of hydrologic models will exist; a framework is needed
  - Site-specific flood protection and mitigation assessment under risk-informed approach

Insights for droughts in Southeast region

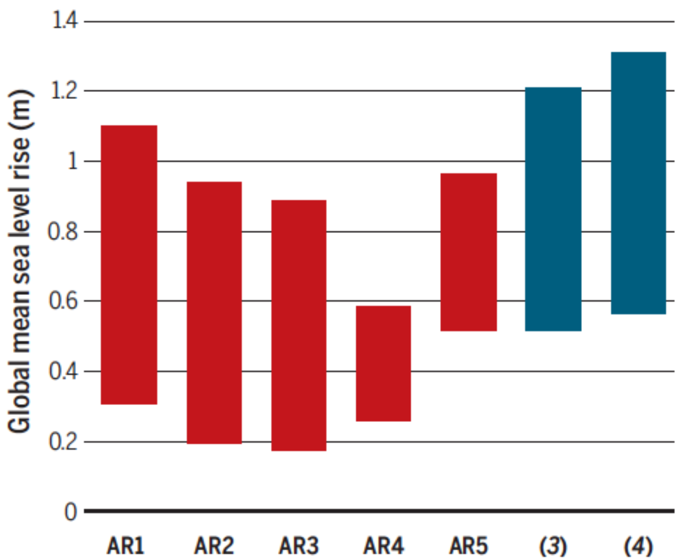
Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle *Since 1965*

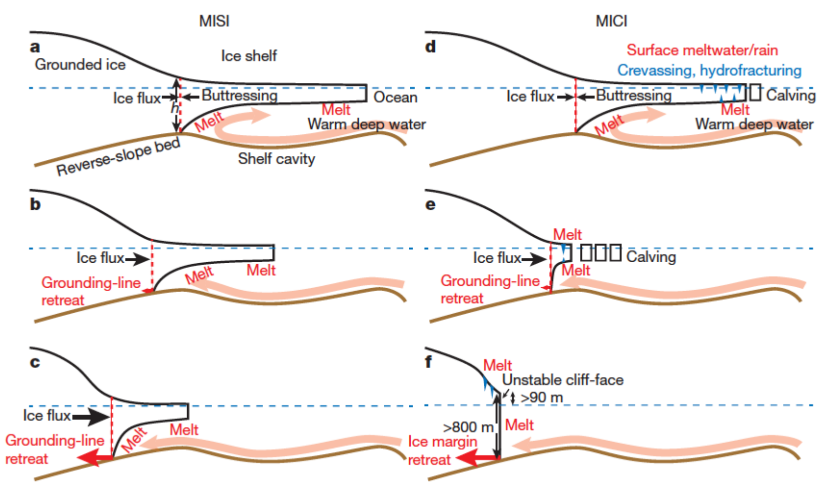
- Many hydrometeorologic parameters that influence droughts are not directly addressed in NCA3
- Studies typically investigate the impacts of climate change on runoff characteristics
  - Mean annual, seasonal, or monthly flows
  - These metrics are useful to the NRC in the review for water use and environmental impacts of plants
- Additional low-flow metrics that are useful to NRC
  - Persistence and frequency of low flows, both seasonally and in the context of multi-year droughts
  - Not directly addressed in current studies
- Insights of interest
  - Site-specific drought assessments
  - Regional and local characteristics may be important
    - Bermuda/Azores high
    - Urbanization and population growth
    - Water management practices
  - Significant uncertainties in all aspects of climate-hydrology assessments is expected to exist
    - Framework needed
    - Periodic refinement of site-specific low-flow assessments

Uncertainty: the evolving SLR projections

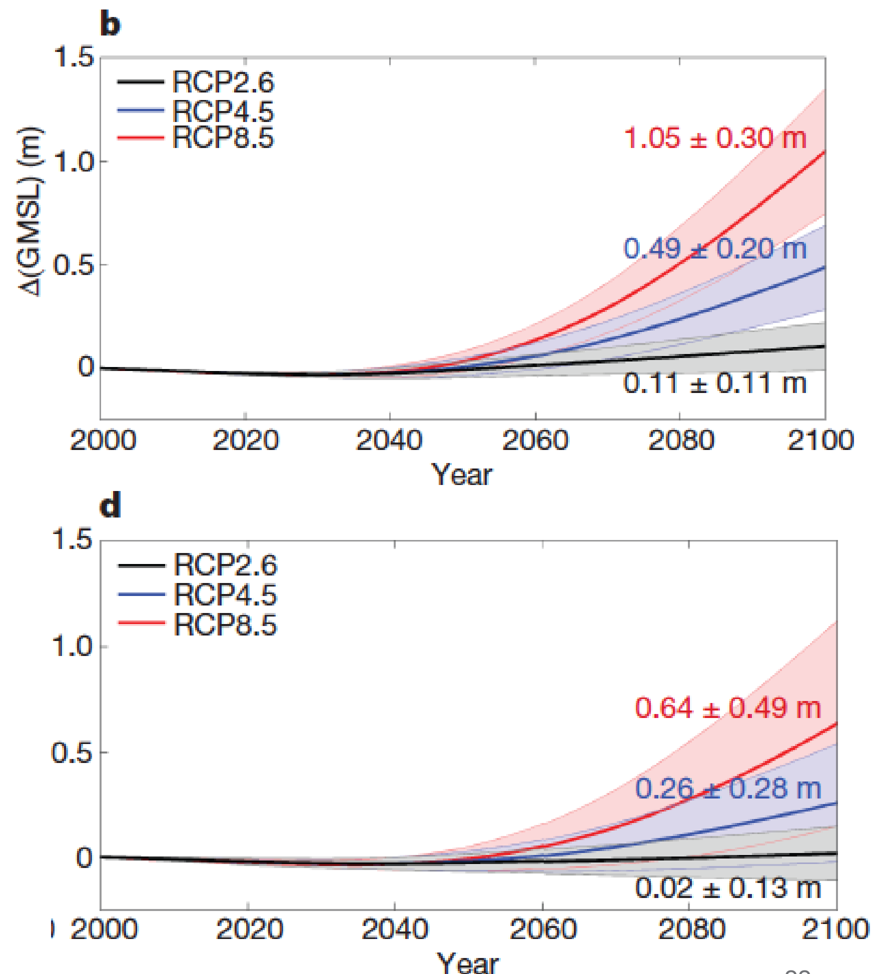
The fall and rise of projected sea level rises



