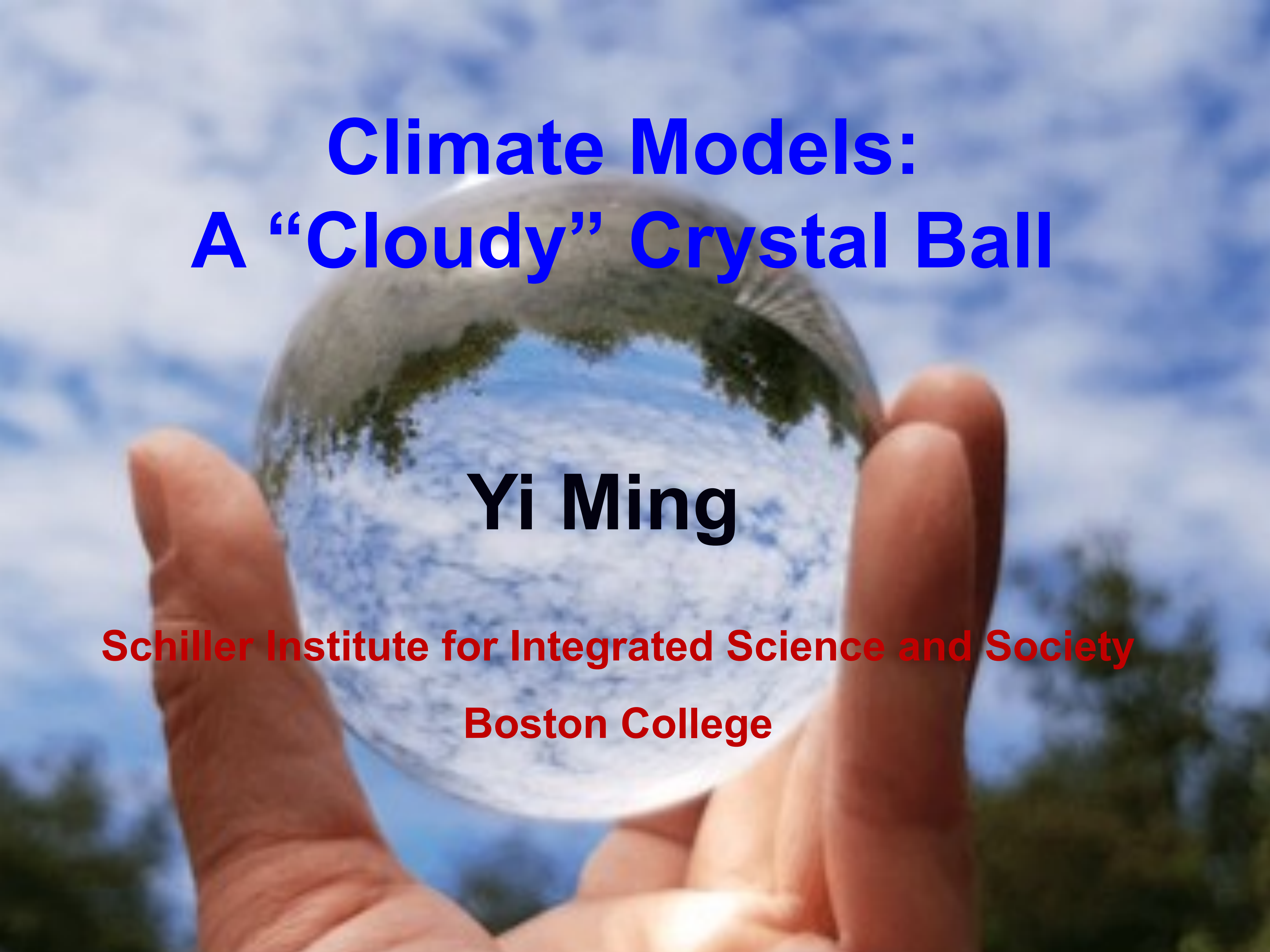


Climate Models: A “Cloudy” Crystal Ball

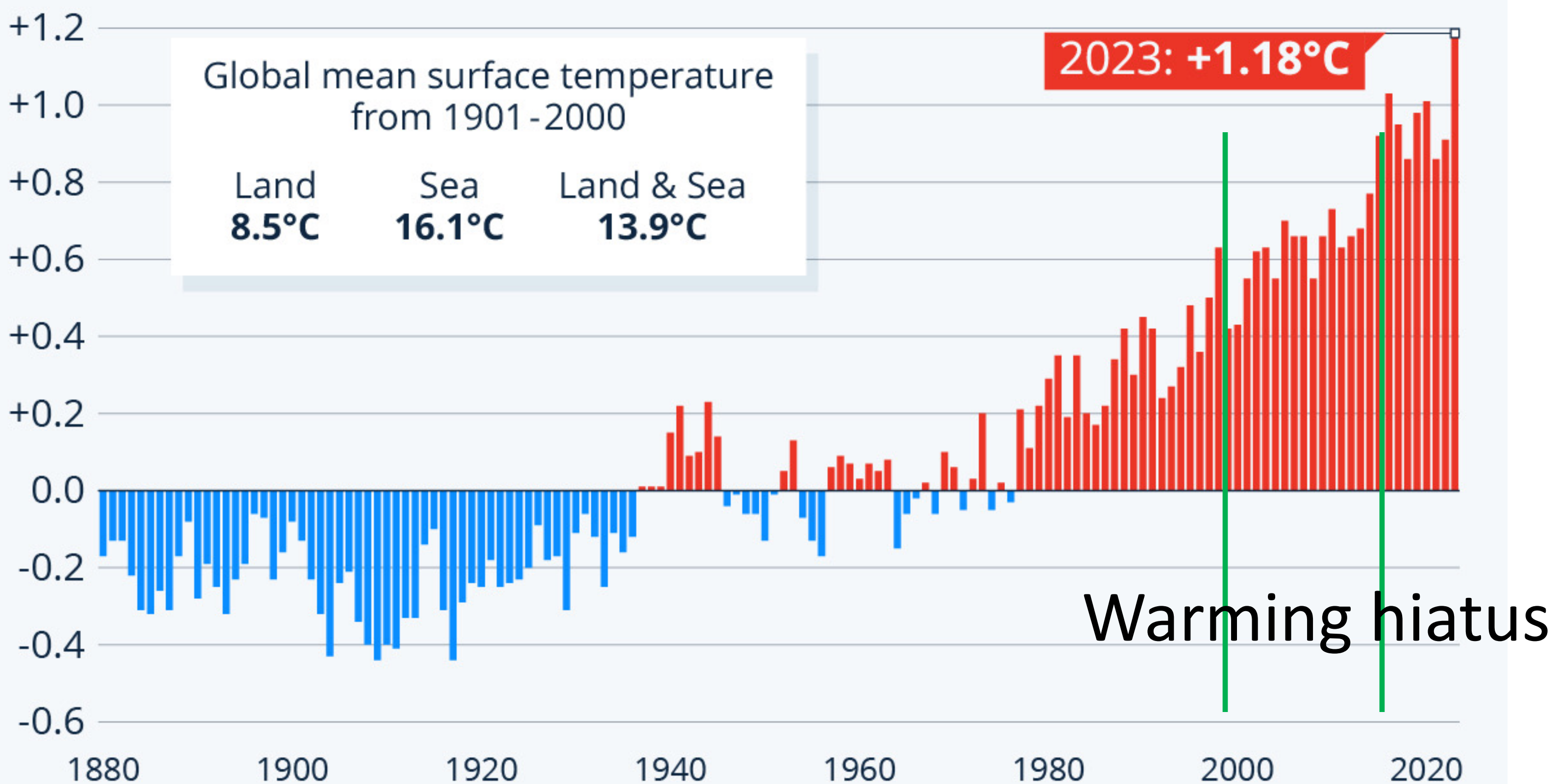
Yi Ming

Schiller Institute for