Pacific Northwest
NATIONAL LABORATORY

Extreme Weather Hazards to Nuclear Power Plants - A Regional Perspective

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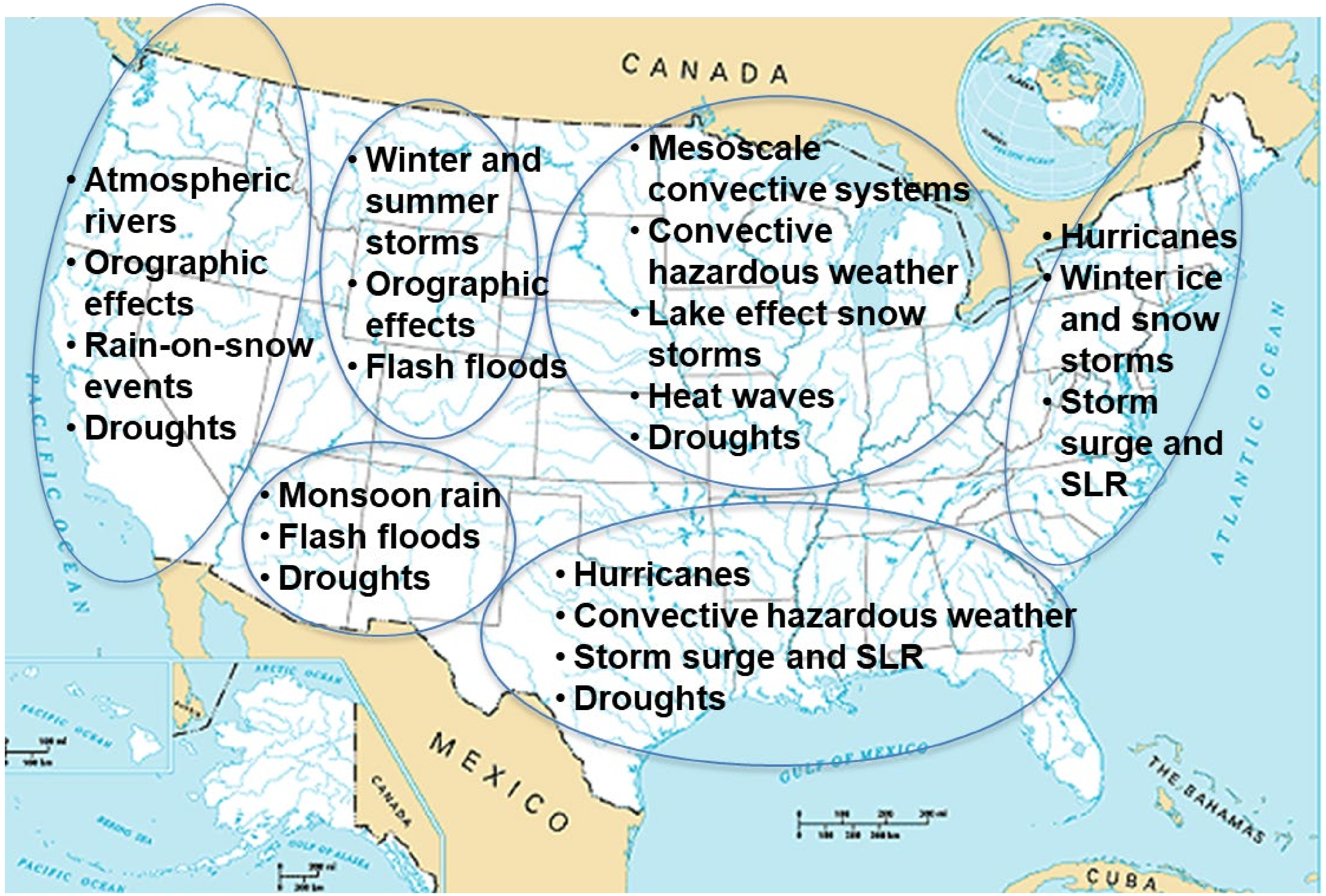
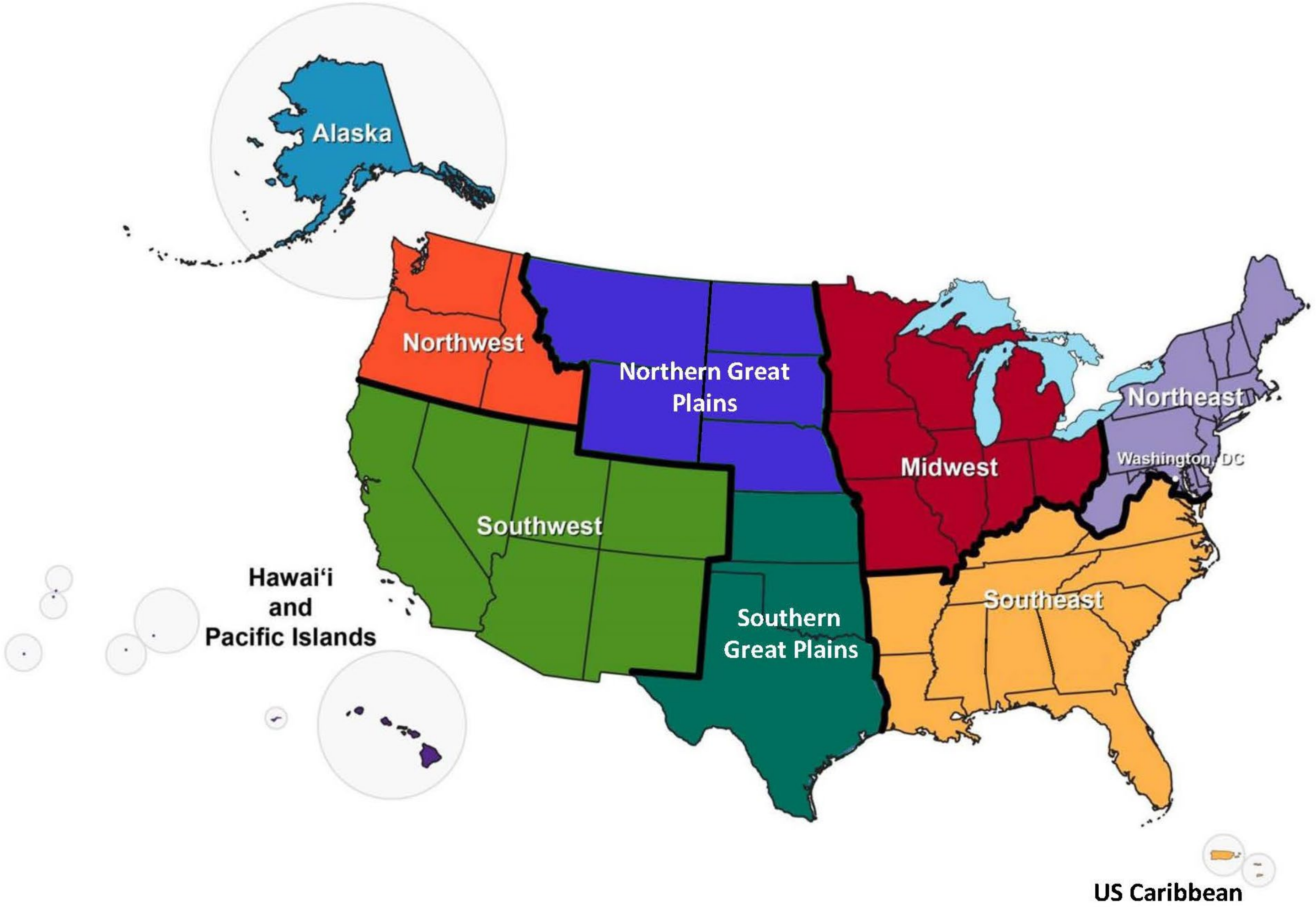
PNNL Climate Change Impacts Study for NRC Research

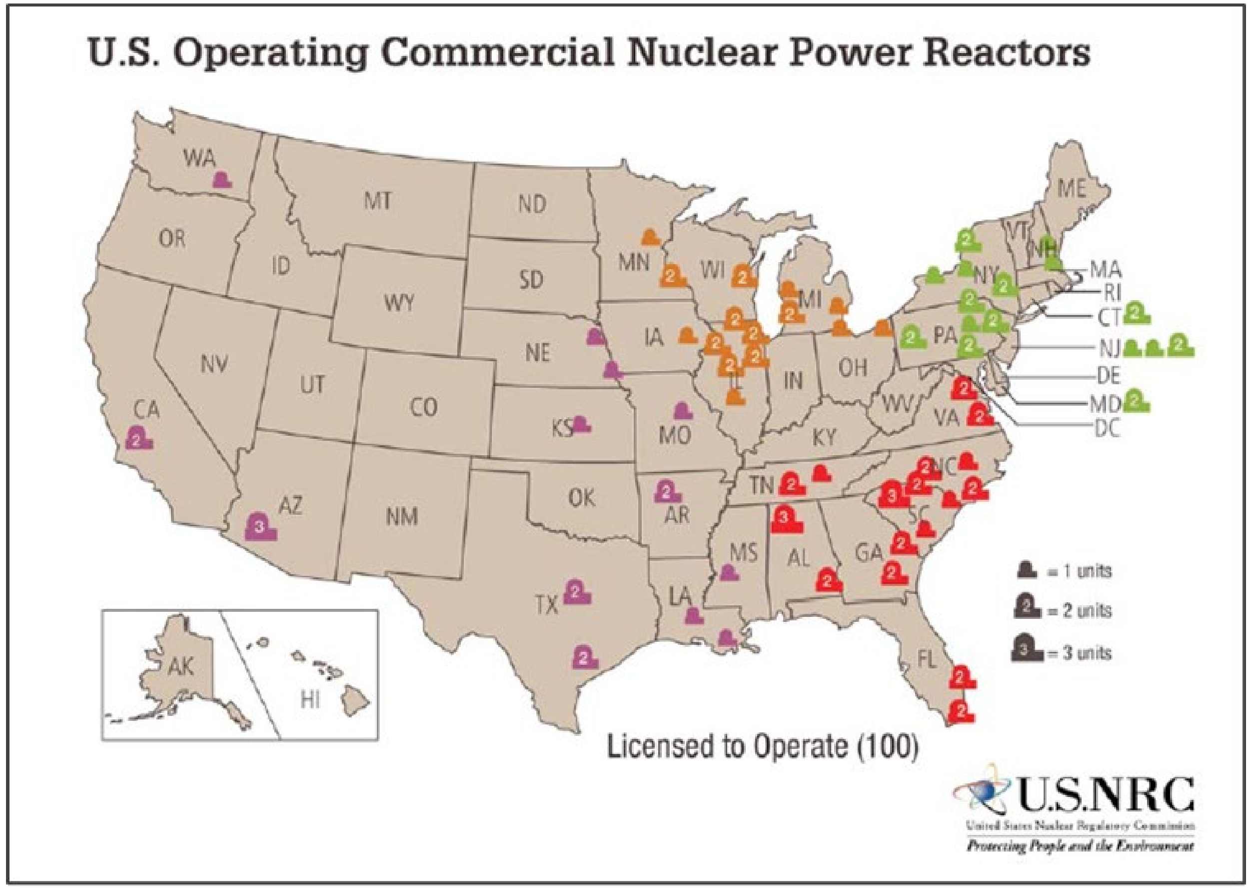
- During 2014-2019, PNNL produced four reports
  - [Year 1 – national scope]
  - [Year 2 – southeastern U.S.]
  - [Year 3 – midwestern U.S.]
  - [Year 4 – northeastern U.S.]
  - These reports are available from OSTI (links above)



SLR – sea level rise

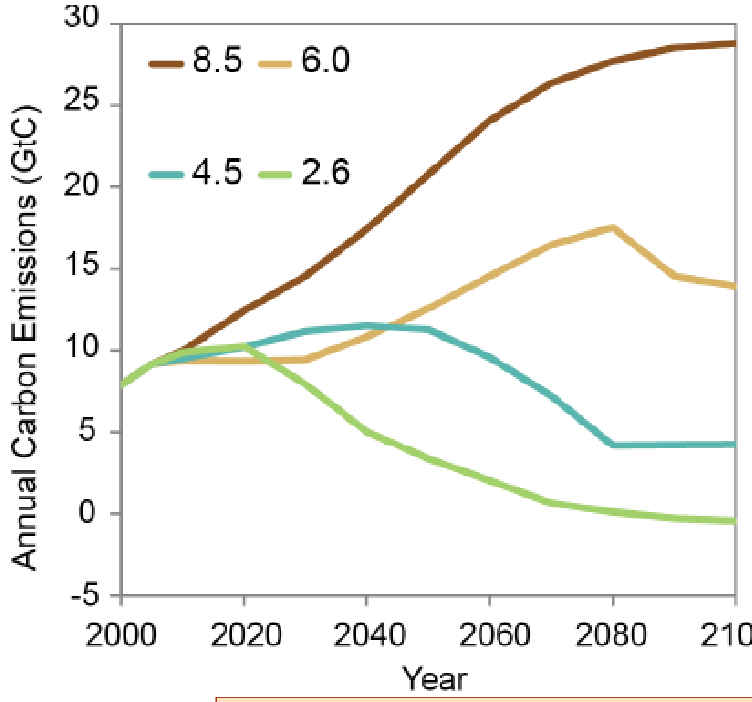
PNNL Climate Change Impacts Study for NRC Research





Scenarios for climate projections

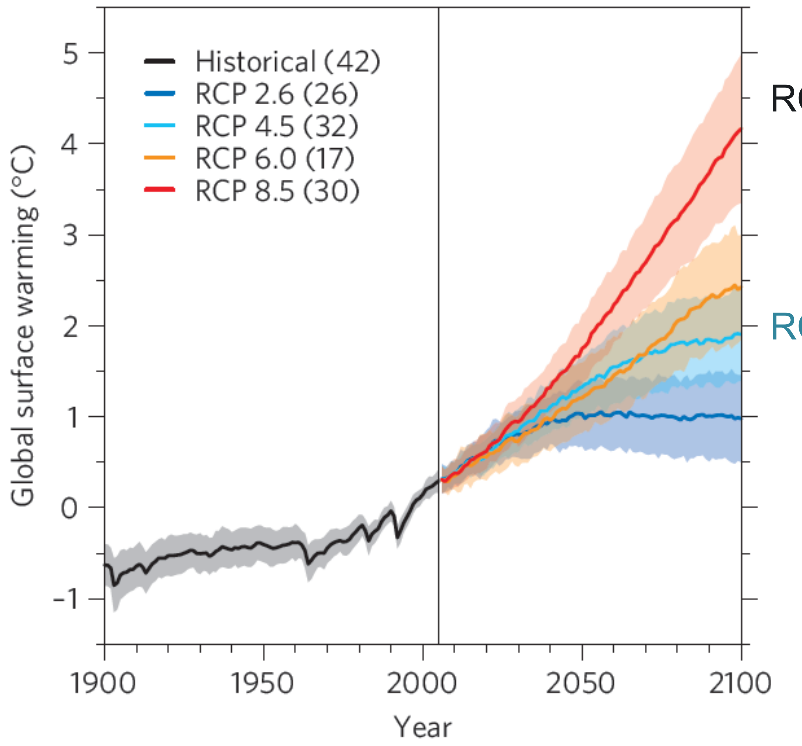
Representative Concentration Pathway (RCP) carbon emission scenarios



RCP8.5: Business-as-usual

RCP4.5: Climate mitigation

Global surface warming simulated by CMIP5 models



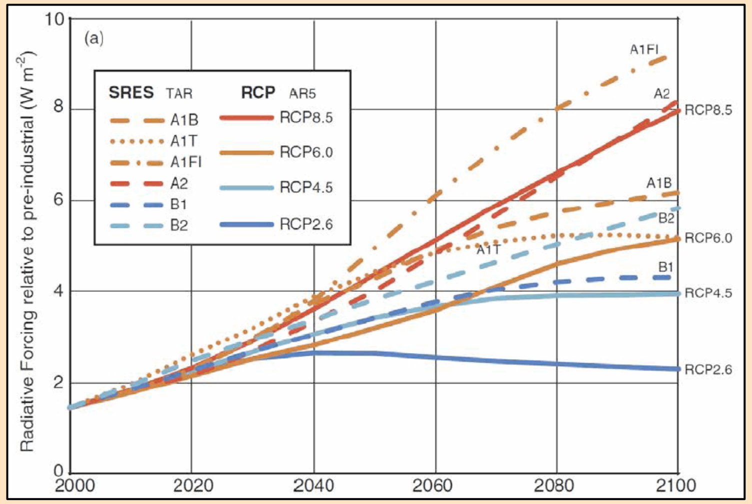
RCP8.5

RCP4.5

Comparison of scenarios used in IPCC AR4 and AR5:

Business-as-usual: A2 – RCP8.5

Climate mitigation: B1 – RCP4.5



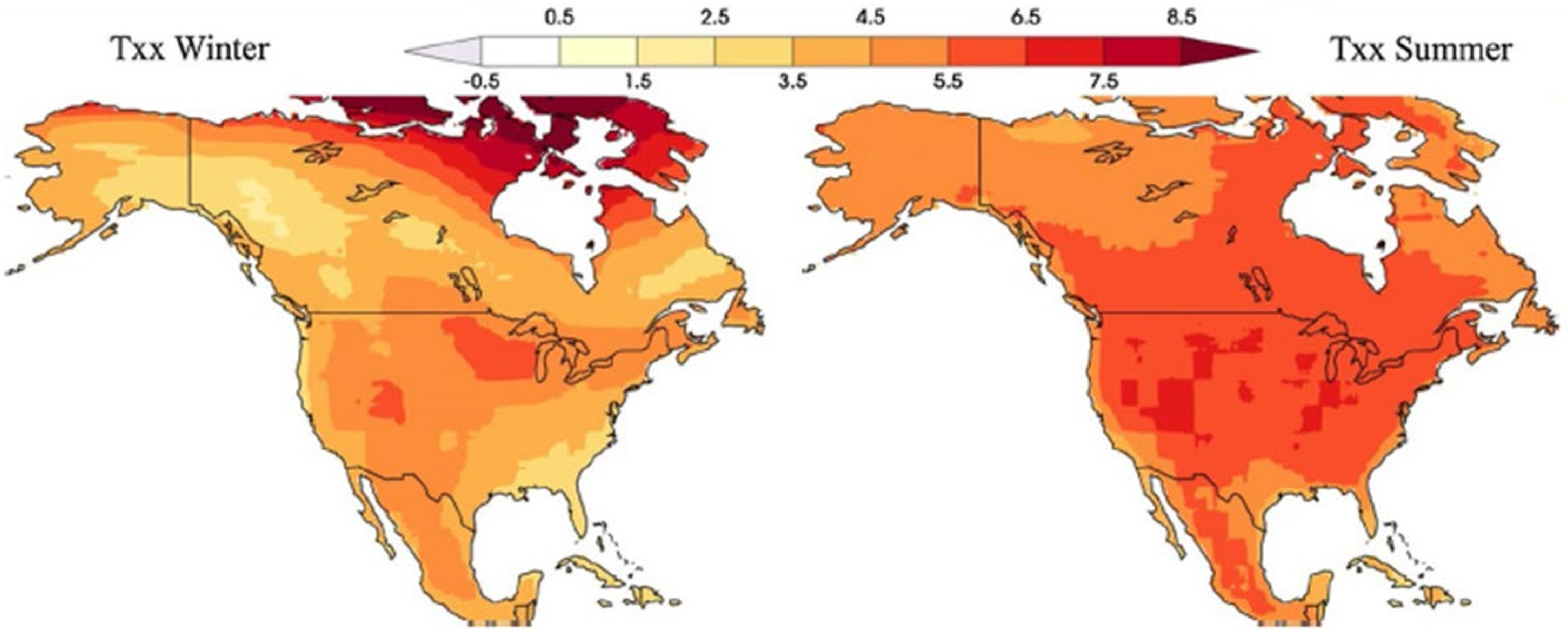
A2 ~ RCP8.5

B1 ~ RCP4.5

Increase in Extreme High Temperatures

- Increase in extreme high temperatures is mainly due to a shift of the probability distribution function by the mean warming
- Changes in large-scale circulation such as blocking may be a factor, but model projections are uncertain (consistent with uncertain change in skewness)
- Reduced soil moisture due to increasing temperature can further increase extreme high temperature through land-atmosphere interactions

Changes in temperature of extreme hot days in K (2080-2100 minus 1985-2005) in RCP8.5

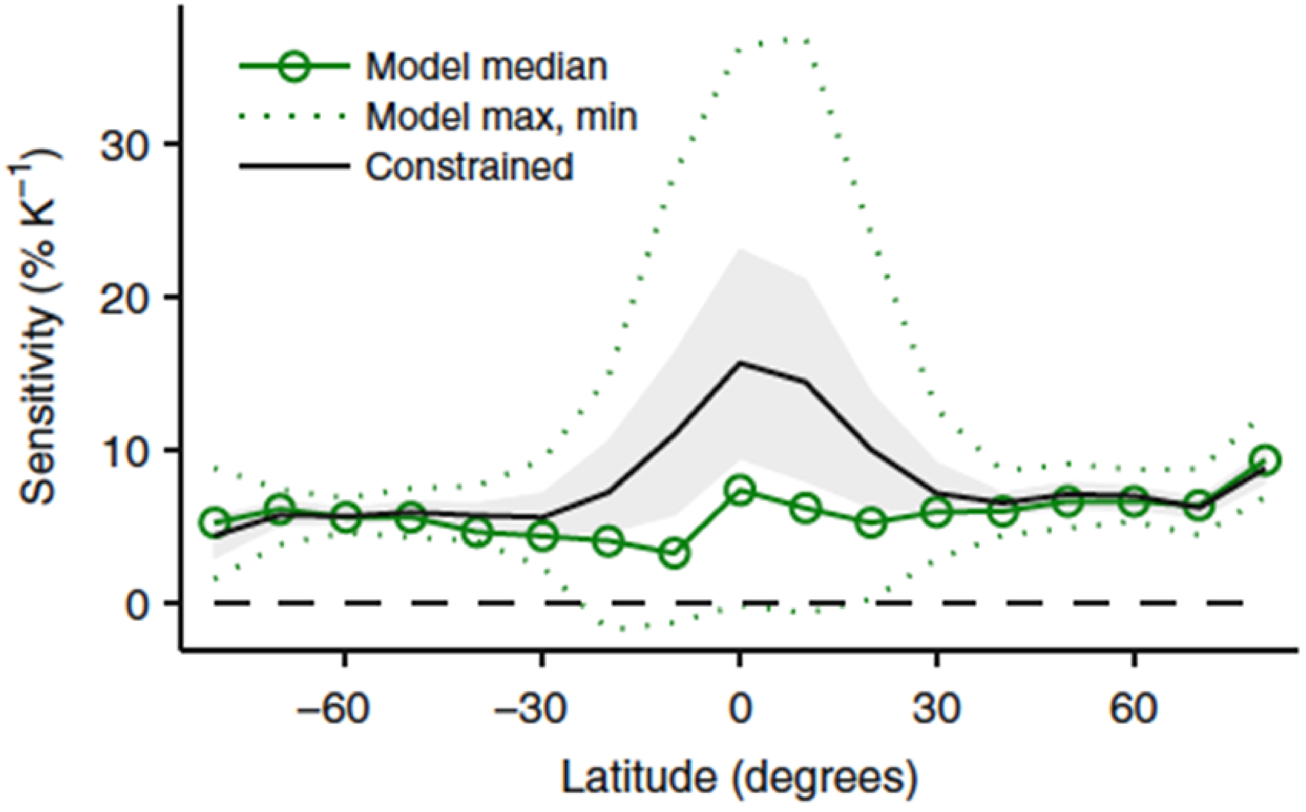


(Grotjahn et al. 2015 Clim. Dyn.)

Extreme Precipitation Changes

- Extreme precipitation depends on three factors: precipitation efficiency, vertical motion, and saturation specific humidity profile
- As the atmosphere holds more moisture in a warmer climate (Clausius-Clapeyron or CC ~ 7% K^{-1}), the last factor plays an important role

Change in 99.9th percentile daily extreme precipitation

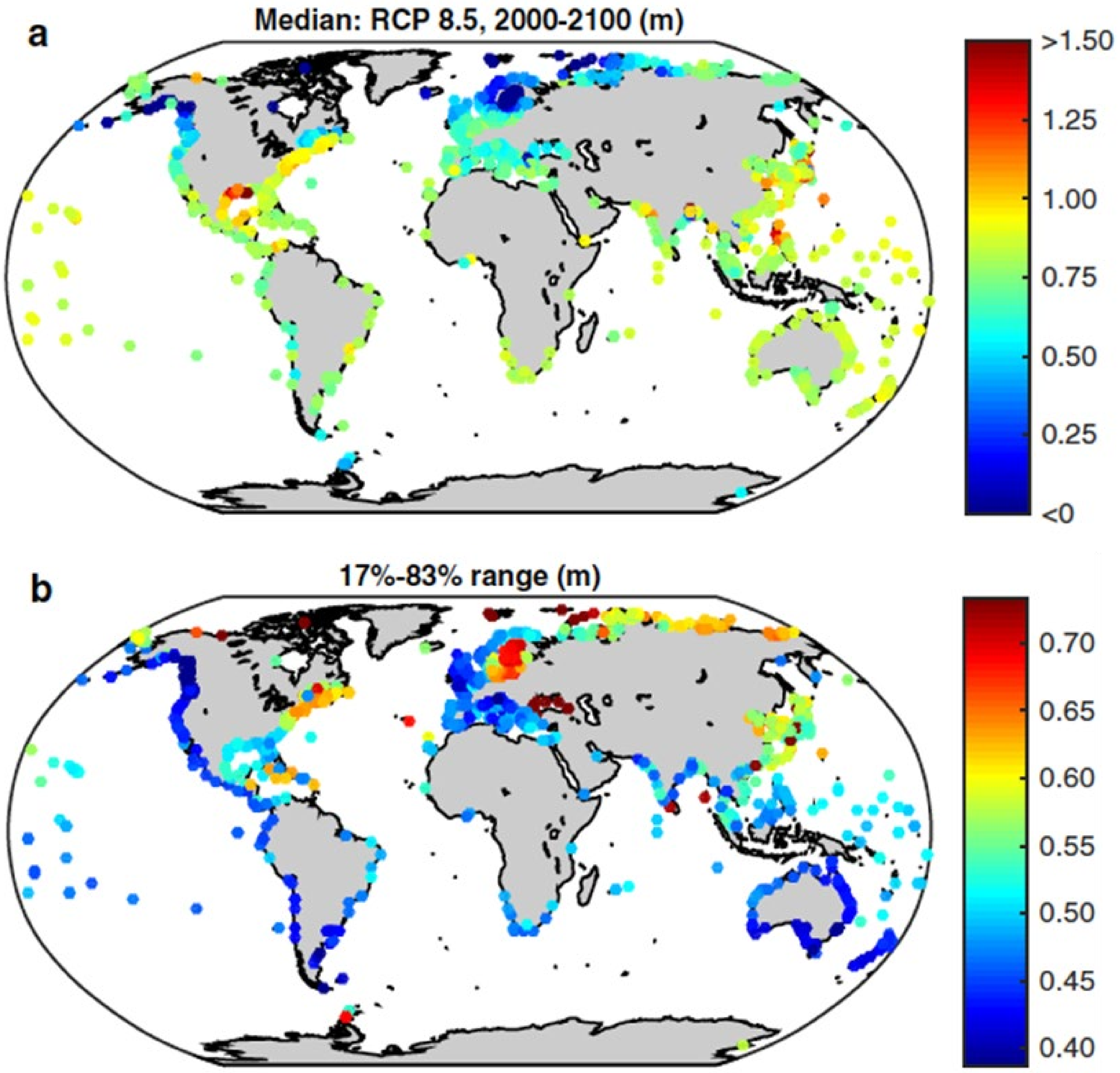


(O'Gorman 2015 CCCR)

- Extreme precipitation changes are often expressed as percentage change per K warming
- Much larger uncertainty in the tropics than extratropics
- In the extratropics, changes ~ 6% K^{-1}

Sea Level Rise

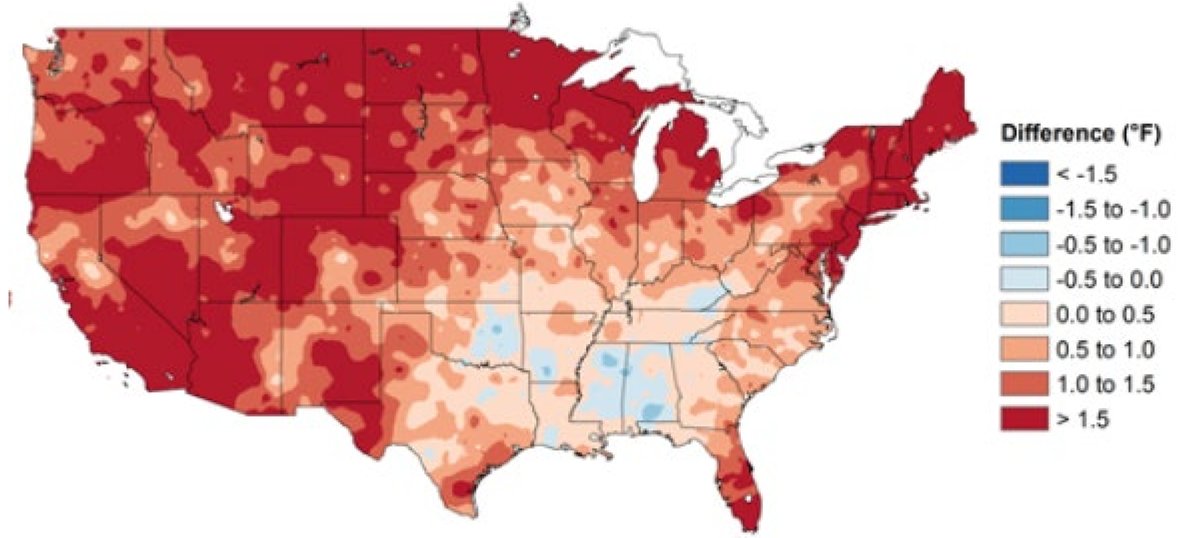
- Global coupled climate models are used to project dynamical sea level changes due to climate
- Large biases remained in equatorial and southern oceans, and continental ice sheet is missing in some coupled models
- By the end of the century, uncertainty related to Antarctic ice sheet dominates uncertainty in projecting regional SLR, but uncertainty in projecting dynamic sea level in North Atlantic dominates uncertainty in projecting SLR in Northeast U.S.