(Oppenheimer and Alley 2016 Science)



Projections of GMSL change with model parameters constrained by geologic criteria (Pliocene and Last Interglacial)



(DeConto and Pollard 2016 Nature)

Summary

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- The US Southeast experiences large subseasonal-to-decadal climate variability that partly obscures the long term trends
- The region is vulnerable to extremes related to hurricanes, severe thunderstorms, storm surge, and flooding and drought
- Despite insignificant changes in mean temperature and precipitation, observational records have revealed past changes in extreme events over the Southeast
- Climate models projected significant changes in extremes in the future (extreme heat and precipitation, intense TCs, severe thunderstorms, SLR, storm surge)
- Multi-model and large ensemble modeling as well as high resolution modeling are becoming more computationally feasible, which may provide opportunities for characterizing and reducing uncertainties
- Potential surprises may arise from tipping elements and compound extreme events that are not well understood/modeled

Contact Information

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

L. Ruby Leung
509-372-6182
Ruby.Leung@pnnl.gov

Elena Yegorova
301-415-2440
Elena.Yegorova@nrc.gov

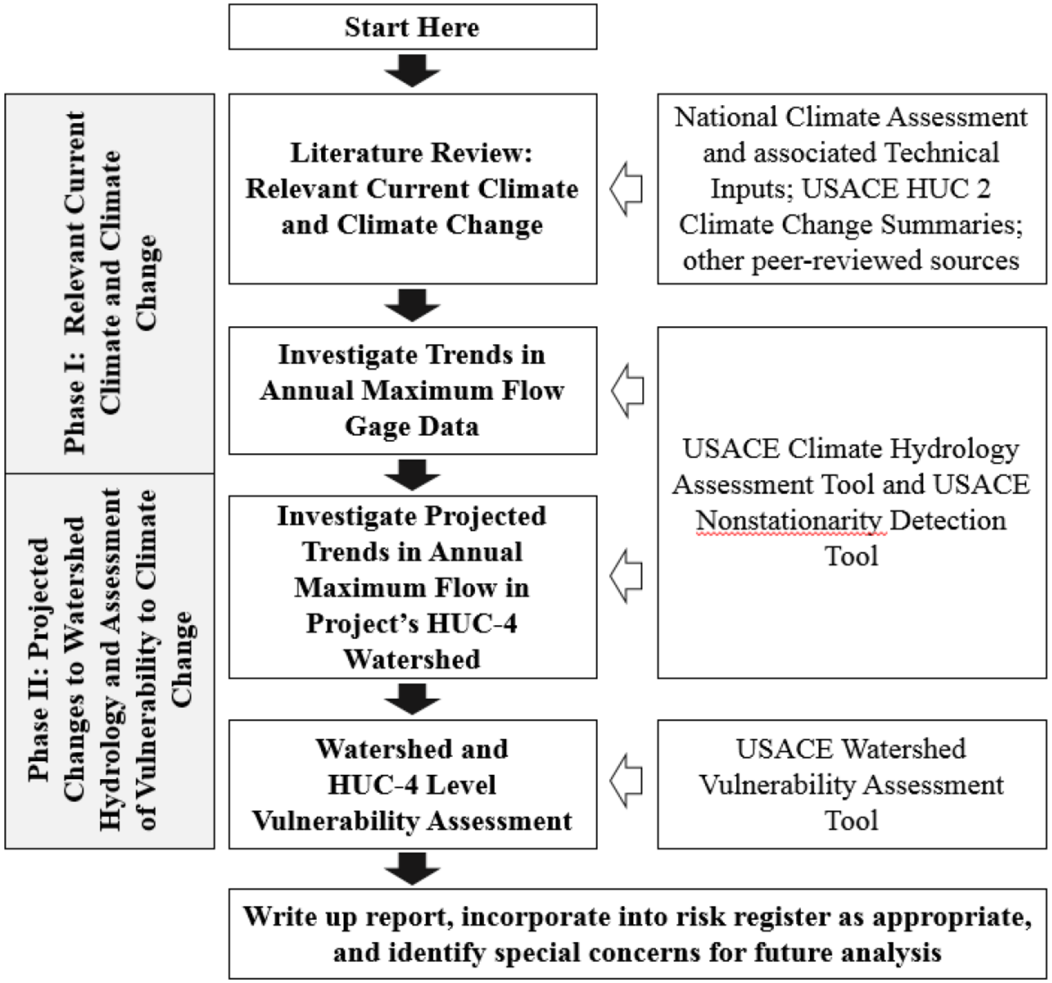
Backup slides

Agency activities

- The Fourth National Assessment Report (NCA4) process has begun, with development of the Climate Science Special Report (CSSR) (third-order draft in review)
- GMD special issue on final CMIP6 experimental design and forcing in review (http://www.geosci-model-dev.net/special_issue590.html).
- DoD released report on "Regional Sea Level Scenarios for Coastal Risk Management: Managing the Uncertainty of Future Sea Level Change and Extreme Water Levels for Department of Defense Coastal Sites Worldwide" in April 2016
- The USACE Responses to Climate Change Program (http://corpsclimate.us/index.cfm)
  - The USACE published the Engineering and Construction Bulletin (ECB) No. 2016-25, Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects (USACE, 2016)

Agency activities

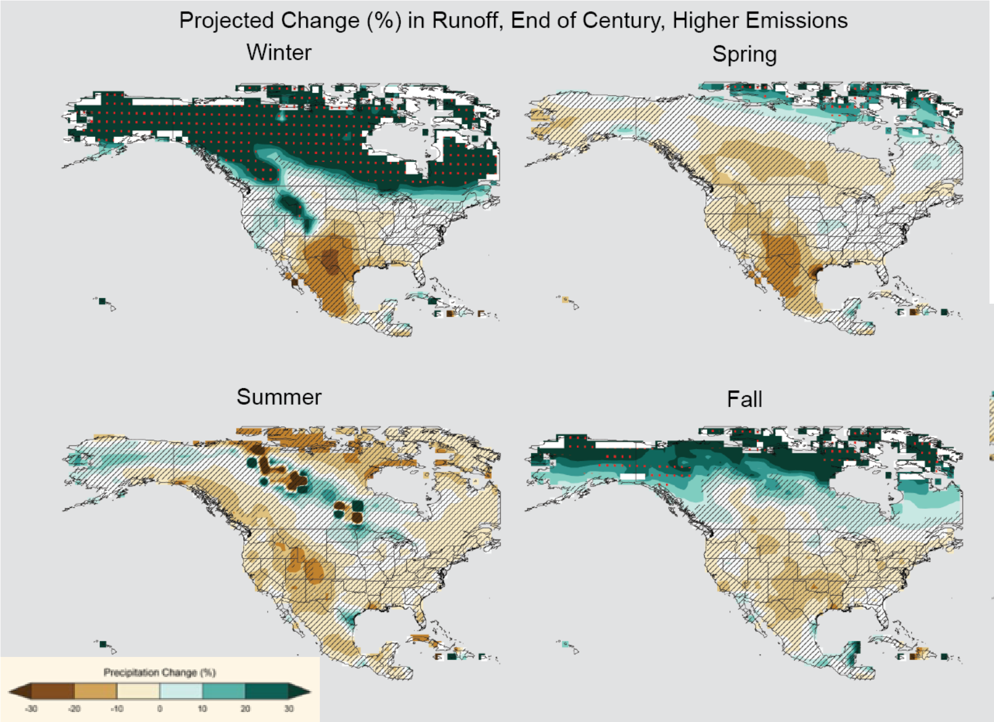
- USACE published "Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects"