Integrated Science and Society

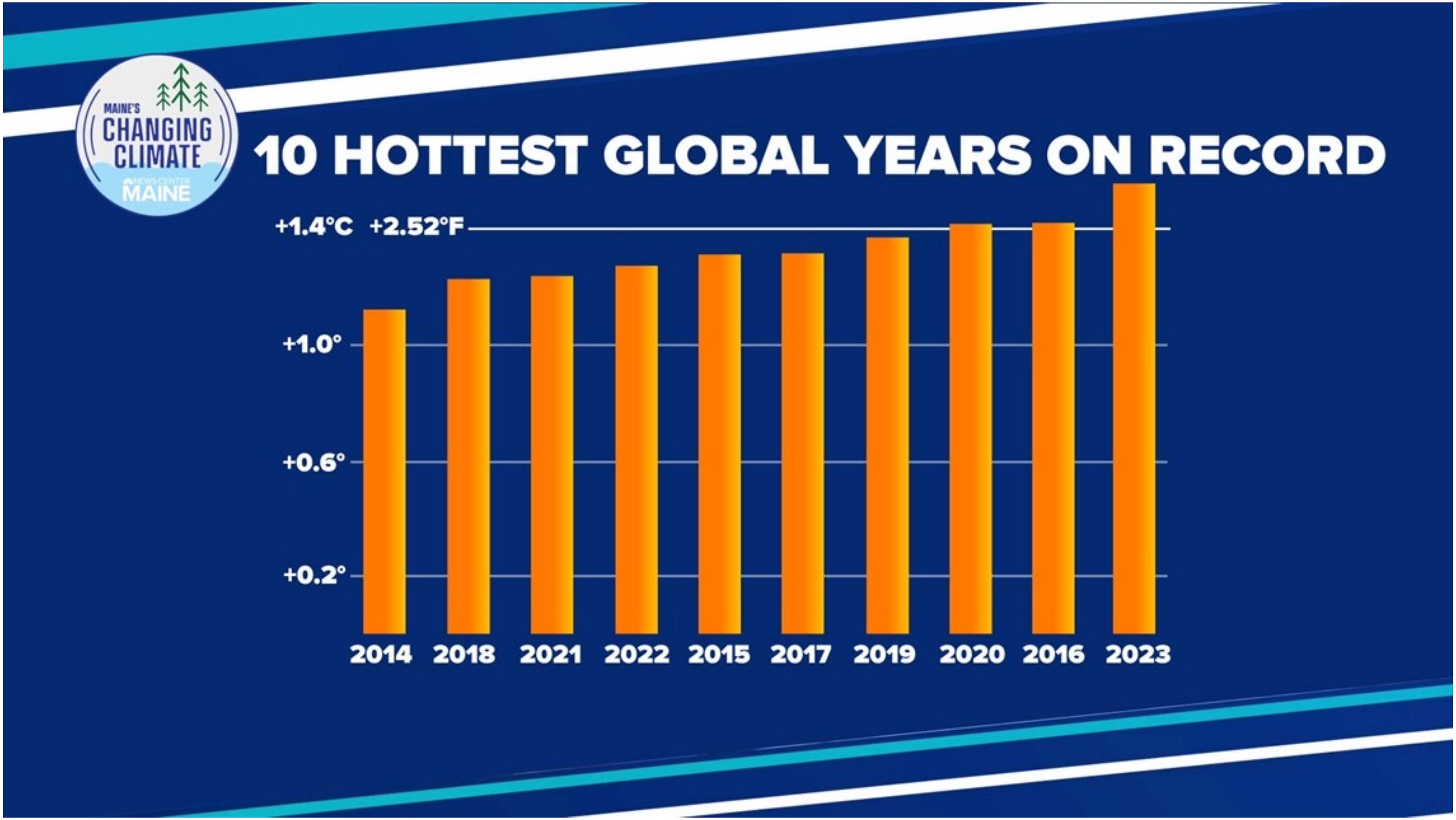
Boston College

2023 Was the Warmest Year on Record – by a Record Margin