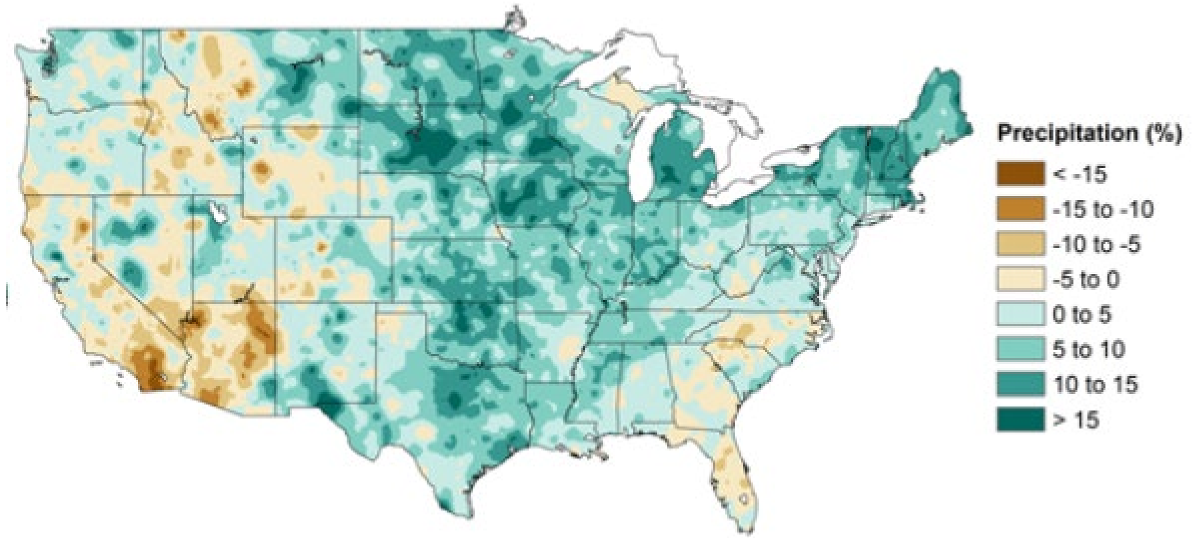
(Kopp et al. 2014 Earth Future)

Observed Temperature and Precipitation Changes

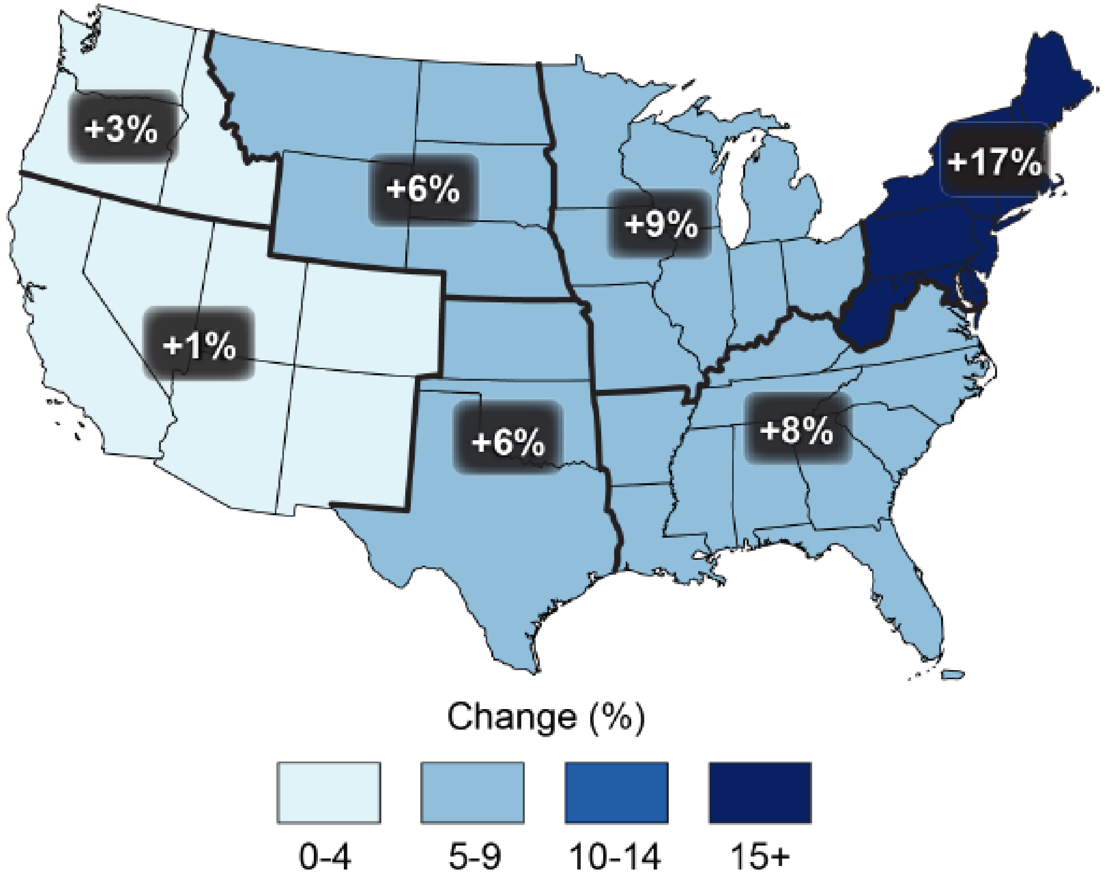
Annual Temperature



Annual Precipitation



Observed Change
in 5-year Extreme Precipitation Events

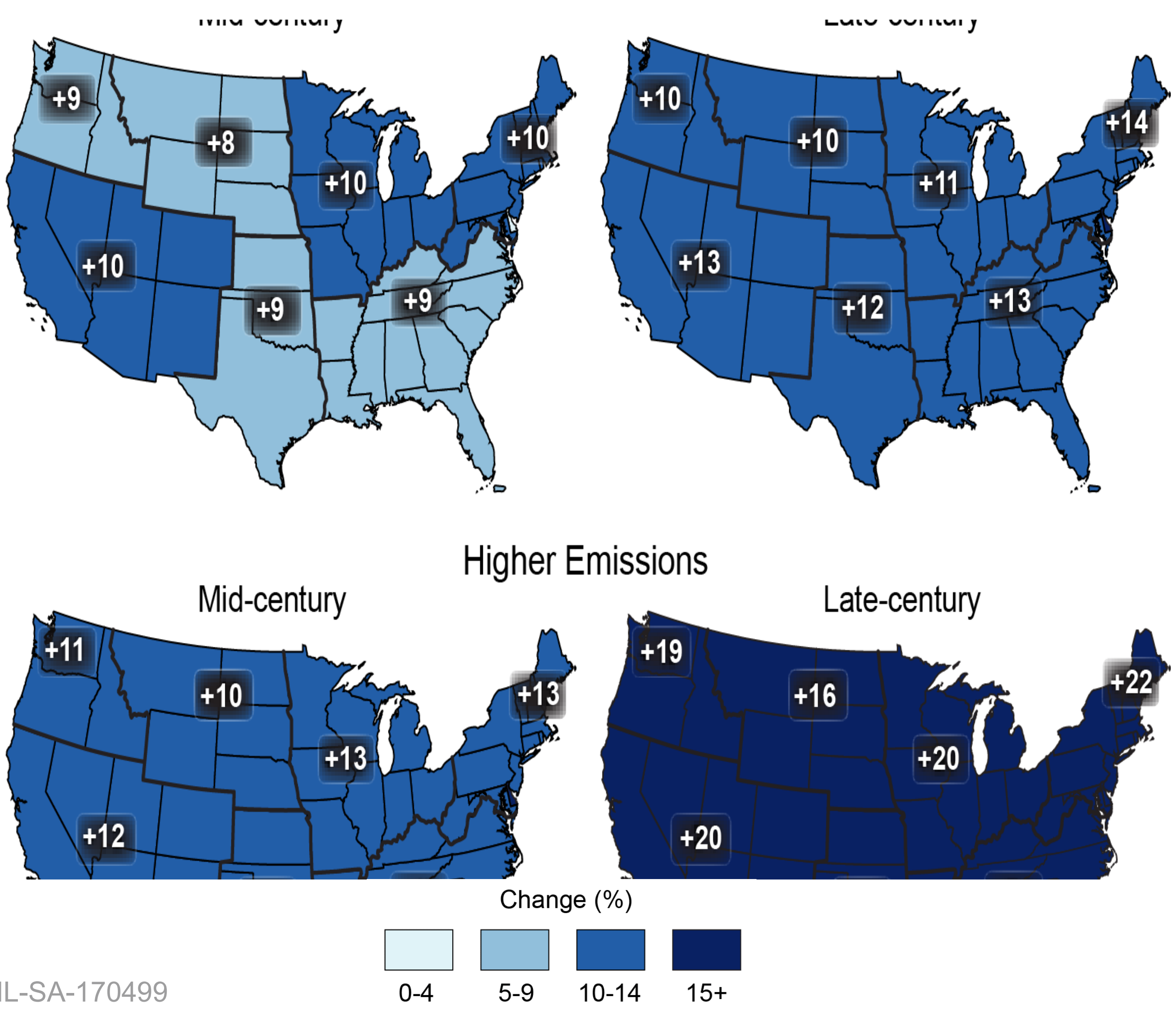


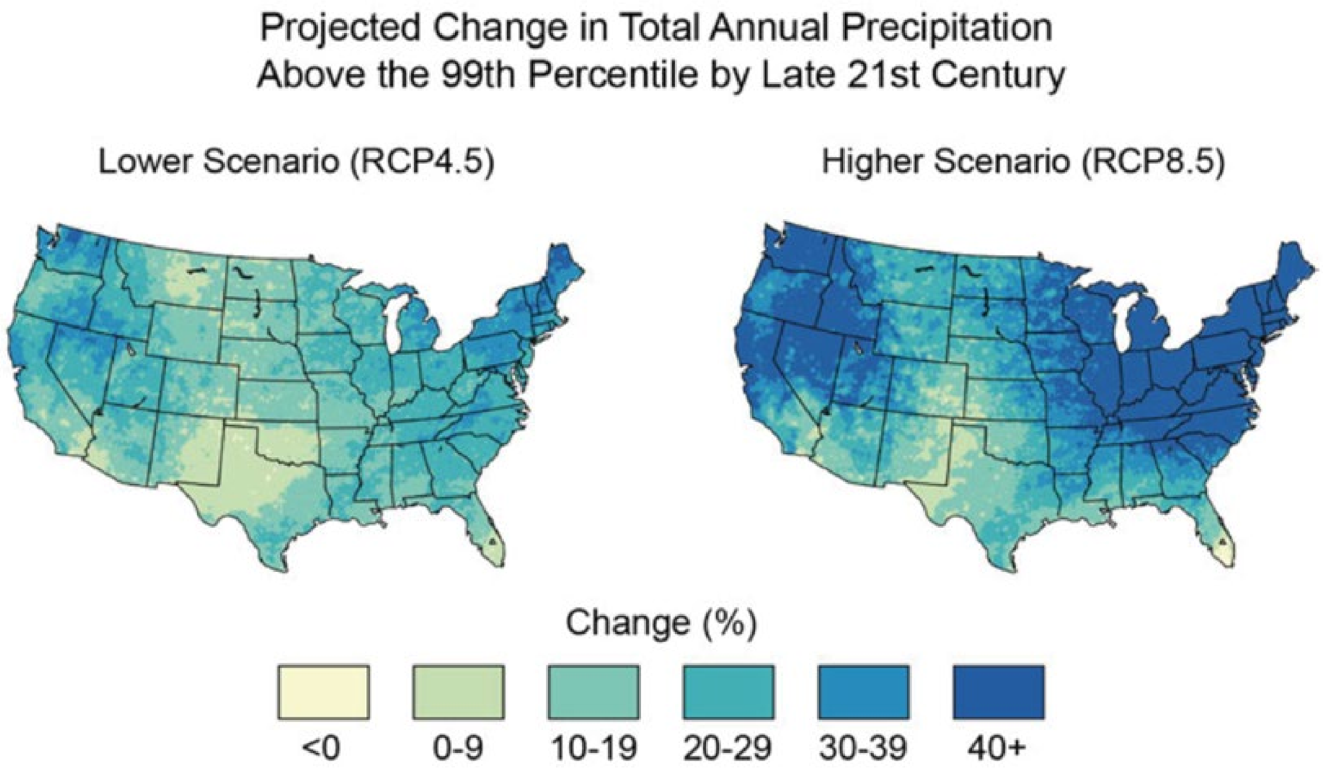
(Wuebbles et al. 2017 CSSR)

Projected Precipitation Changes

- Extreme precipitation scales with magnitude of warming

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

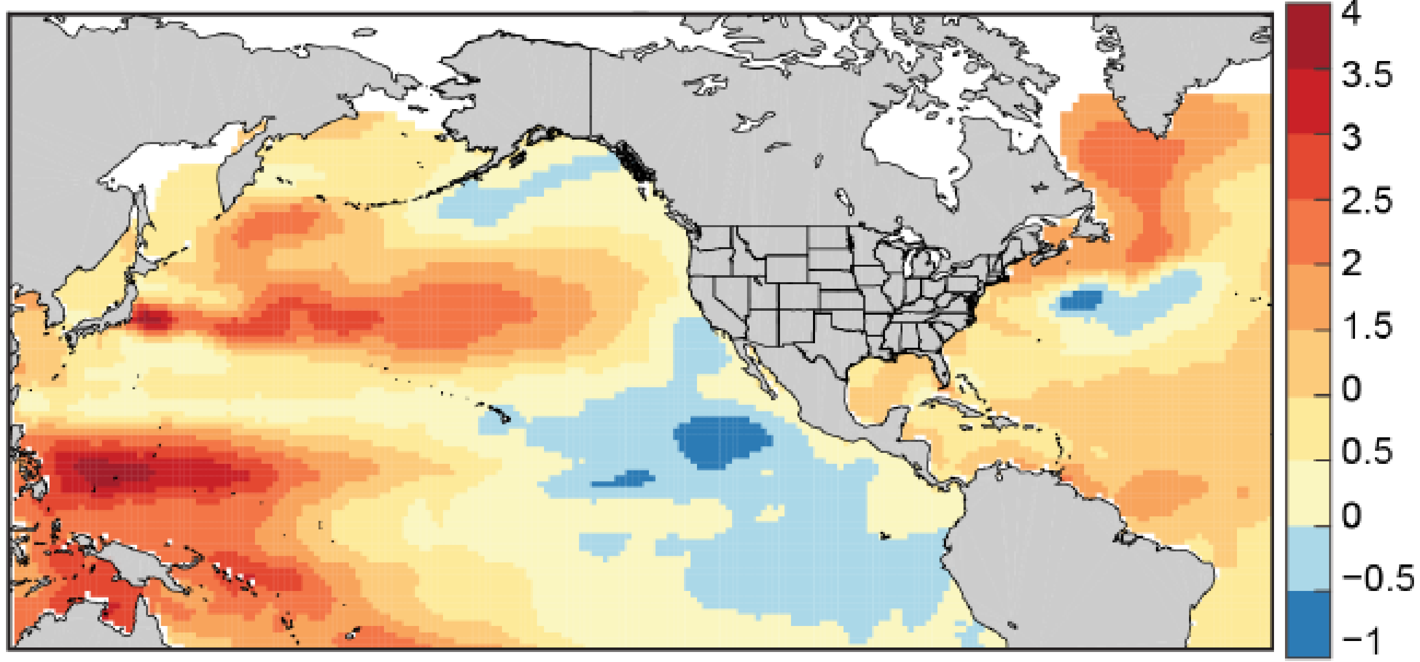




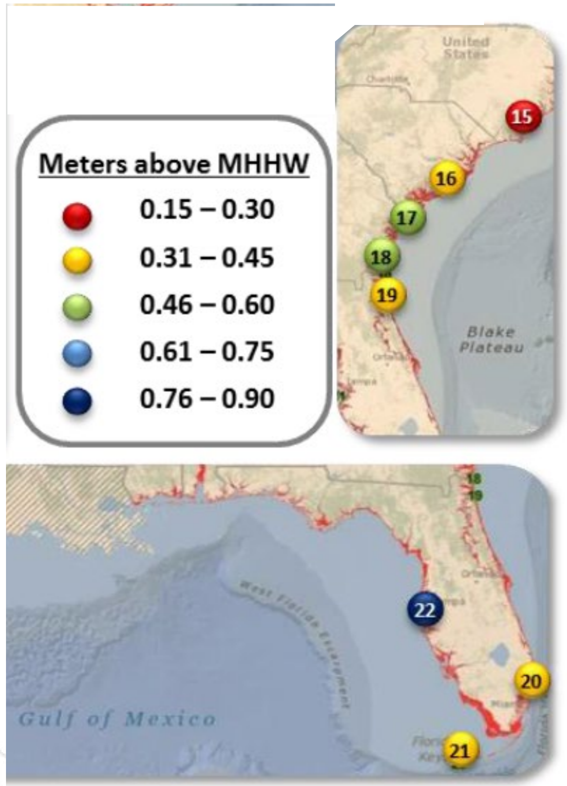
Southeastern U.S. – Observed Effects of Sea Level Changes