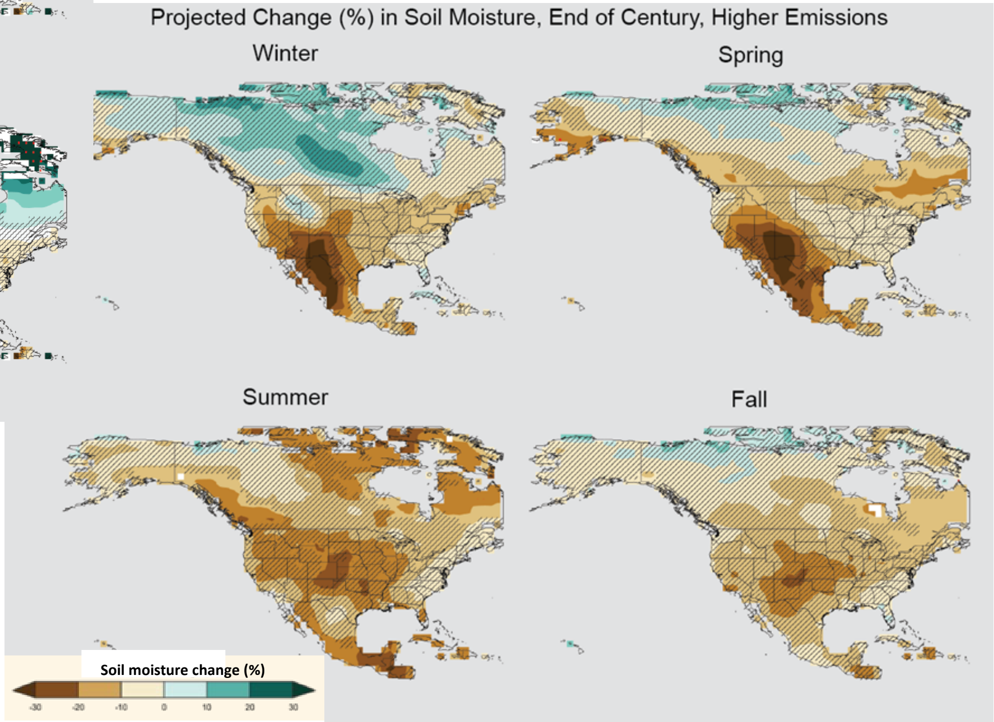


USACE, 2016

Projections for the Southeast region

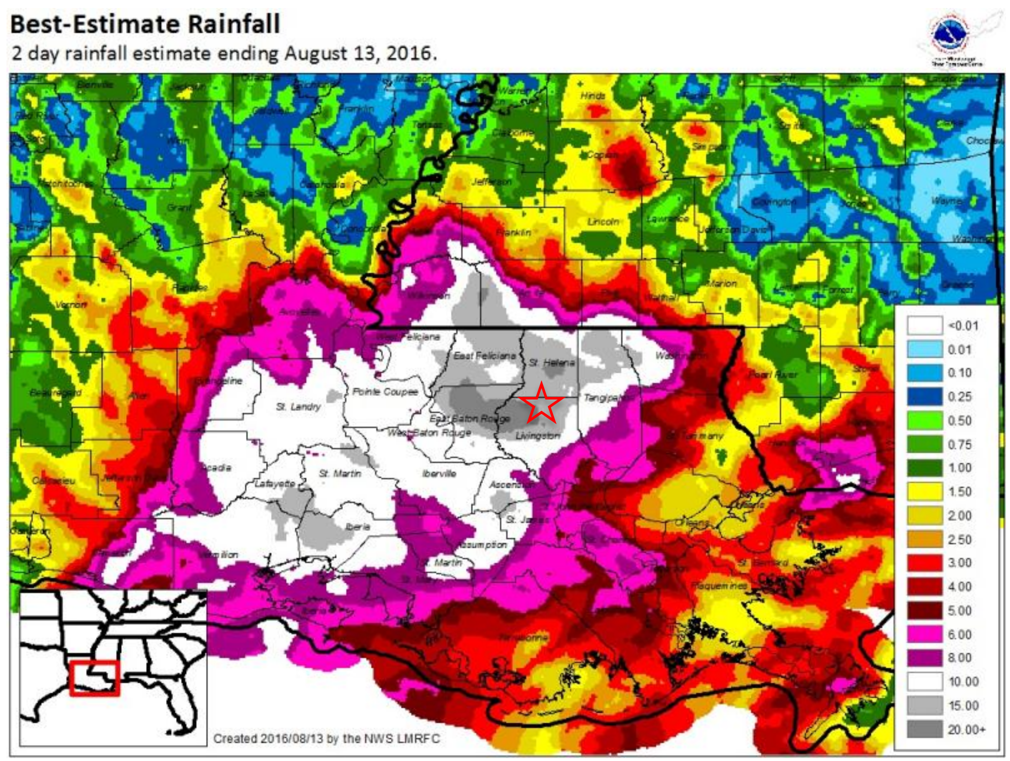
- Projected change in soil moisture and runoff (CSSR 2017)