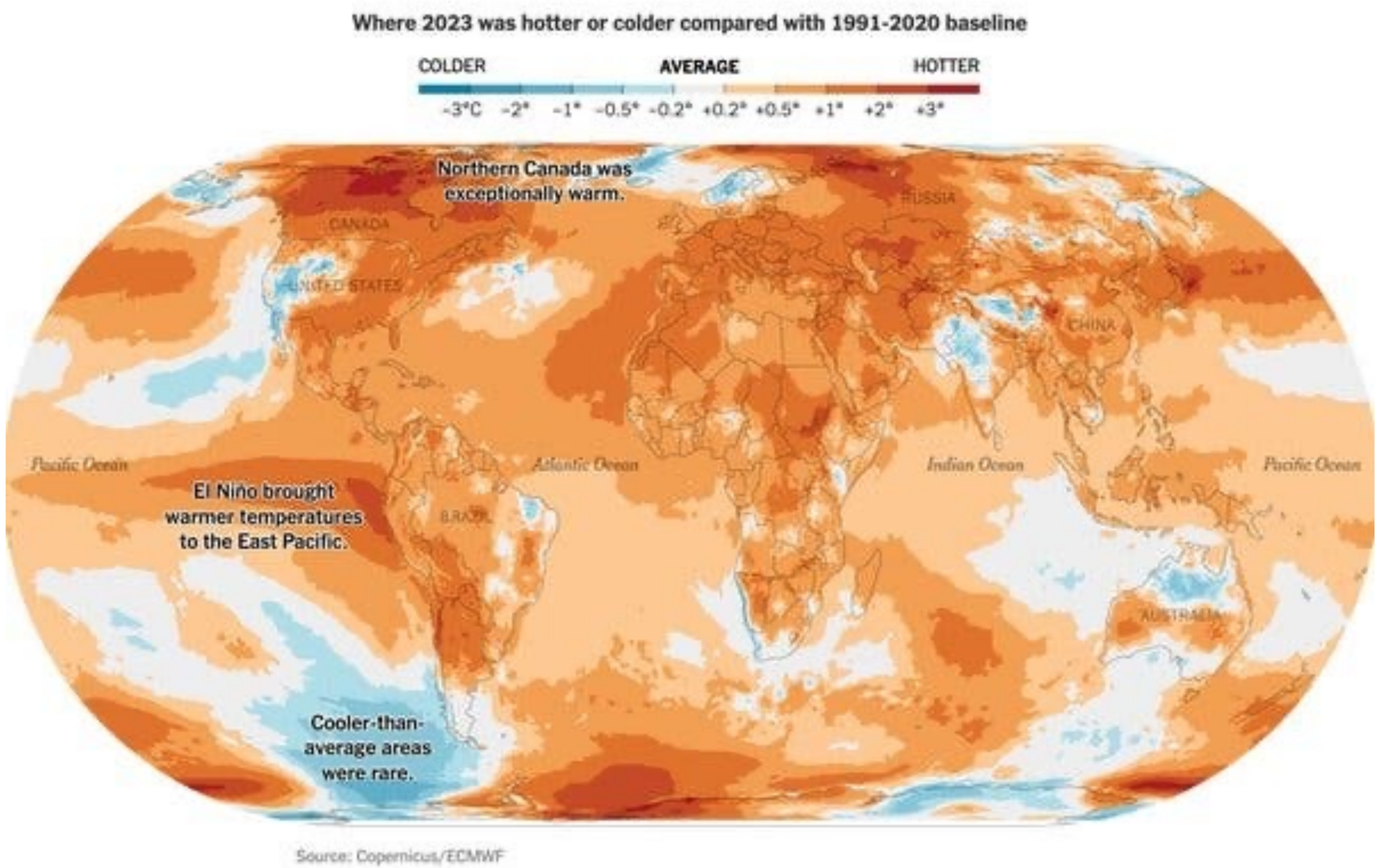
Global land and ocean surface temperature anomalies (in degrees Celsius compared to the 20th century average)



Source: NOAA


MAINE'S
CHANGING
CLIMATE
NEWS CENTER
MAINE
10 HOTTEST GLOBAL YEARS ON RECORD
+1.4°C +2.52°F
+1.0°
+0.6°
+0.2°
2014
2018
2021
2022
2015
2017
2019
2020
2016
2023