- 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

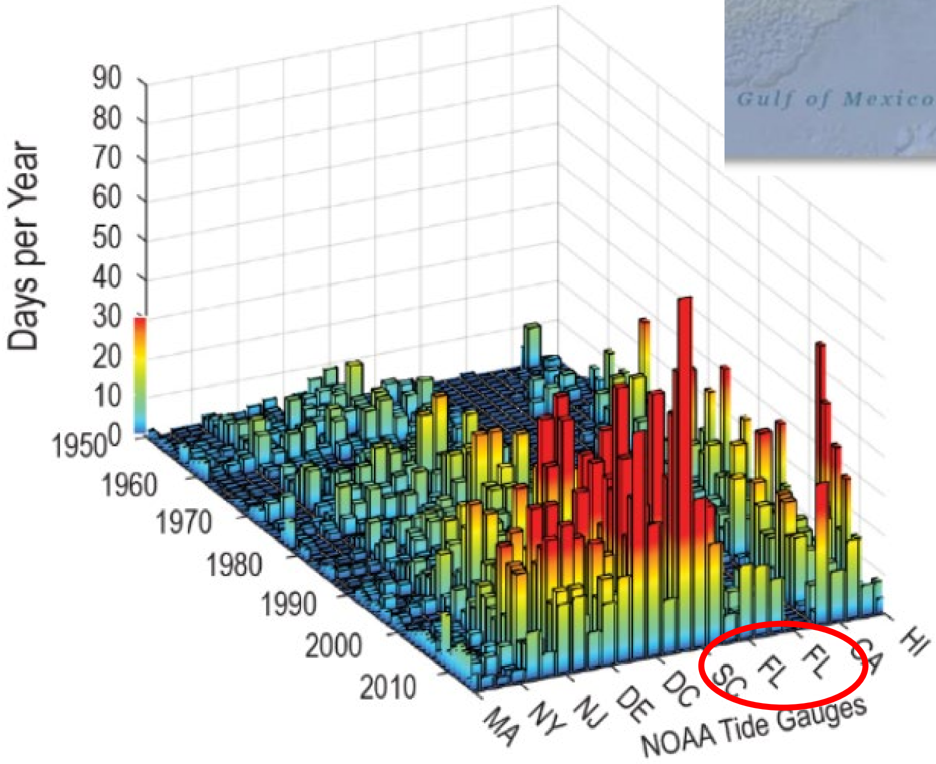
Rate of Change in
Sea Surface Height (1993–2014)



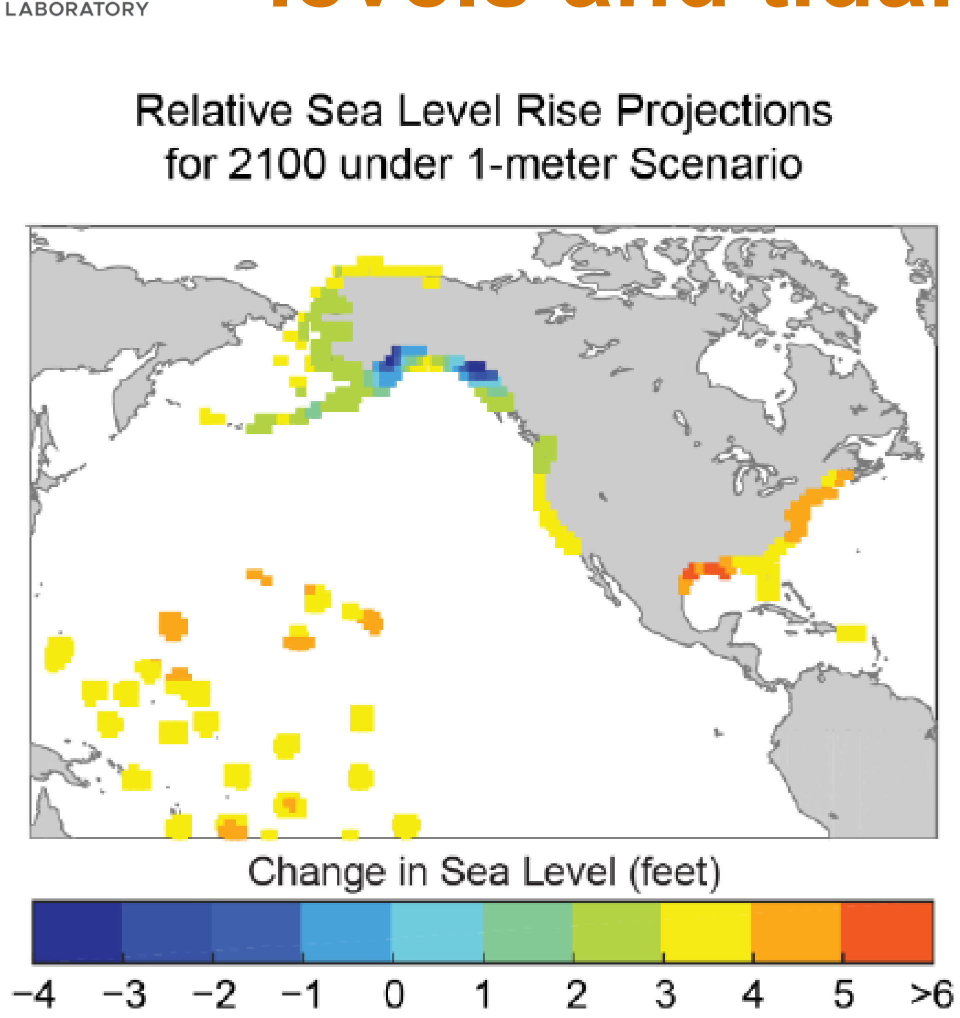
Nuisance elevation thresholds relative to mean higher high water (MHHW)

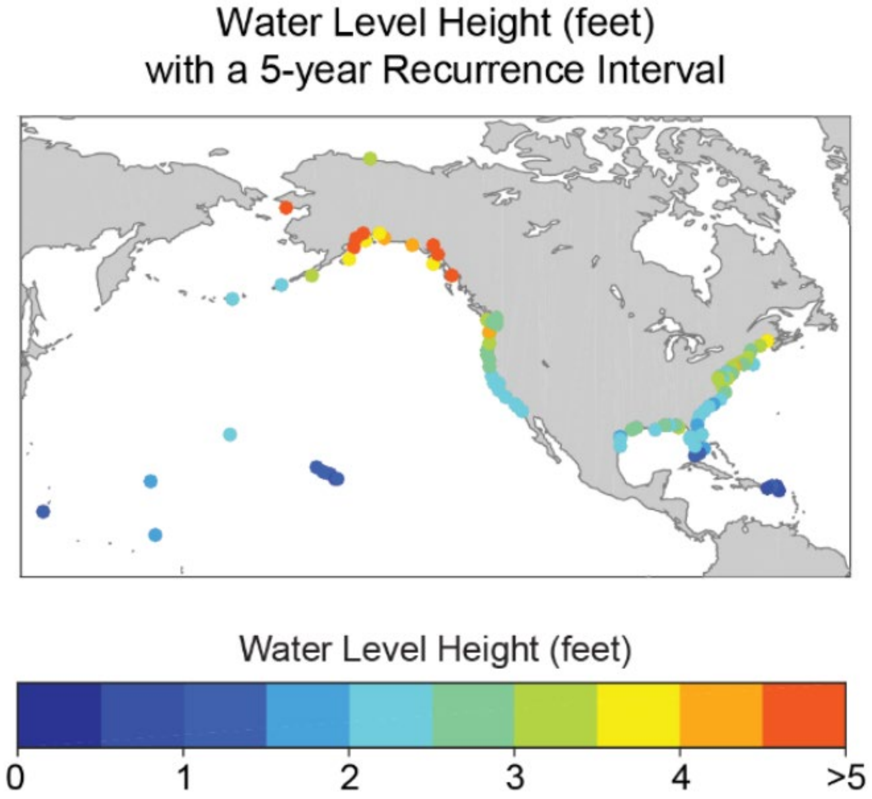


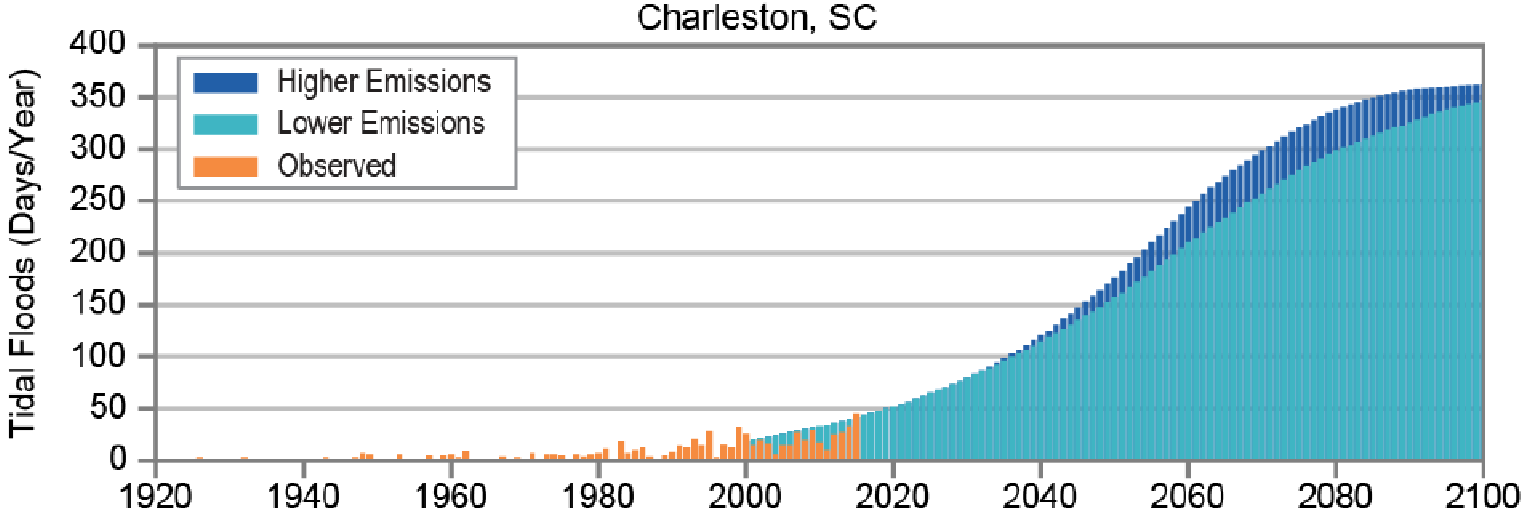
Nuisance Tidal Floods



Southeastern U.S. – Increase in regional sea levels and tidal floods

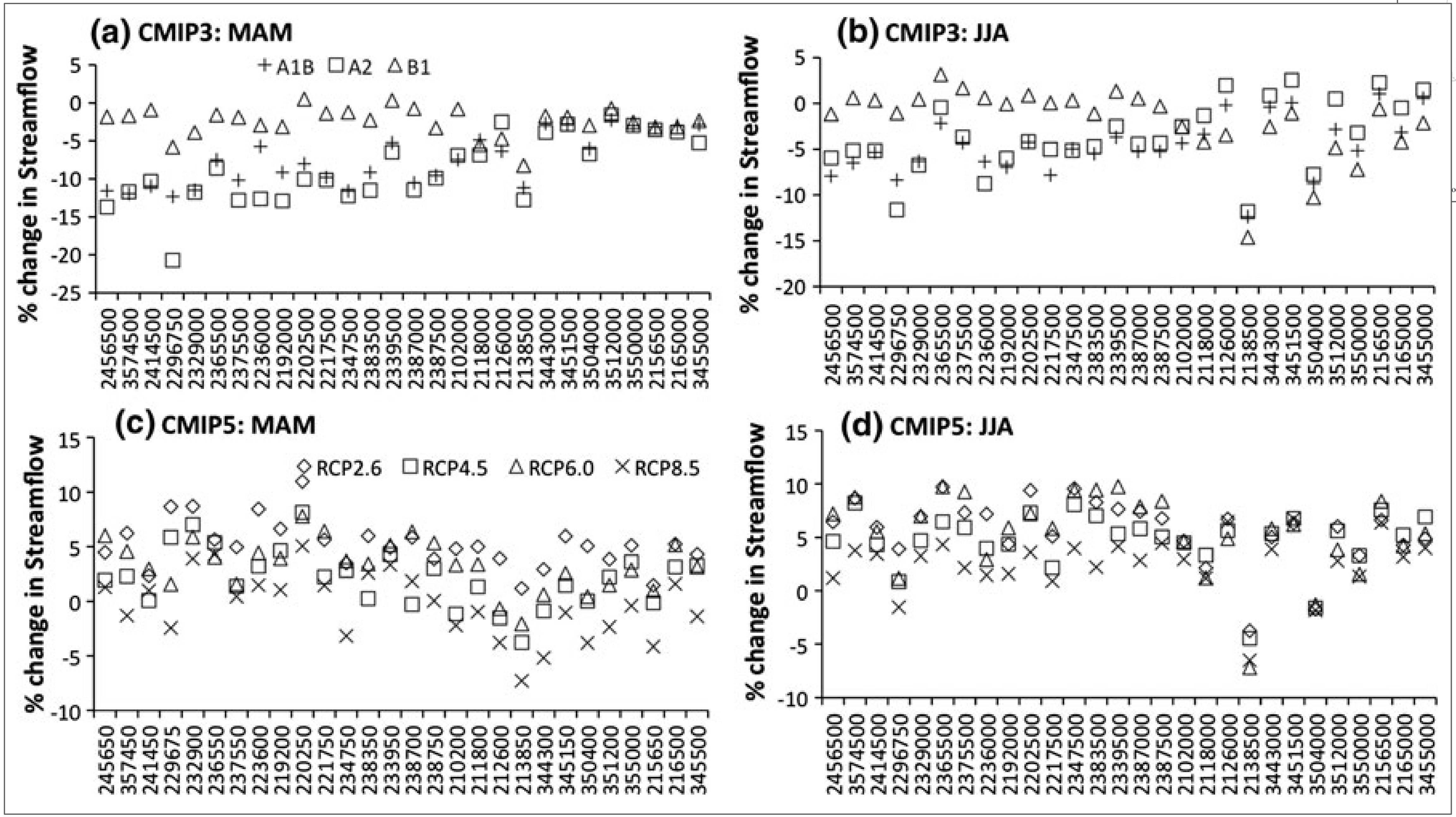


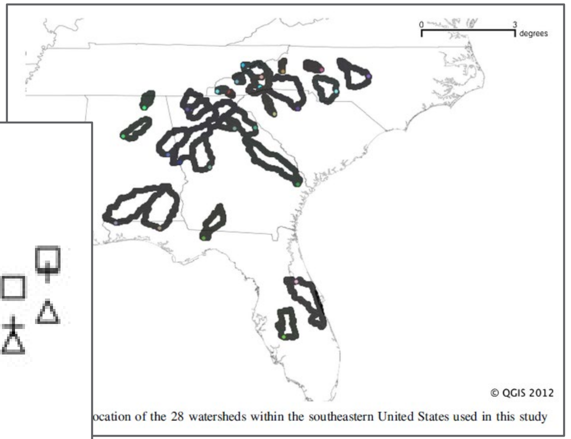




(Wuebbles et al. 2017 CSSR)

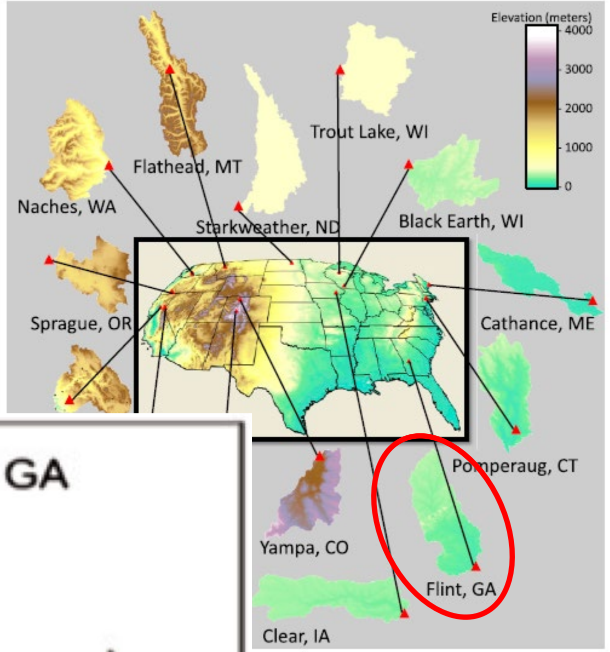
Southeastern U.S. – Projected streamflow changes