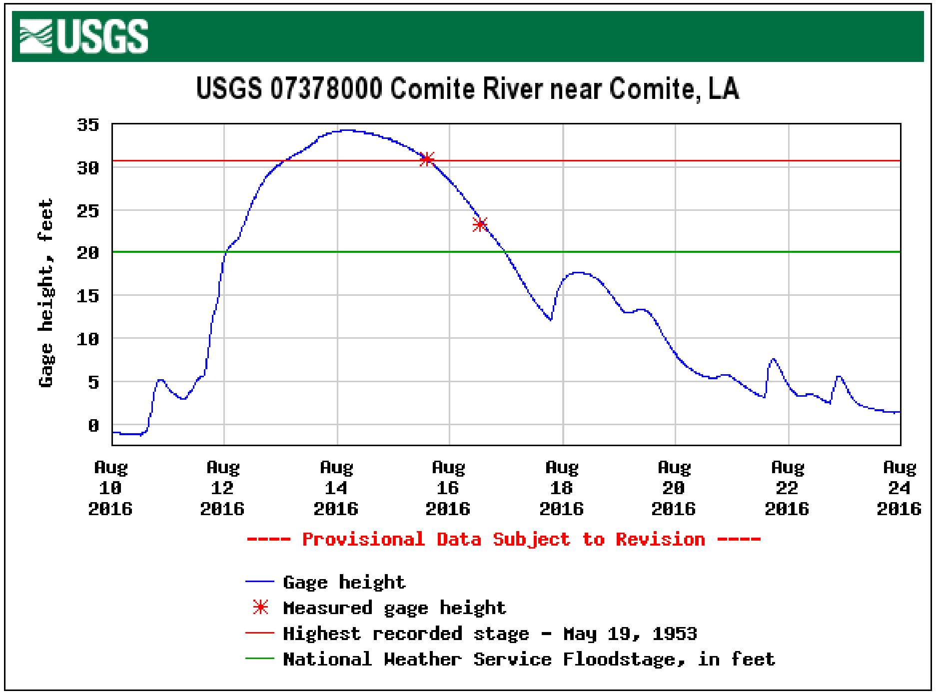
Floods in the Southeast region

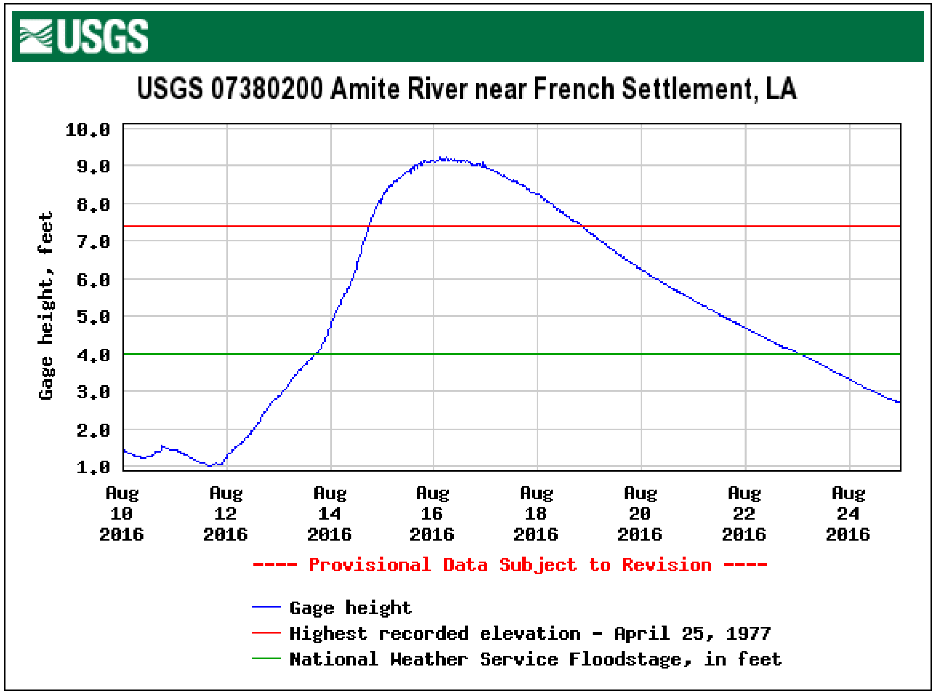
- The August 2016 Louisiana floods
  - On August 5 a storm front developed near AL and FL
  - NHC stated it may become a TD after moving into the Gulf of Mexico
  - Storm slowly moved over land
  - Stationary over southern LA on August 12
  - Multiple thunderstorms next 3 days
  - Livingston, LA received 25.5 in. during this period
  - 3-day total precipitation exceeded both the August average and 3-day annual maximum precipitation 3 times



Floods in the Southeast region

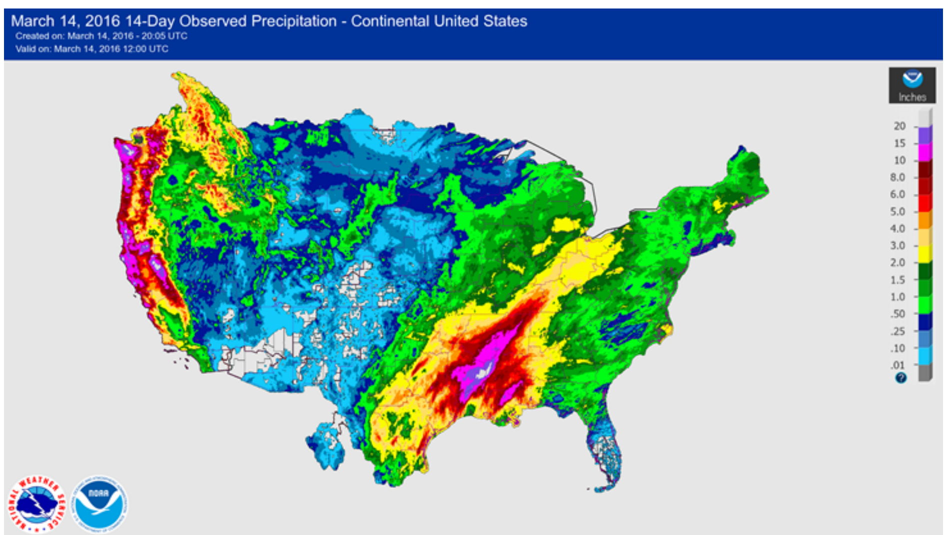
- The August 2016 Louisiana Floods
  - Local drainages and rivers draining to Lakes Ponchartrain and Maurepas flooded
  - Comite River near Comite, LA and Amite River near French Settlement, LA exceeded historical maximum flood stages