Source

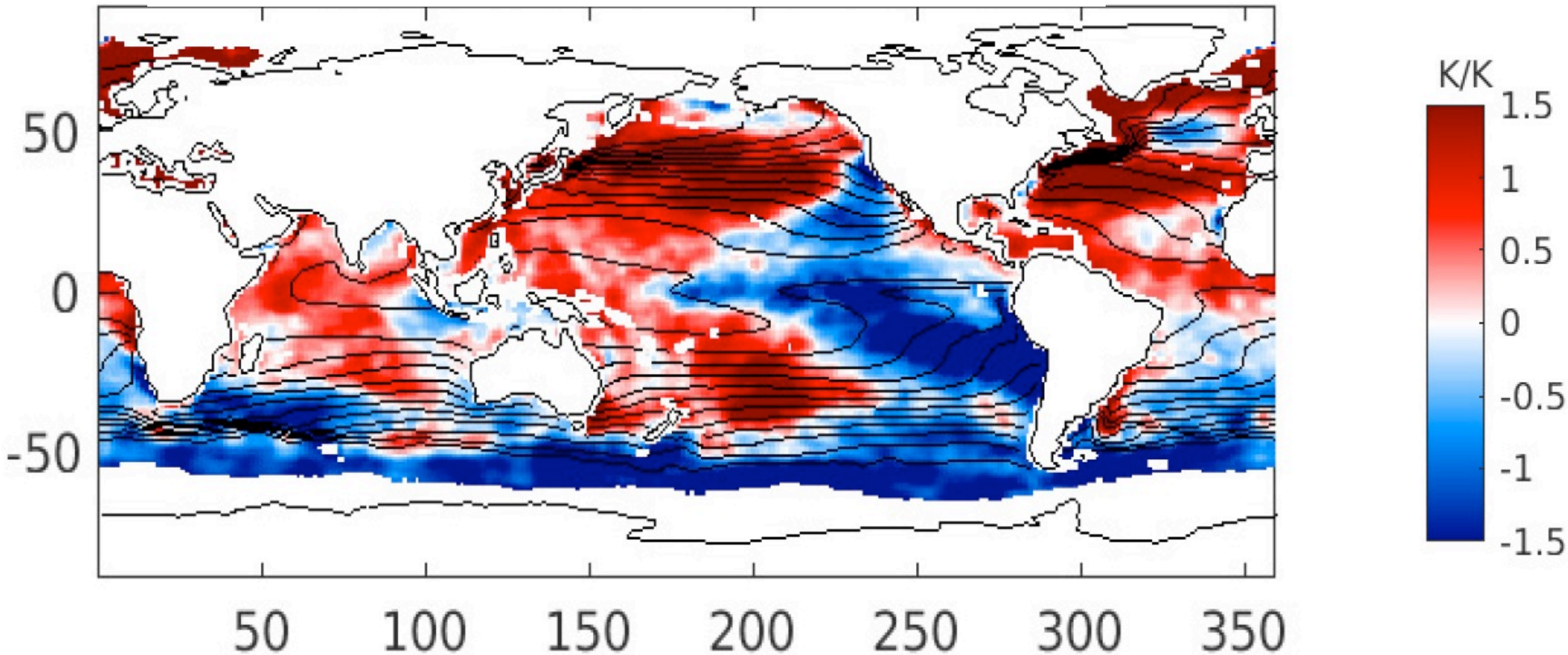


- **El Niño** (natural variability in general)
- Stratospheric water vapor from the Tonga volcanic eruption
- Reduced sulfur emission from international shipping
- Greenhouse gases

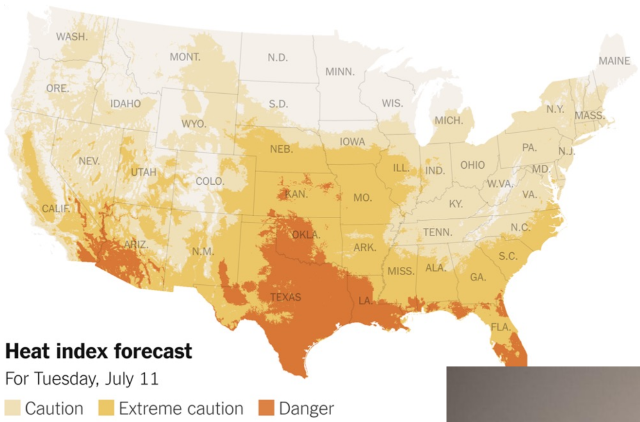
La Niña pattern of warming (1979-2020)

HadISST $\overline{SST_A}$ = 0.09 K/decade

Observed−pattern; $(SST_A - \overline{SST_A})/\overline{SST_A}$



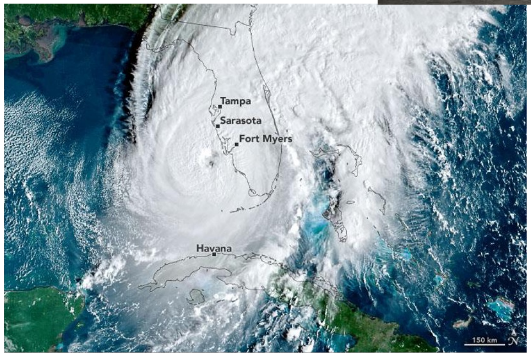
The country is on fire, literally!