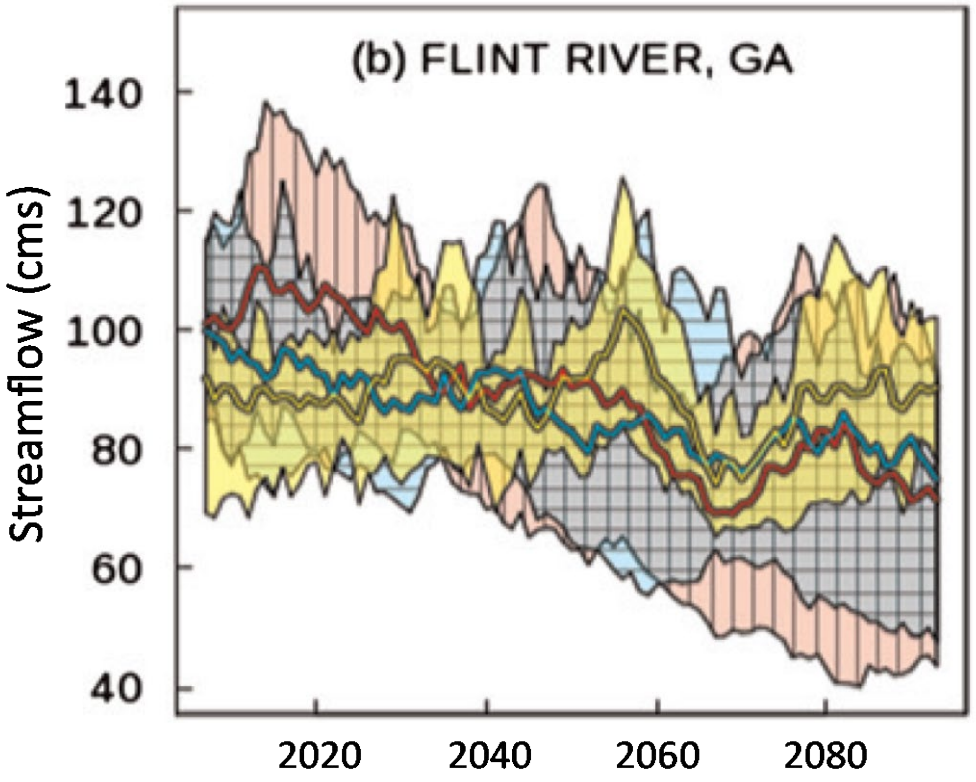




(Bastola 2013)

Southeastern U.S. – Projected streamflow changes (cont.)





(Bastola 2013)

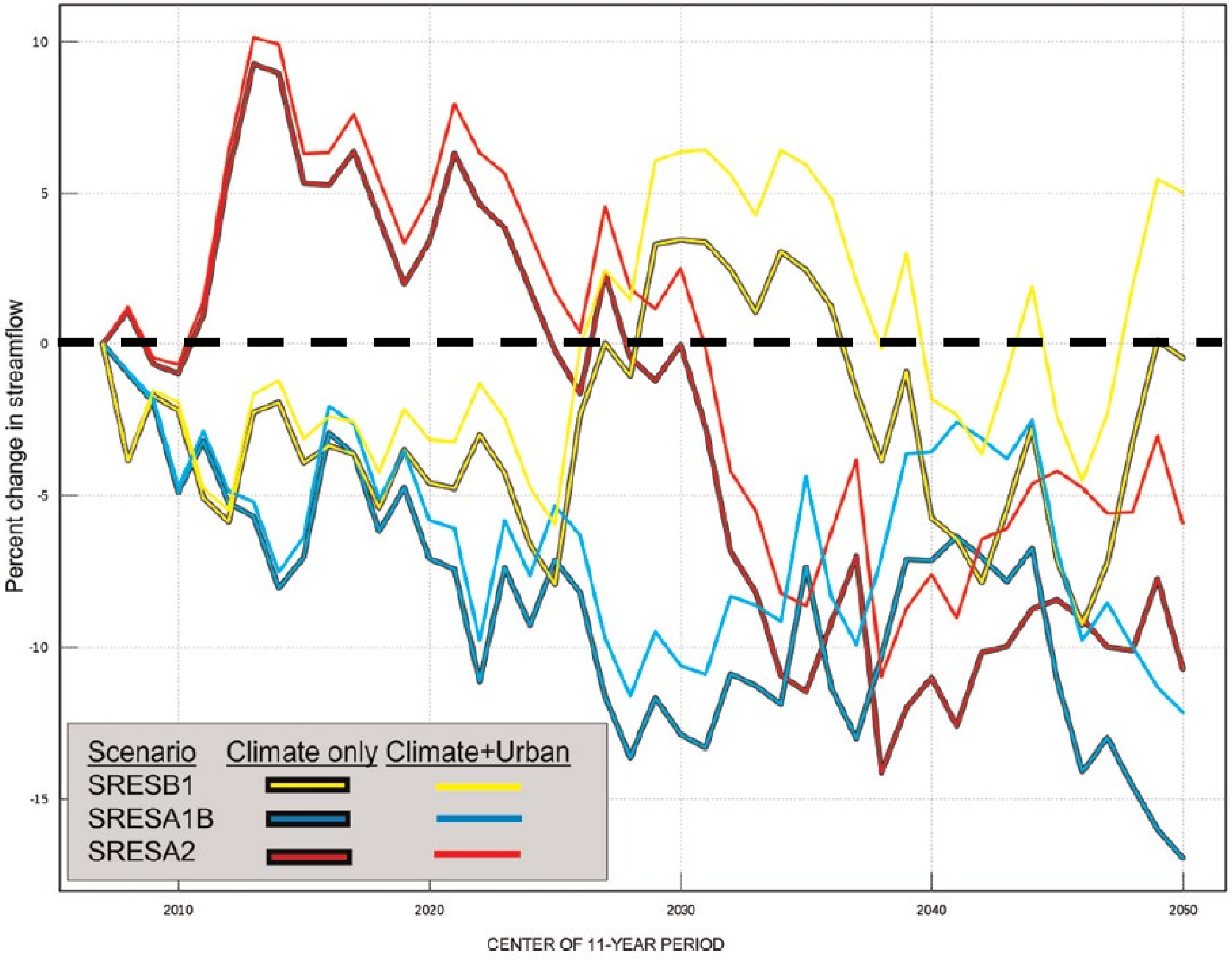
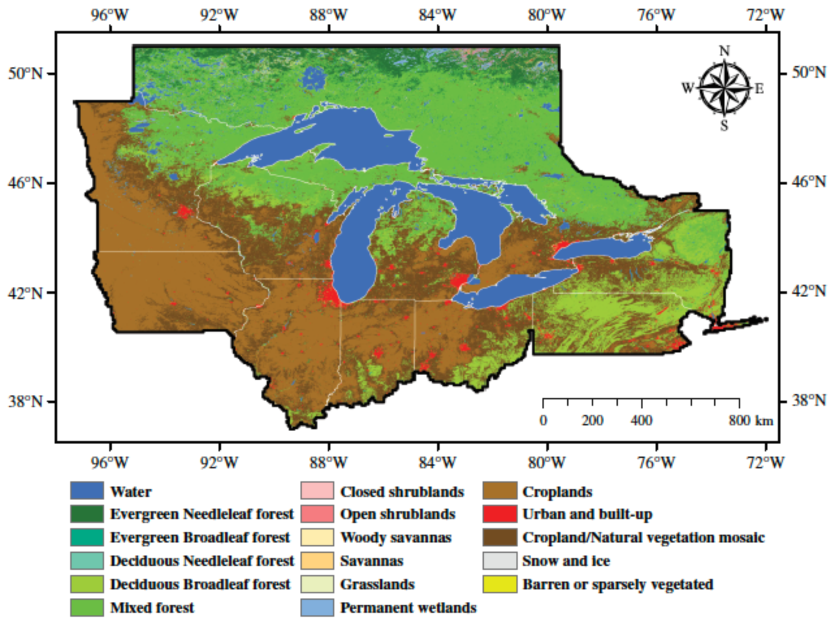
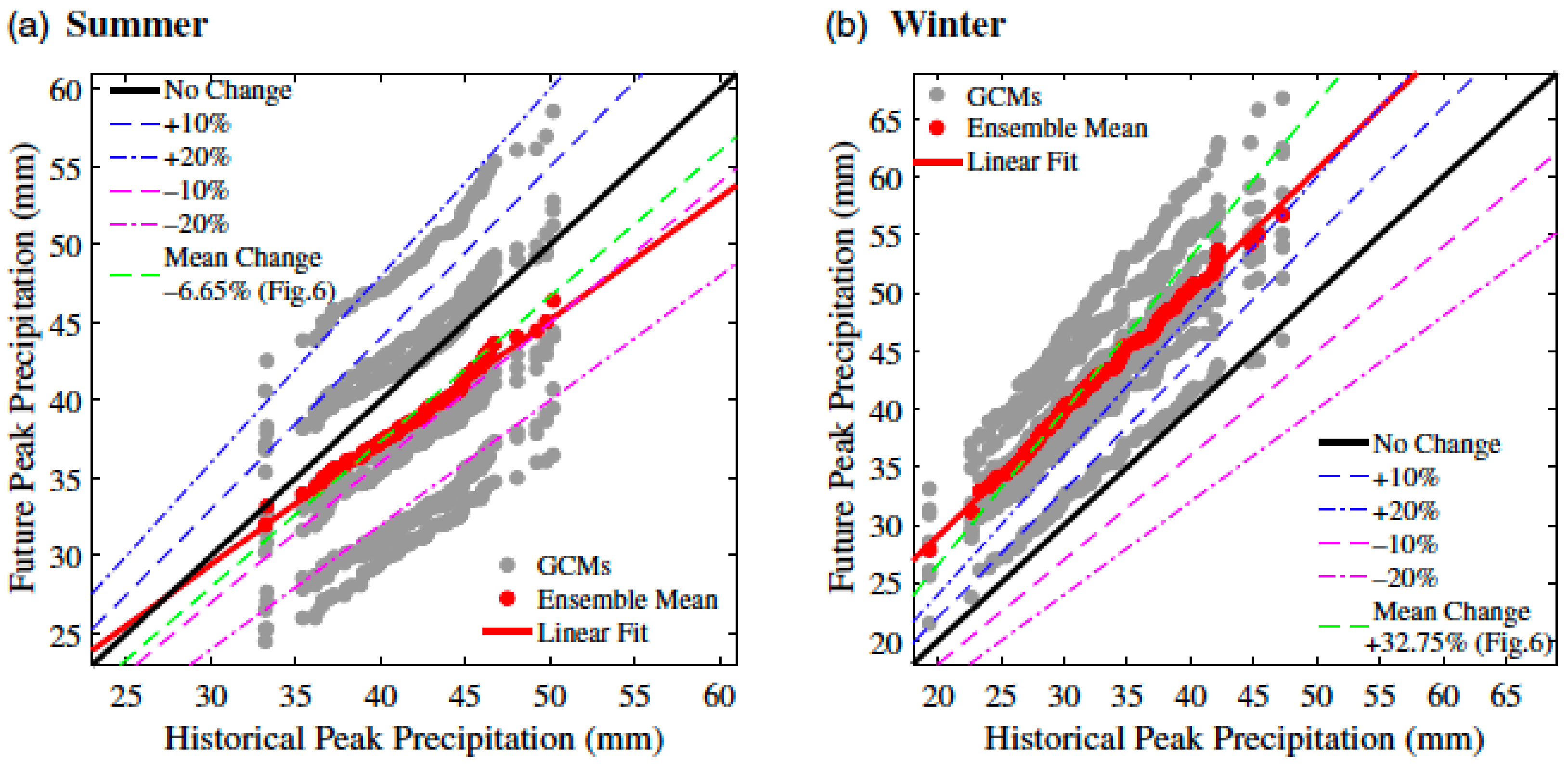


Figure 11. Percent change in 11-yr moving mean daily values of streamflow derived from the five GCMs, with (solid lines) and without (outlined in black) urbanization forecasts, grouped by climate-change scenario.

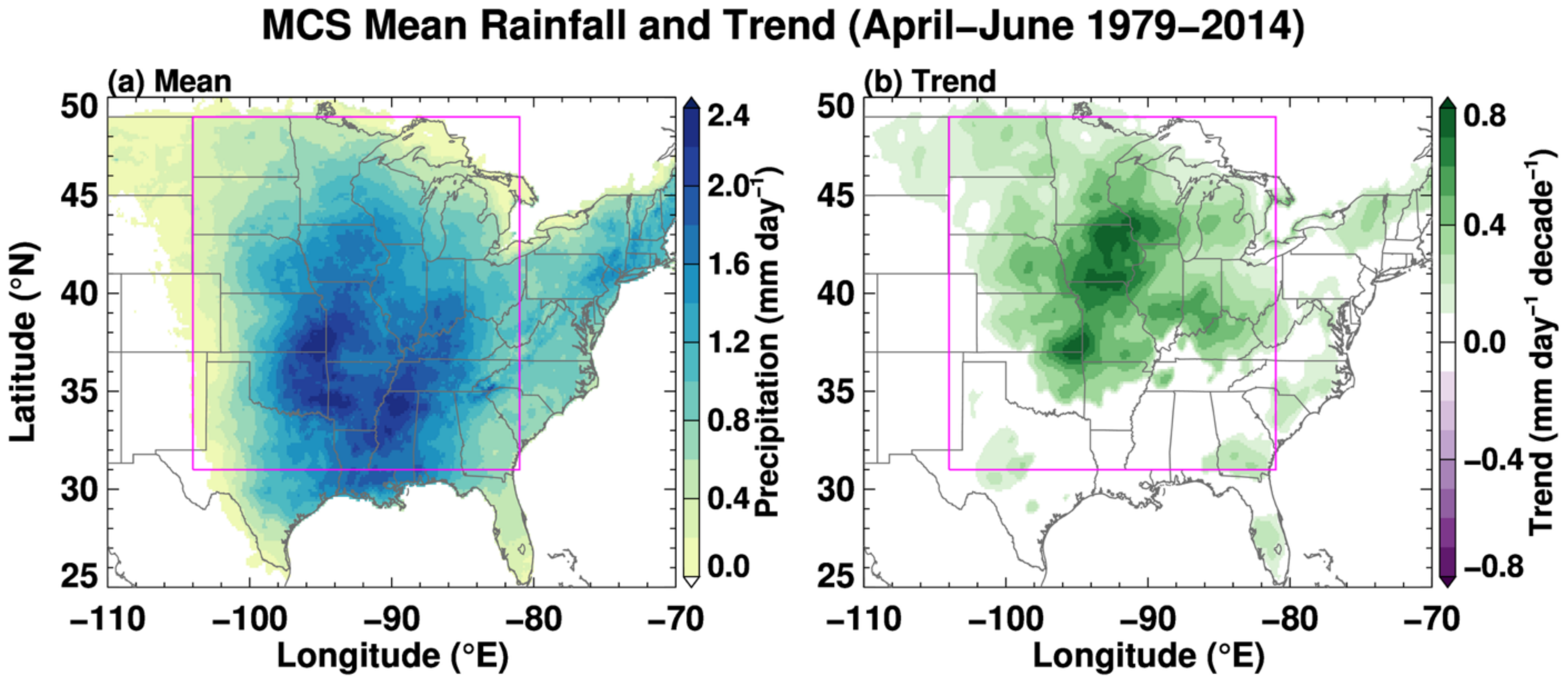
Midwestern U.S. – Future Extreme Precipitation Changes