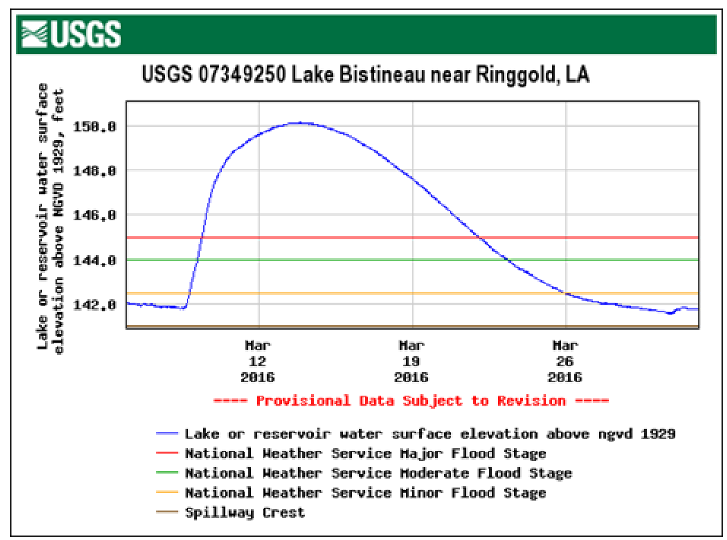




Floods in the Southeast region

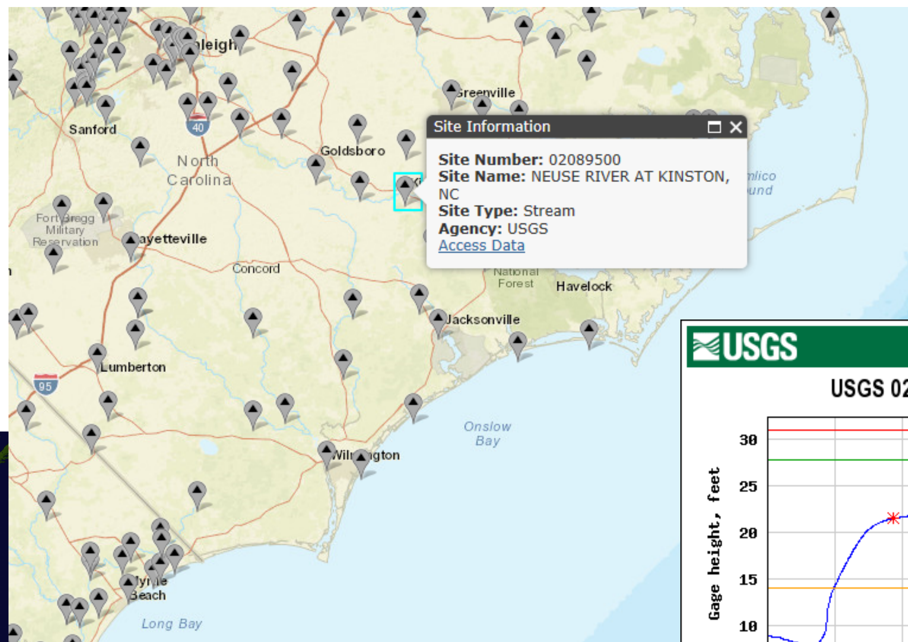
- The March 2016 Southern Floods
  - During mid-March 2016, an unusual combination occurred
    - A low-pressure system to the southwest of the southwest region
    - A high-pressure system to the east of the region, and
    - The jet stream over Mexico much farther south than normal
  - Large amount of moisture from Central America transported to the region
    - The "Maya Express"
    - 4-day total precipitation 1 to 2 ft in northern LA, southeast AR and southwest MS
  - Widespread flooding