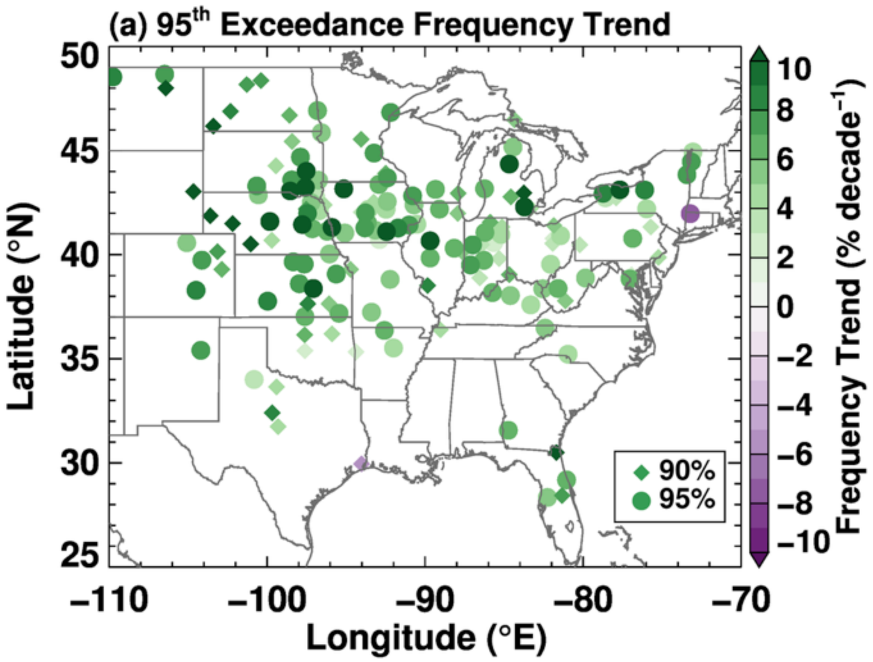
(Byun and Hamlet 2018)



Midwestern U.S. – Observed changes in Mesoscale Convective System (MCS) rainfall



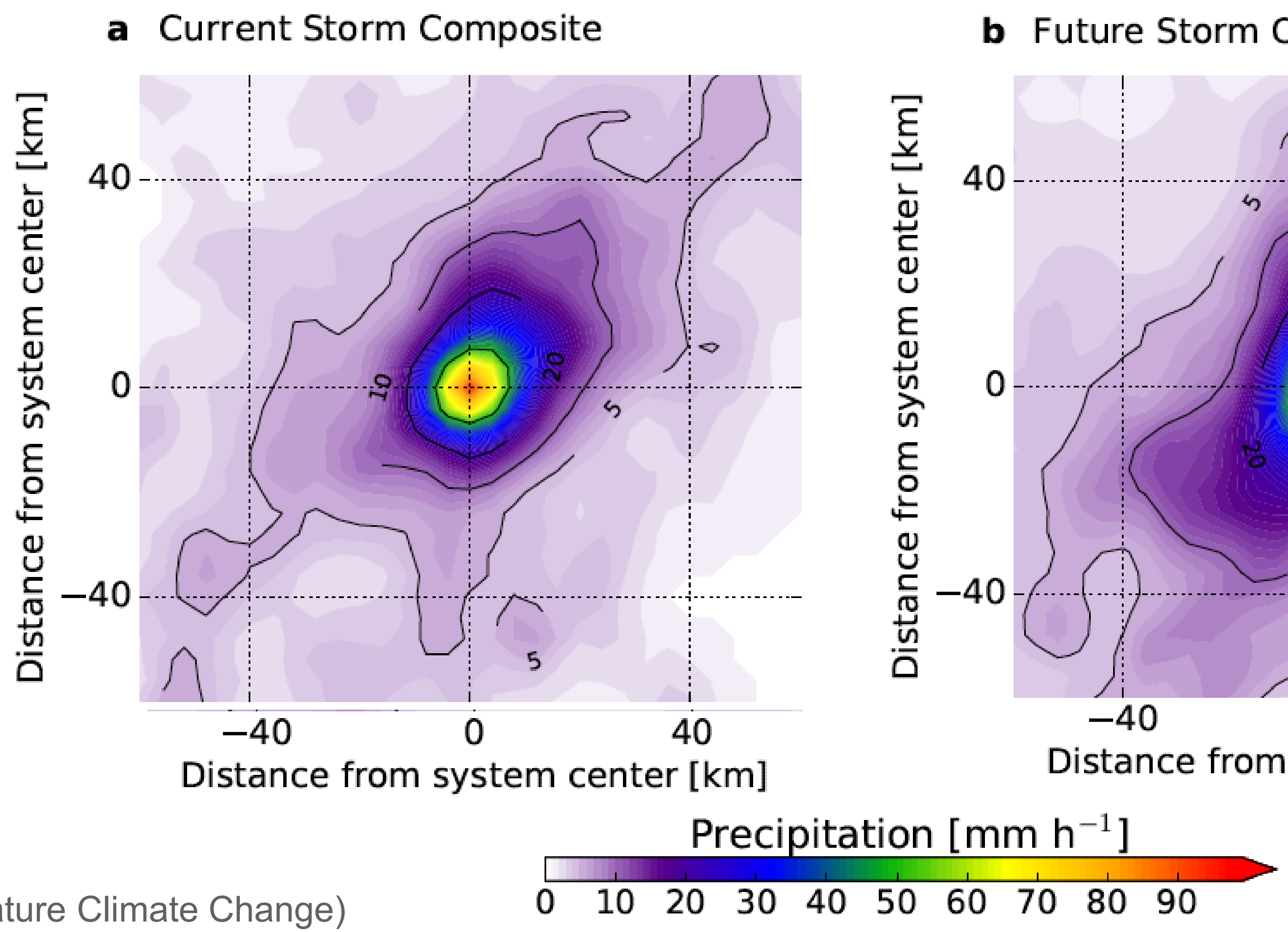
(Feng et al. 2016 Nature Commun.)



- Some regions in the Midwest experienced 0.4-0.8 mm day^{-1} (20-40%) increase in MCS precipitation
- 95th percentile MCS hourly rain-rate increase
- Moderate to heavy rain-rate (5-30 mm h^{-1}) become more frequent

Midwestern U.S. – Projected changes in MCS rainfall

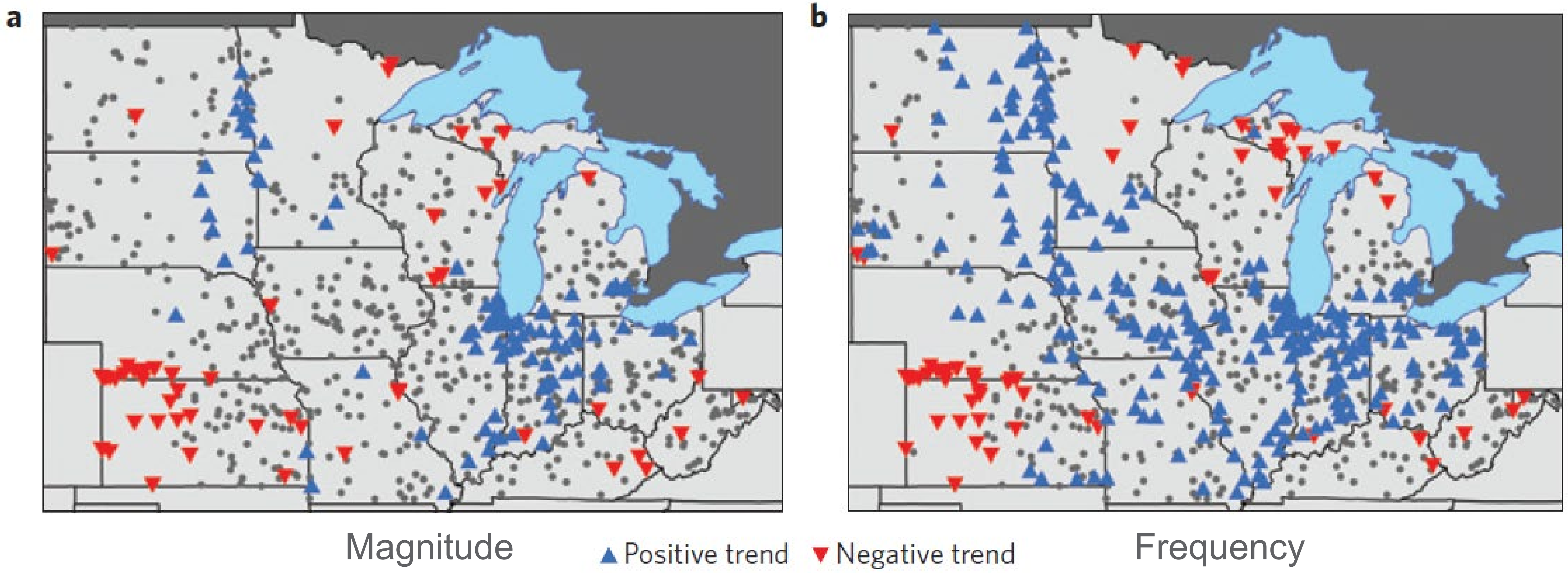
- Intense summertime MCS frequency will more than triple in North America
- MCSs that move slower than 20 km h^{-1} reduce their speed by up to 20% in the Midwest, Mid-Atlantic, and Canada



(Prein et al. 2017 Nature Climate Change)

Midwestern U.S. – Observed changes in floods

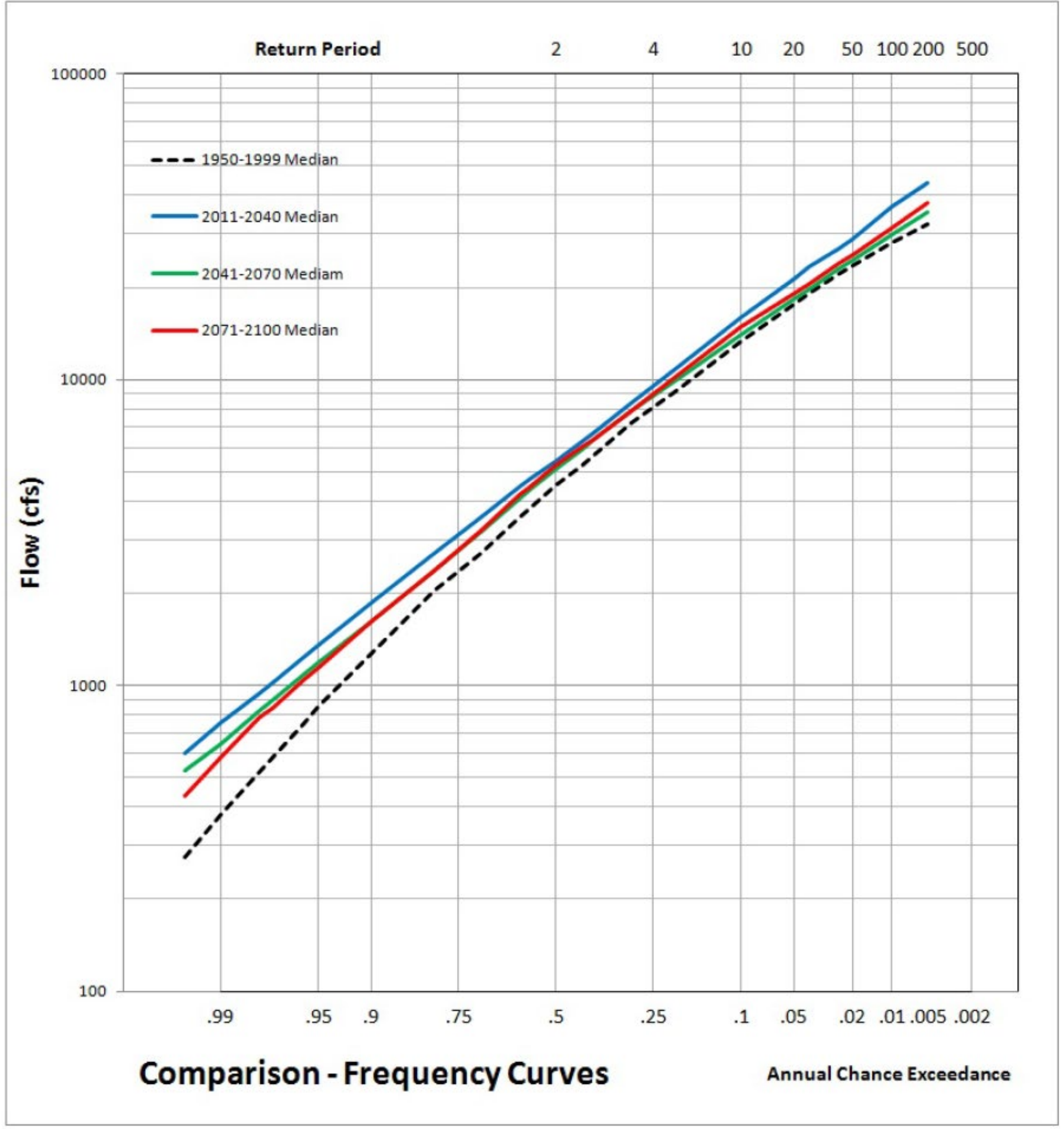
- Mallakpour and Villarini, 2015, 2016
  - 774 USGS streamflow gauges with 50 years of record
  - frequency of largest flood events has been increasing in the Midwestern U.S.



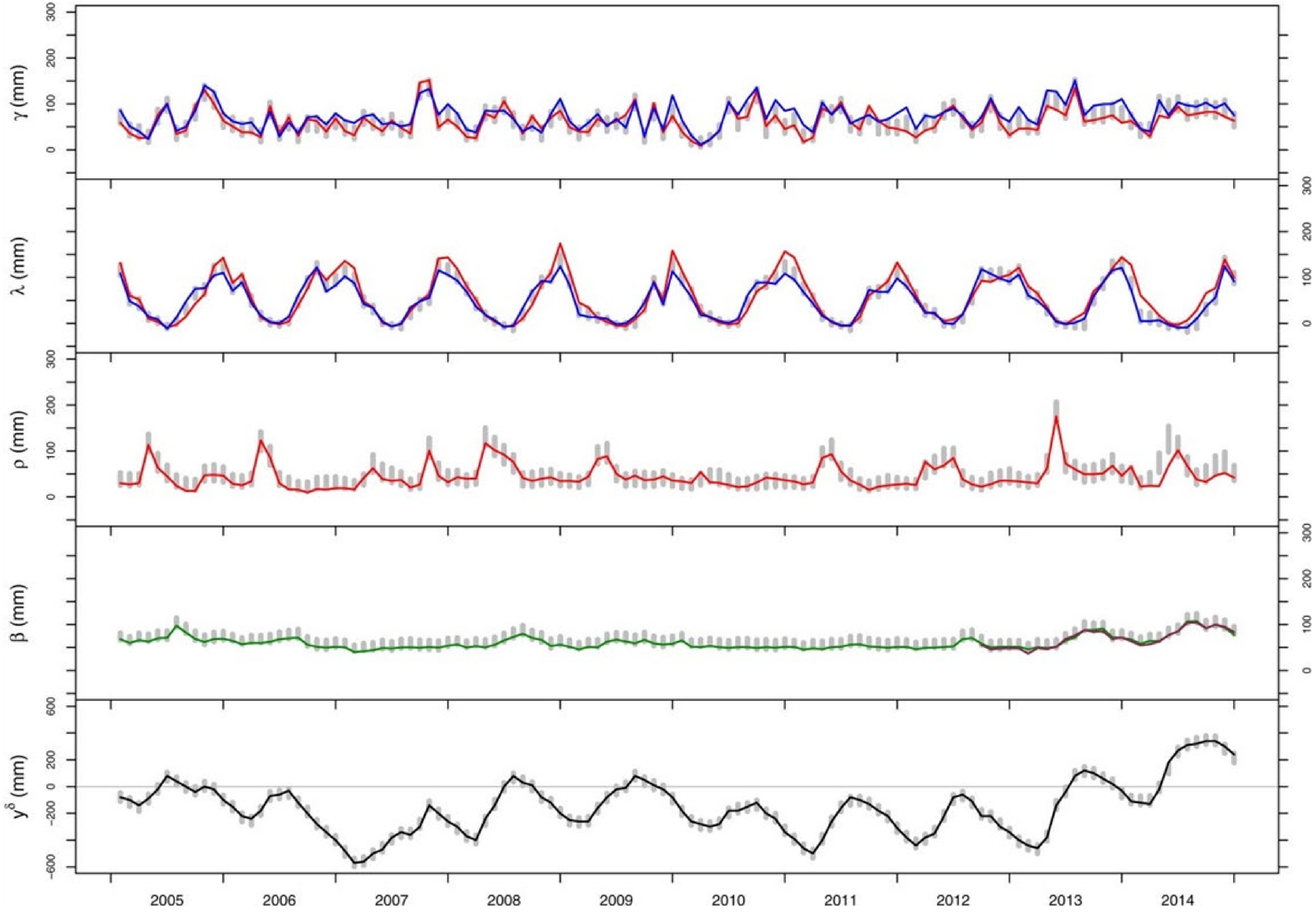
Midwestern U.S. – Projected changes in floods

- USACE 2015
  - Red River of the North at Fargo, ND
  - Changes to flood frequency curves
  - 1 in 100 flood projected to increase 31% by 2040 compared to 2nd half of 20th century, then reducing over the next six decades

Annual Exceedance Probability	Return Period (yr)	Baseline, 1950-1999 (cfs)	2011-2040 Median (cfs, change from baseline)	2041-2070 Median (cfs, change from baseline)	2071-2100 Median (cfs, change from baseline)
0.5	2	4,500	5,400, 20%	5,100, 13%	5,200, 16%
0.1	10	13,300	16,000, 20%	14,000, 5%	14,900, 12%
0.02	50	23,500	28,900, 23%	24,500, 4%	25,600, 9%
0.01	100	28,000	36,800, 31%	29,700, 6%	31,300, 12%
0.005	200	32,400	43,800, 35%	35,400, 9%	37,900, 17%

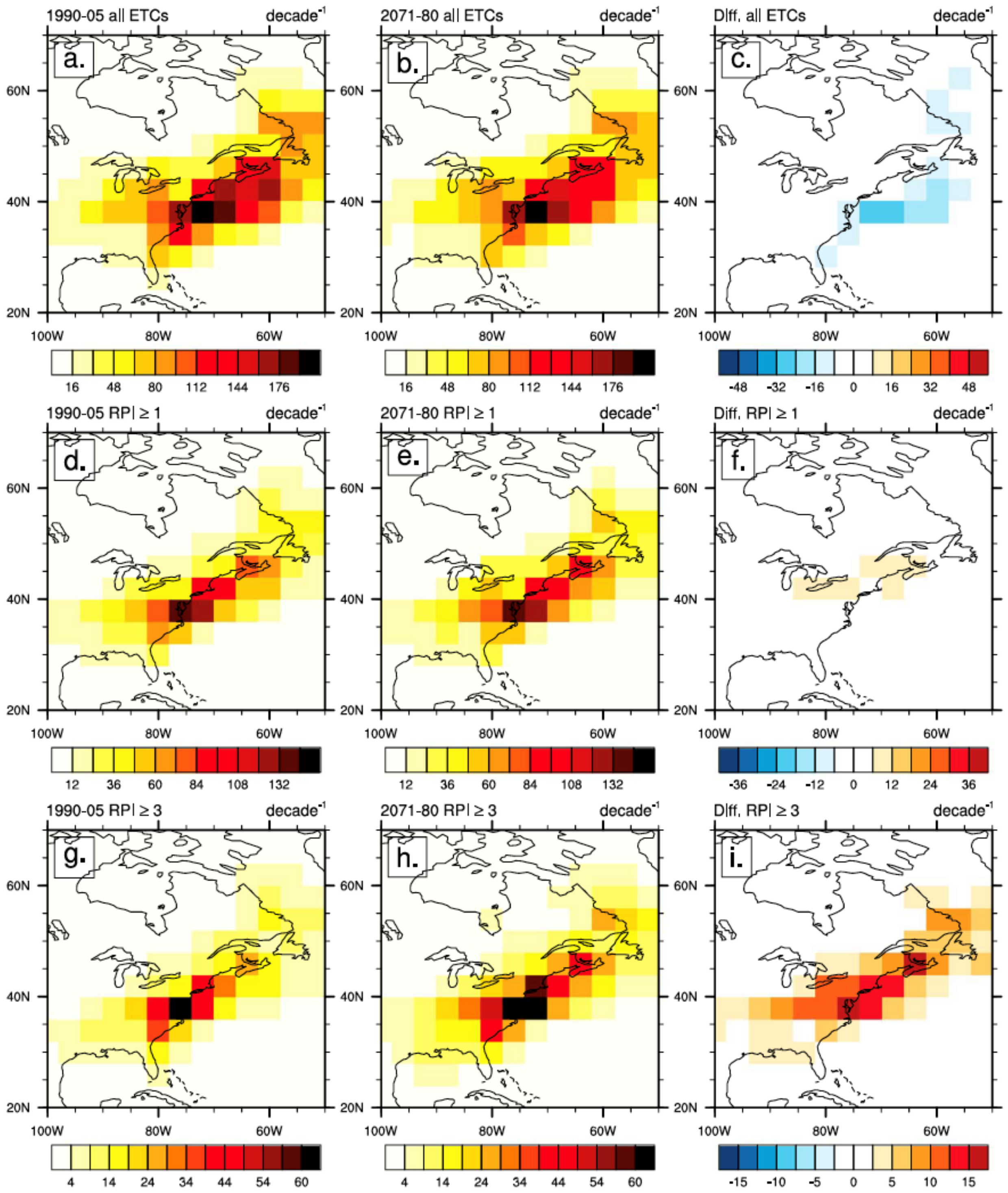


Midwestern U.S. – Great Lakes Water Levels



Northeastern U.S. – Projected Changes in Extratropical Cyclones

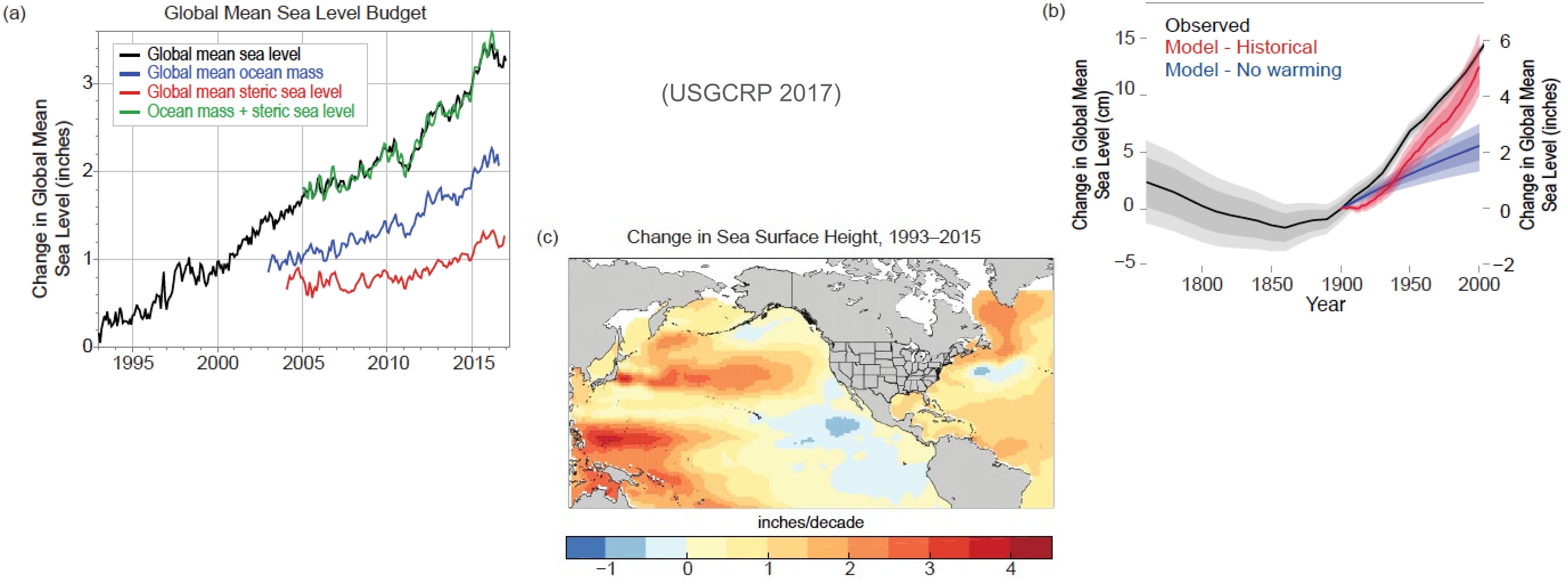
- Analyze CESM LENS simulations for RCP8.5
- Track ETCs in the simulations and define a RPI index that applies area and population weightings to the precipitation
- Track density decreases when all storms are considered
- Track density increases mainly for intense storms



End of century (2071–2080) minus present day (1990–2005), Zarcycki 2018 GRL

Northeastern U.S. – Observed increase in global and regional sea levels

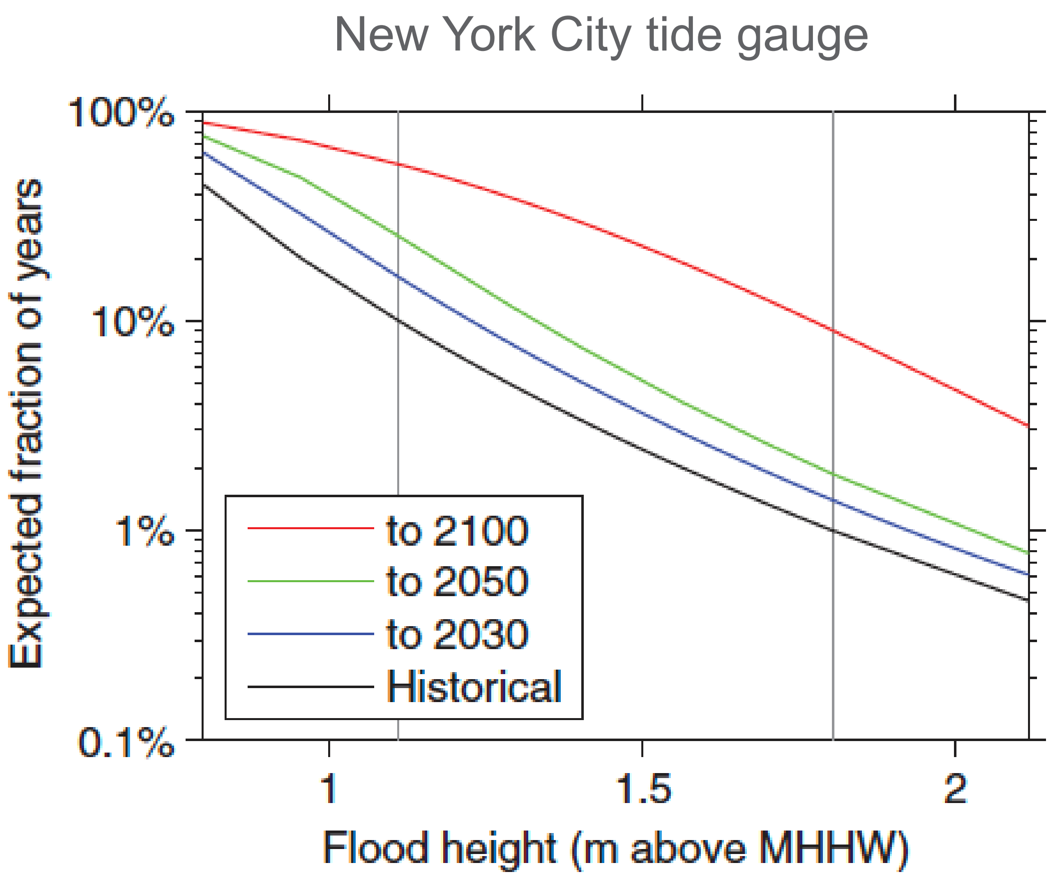
- The higher local sea level rise in northeastern U.S. has been attributed to land subsidence induced by glacial isostatic adjustment and weakening of the Gulf Stream that may be related to the weakening of the Atlantic meridional overturning circulation (AMOC)

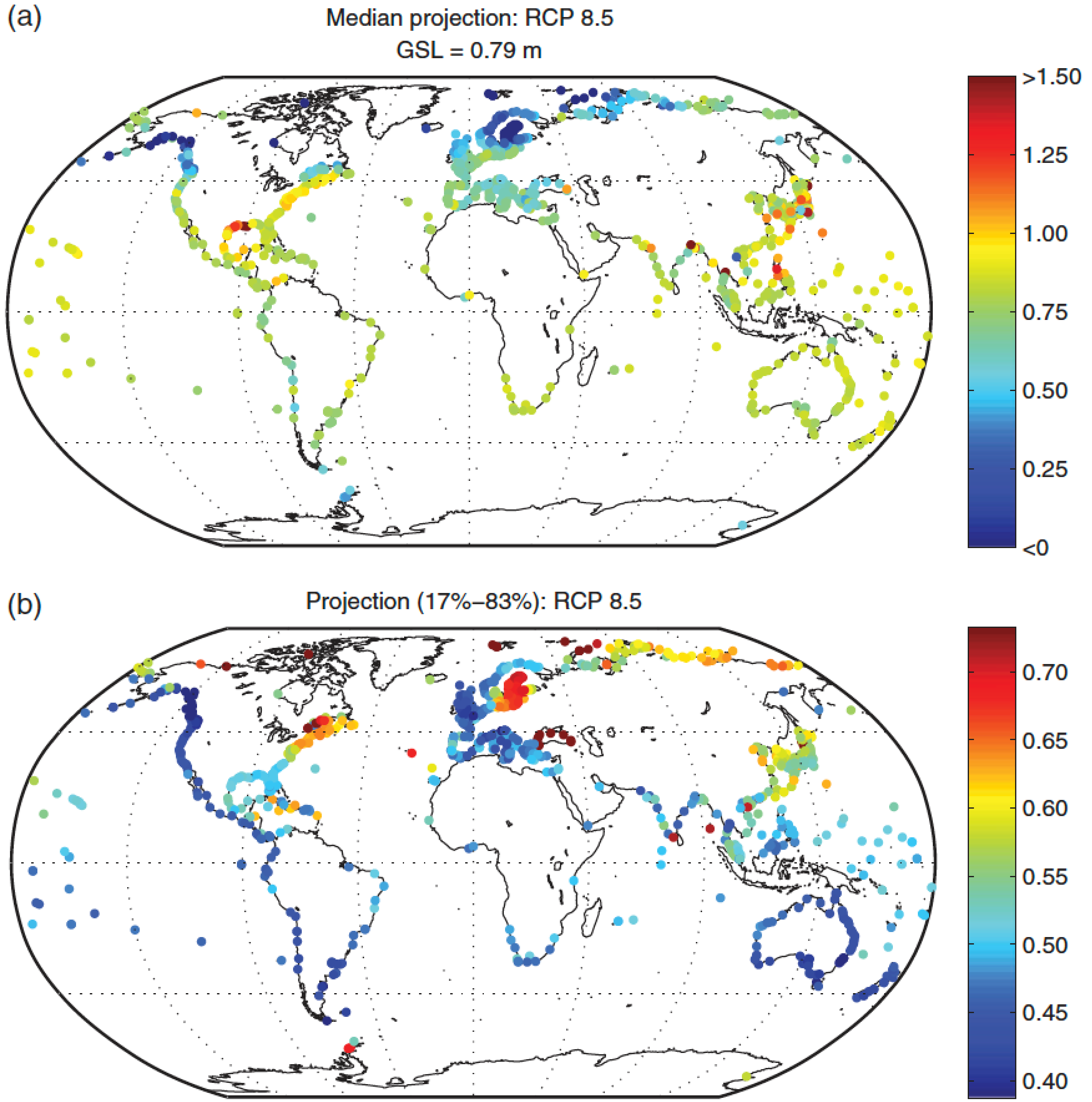


(USGCRP 2017)