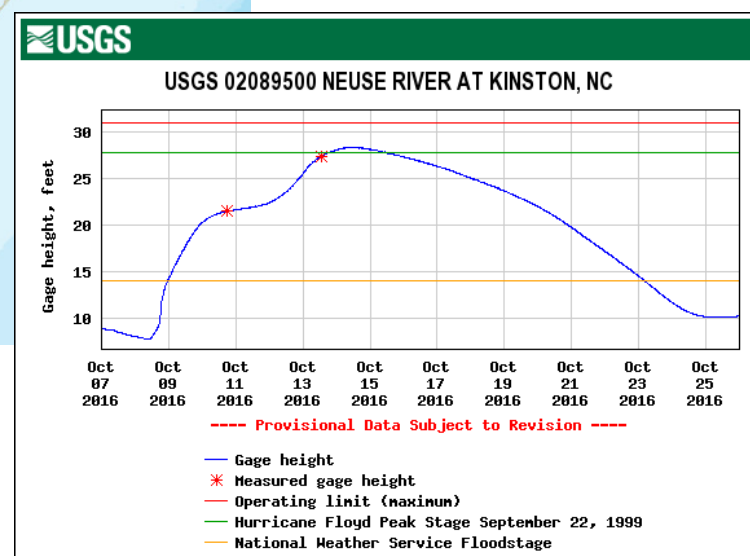




Floods in the Southeast region

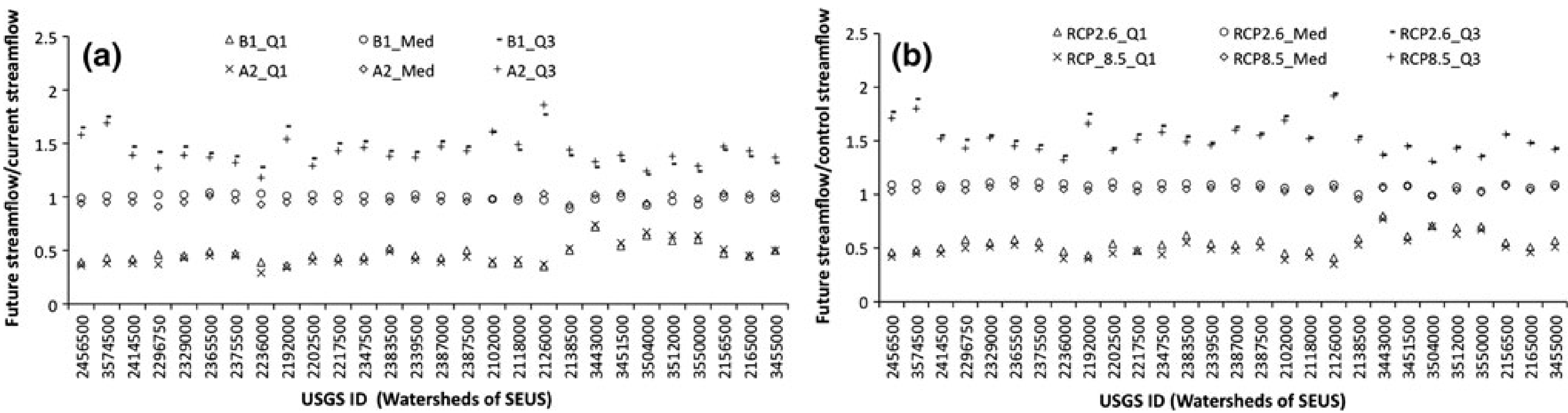
- The Hurricane Matthew Floods
  - Hurricane Matthew passed the eastern US seaboard October 7-9, 2016
  - Rivers flooded, coastal areas affected by large surges
    - Neuse River at Kinston, NC exceeded its historical peak stage by 1.6 ft





Hydrologic impacts to Southeast region

- Results from Bastola (2013)



Hay et al. 2011 modeling schematic

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

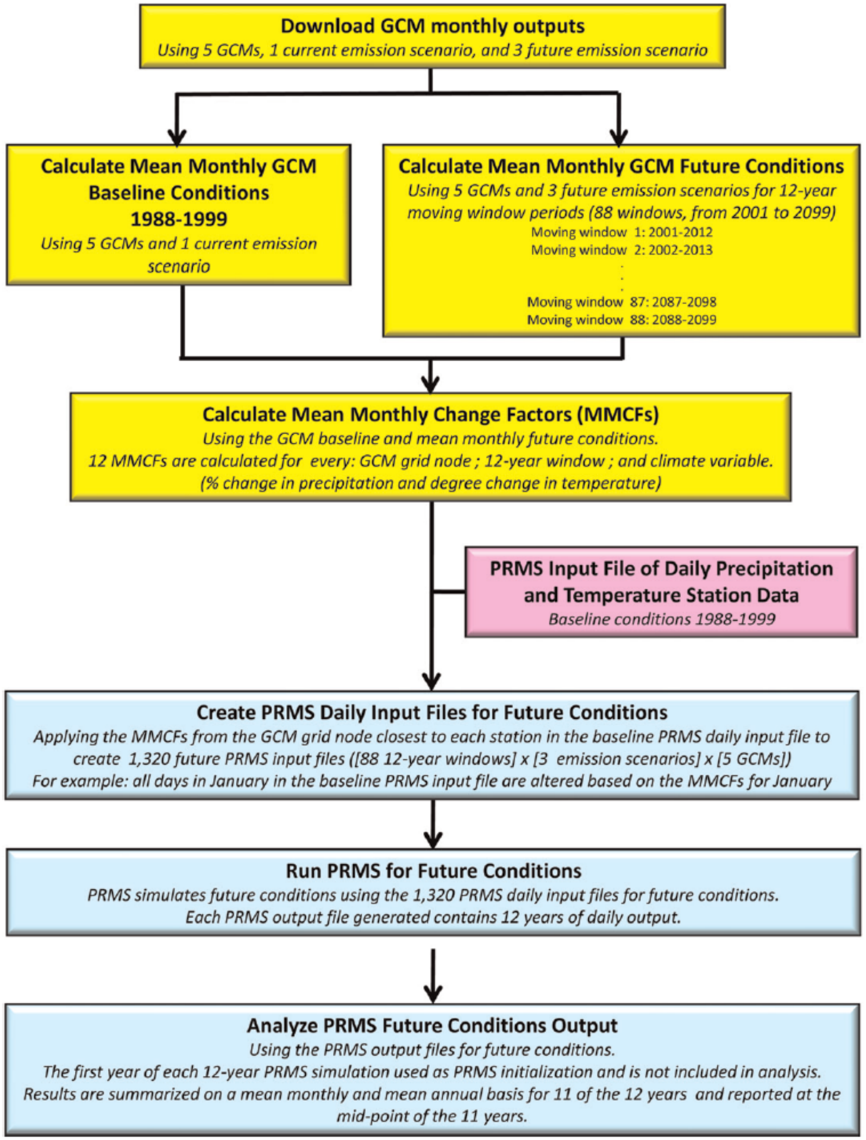


Figure 5. Schematic of the climate-change factor method as applied in this study.

Viger et al. (2011) Results

- Viger et al. (2011)
  - Same hydrologic analysis as in Hay et al. 2011. Flint River basin only.
  - Three configurations were evaluated
    - effects of changes in urbanization
    - effects of changes in climate under constant urbanization
    - effects of changes in urbanization and climate
  - Future trend of land cover estimated using the USGS land-cover data with process-based and statistical extrapolation

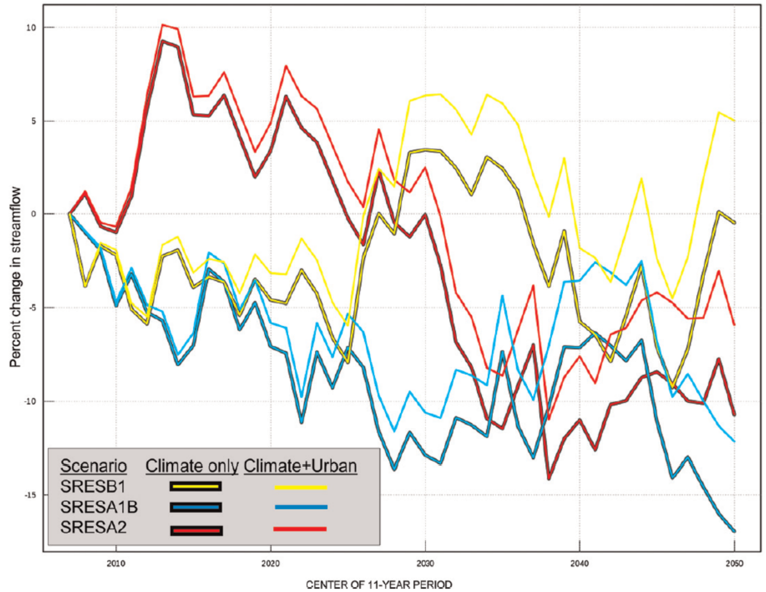


Figure 11. Percent change in 11-yr moving mean daily values of streamflow derived from the five GCMs, with (solid lines) and without (outlined in black) urbanization forecasts, grouped by climate-change scenario.

The USACE Responses to Climate Change Program

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

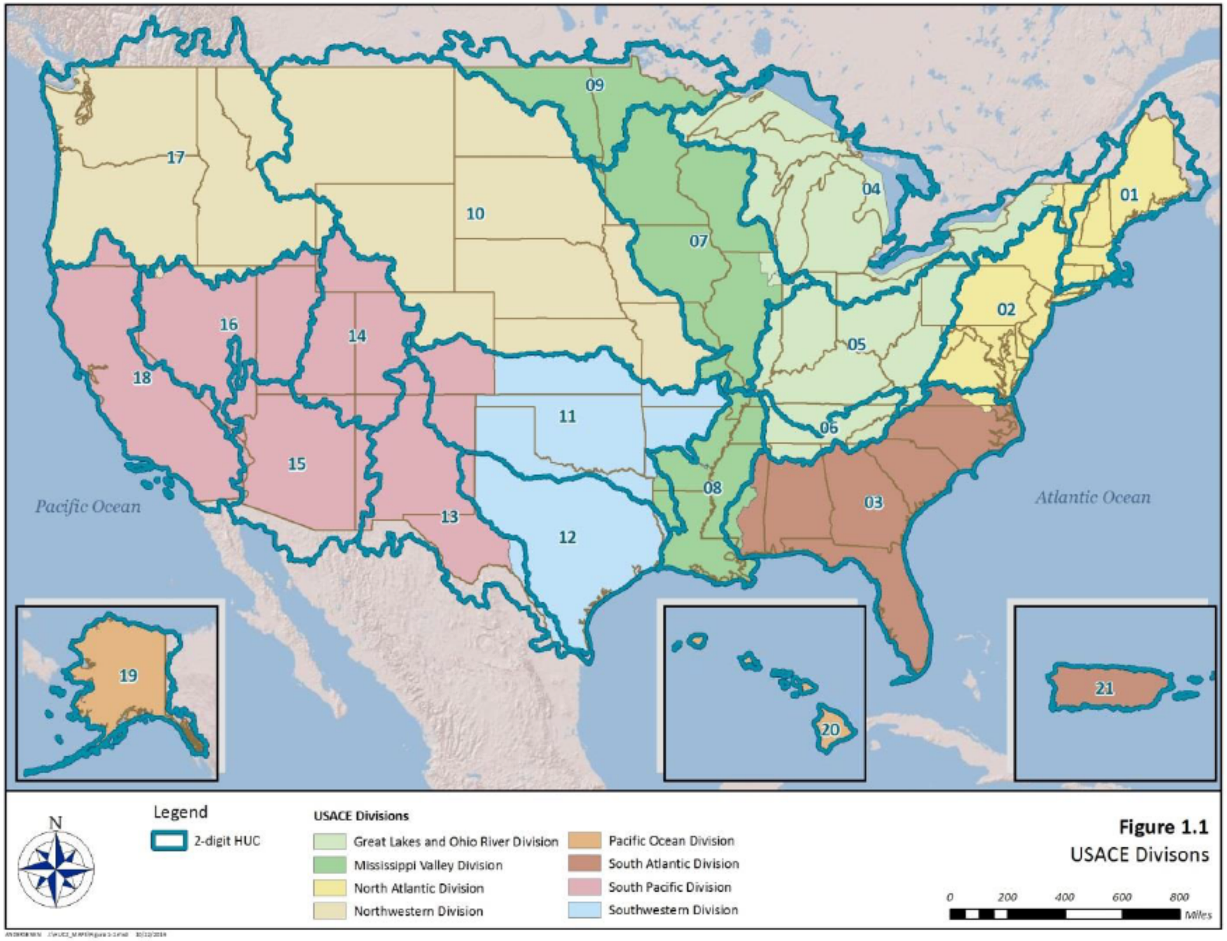


Figure 1.1. 2-digit Hydrologic Unit Code Boundaries for the Continental United States, Alaska, Hawaii, and Puerto Rico.