Northeastern U.S. – Projected sea levels

- Local sea level rise (m) in 2100 under RCP8.5



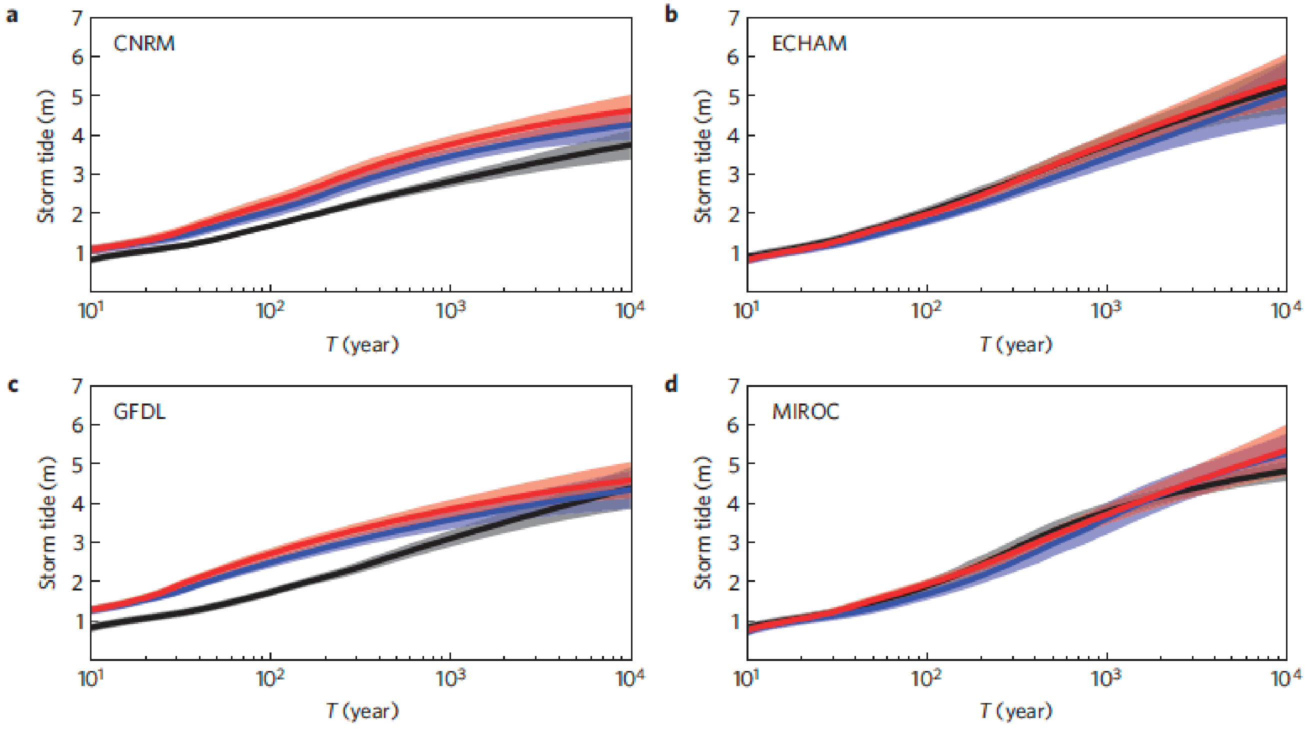


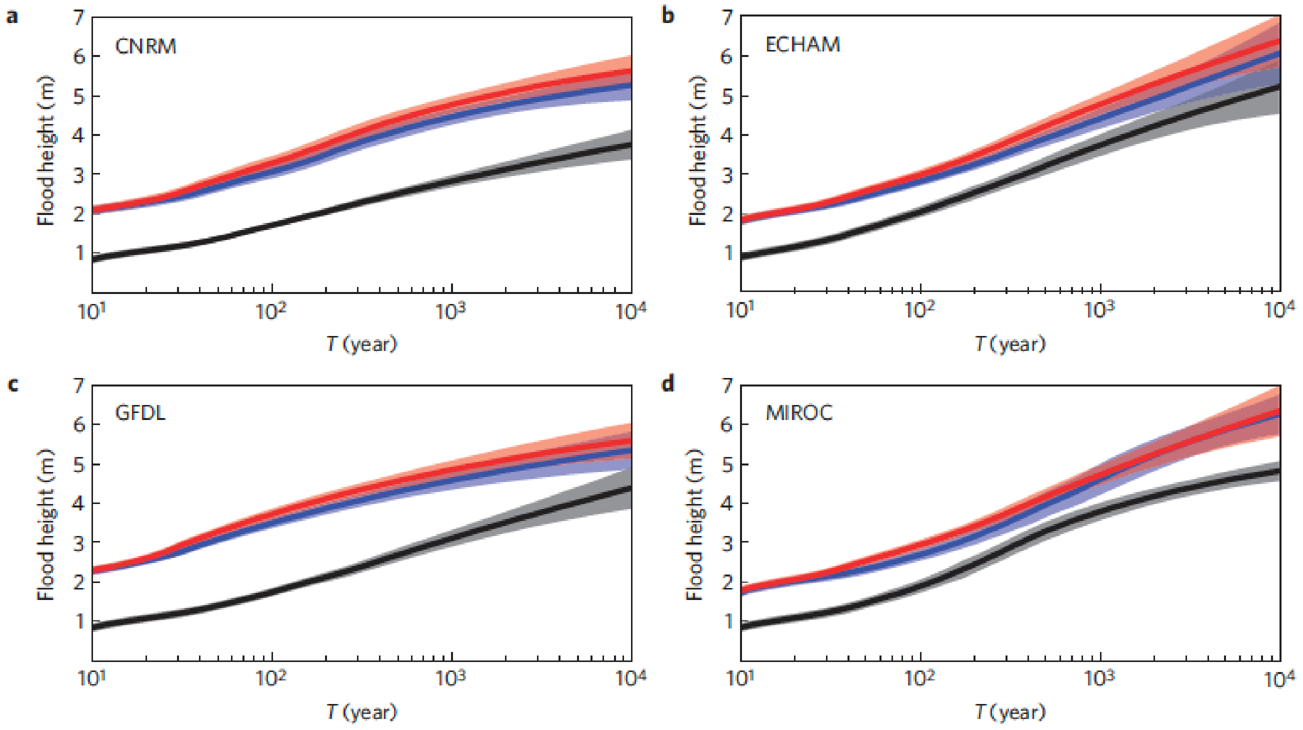
(Kopp et al. 2014 Earth's Future)

Northeastern U.S. – Projected storm surge and flood levels

- Estimated storm tide return levels for the Battery in New York City. Black (present - 1981-2000), blue (A1B - 2081-2100) and red (A1B with R_o increased by 10 percent and R_m increased by 21 percent). Shade shows the 90% confidence interval. *A1B ~ RCP4.5; R_o – outer radius of storm; R_m - storm's radius of maximum winds.
- Estimated flood return levels for the Battery. The sea-level rise for the A1B climate is assumed to be 1 m.

(Lin et al. 2012 Nature Clim. Change)

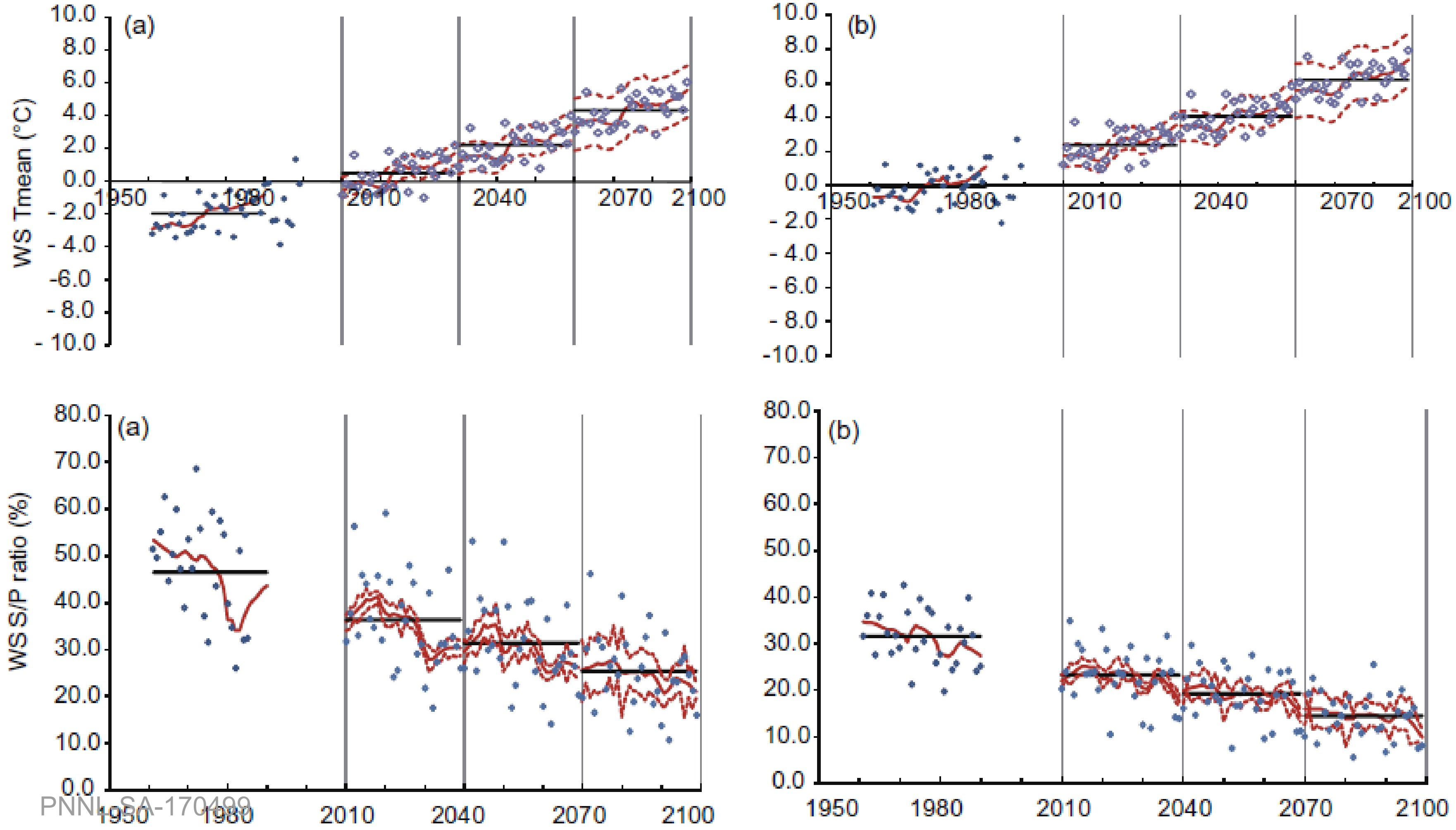


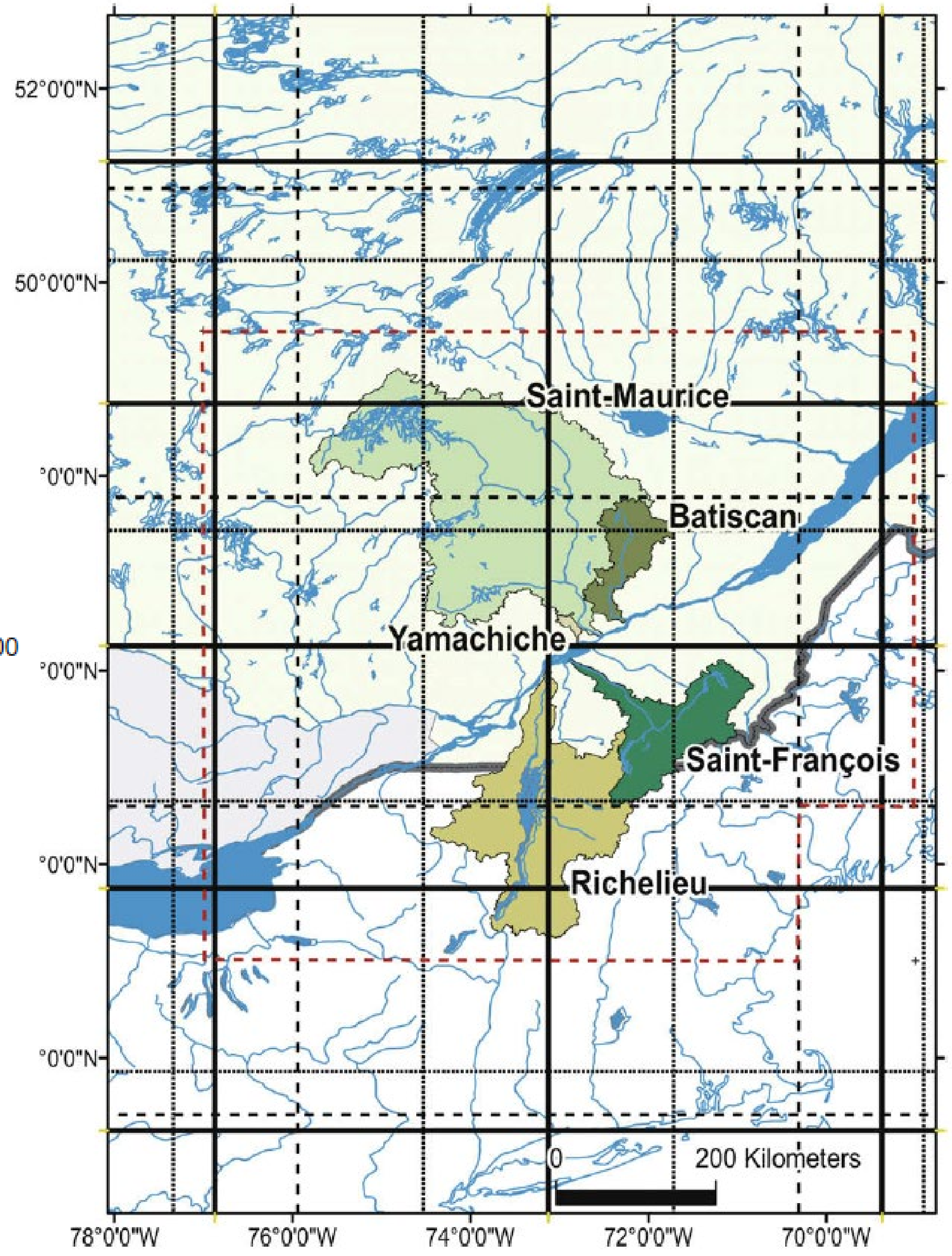


Northeastern U.S. – Observed changes in streamflow

- Boyer et al. (2010)
  - Changes in hydrology of tributaries to St. Lawrence River in Québec, Canada; 3 GCMs and 2 scenarios (SRES A2 and B2)
  - 18 future hydrologic simulations

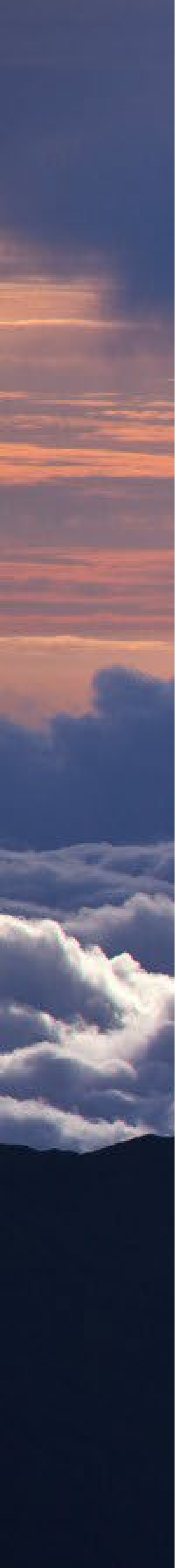
(a) St-François (b) Richelieu





Summary

- Changes in sea level affect coastal NPPs
  - Combine with changes in tropical and extratropical storms
- Changes in air temperatures are variable across the U.S.
  - Extremes may have NPP operation-related impacts
- Changes in MCSs can result in greater precipitation in the midwestern U.S.
  - May result in increased flood risk, some changes have already been observed
- Changes in Great Lakes water levels are more uncertain
- Changes in seasonality of snowmelt and springtime runoff in northern areas
  - May result in changes to both flood magnitude and timing
- Current state of information from climate science can inform NPP operations-related issues



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Thank you

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