Heat wave 7/11/23

Heavy Flooding in Vermont

NYC shrouded in wildfire smoke 6/6/23



Hurricane Ian hitting Florida (9/28/2022)

Colorado River drying up

Organization of this talk

- A primer on climate models
- Past successes
- Ongoing challenges
- Future plans
    - ❑ Seasonal/decadal prediction
    - ❑ Bias correction

The primitive equations

$$\frac{du}{dt} - \left(f + u\frac{\tan\phi}{a}\right)v = -\frac{1}{a\cos\phi}\frac{1}{\rho}\frac{\partial p}{\partial\lambda} + F_\lambda$$

$$\frac{dv}{dt} + \left(f + u\frac{\tan\phi}{a}\right)u = -\frac{1}{\rho a}\frac{\partial p}{\partial\phi} + F_\phi$$

$$g = -\frac{1}{\rho}\frac{\partial p}{\partial z}$$

momentum

$$\frac{\partial\rho}{\partial t} = -\frac{1}{a\cos\phi}\left[\frac{\partial}{\partial\lambda}(\rho u) + \frac{\partial}{\partial\phi}(\rho v\cos\phi)\right] - \frac{\partial}{\partial z}(\rho w)$$

mass

$$C_p\frac{dT}{dt} - \frac{1}{\rho}\frac{dp}{dt} = Q$$

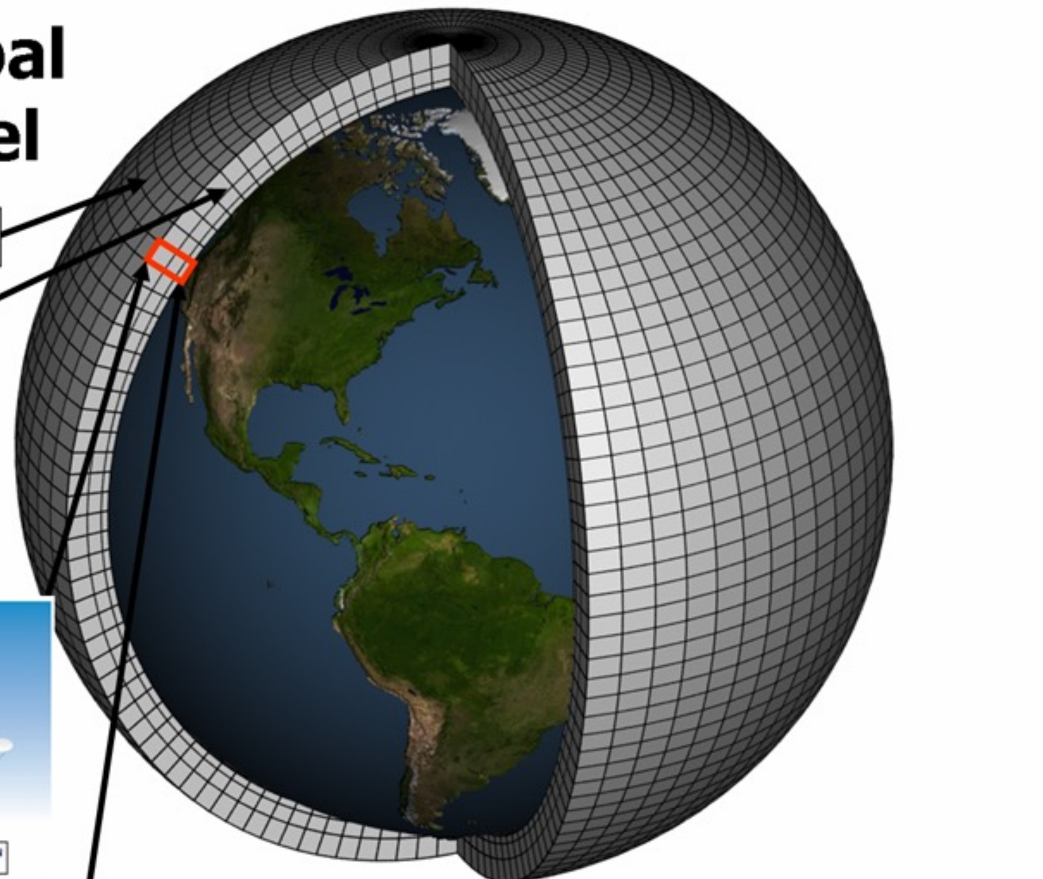
energy

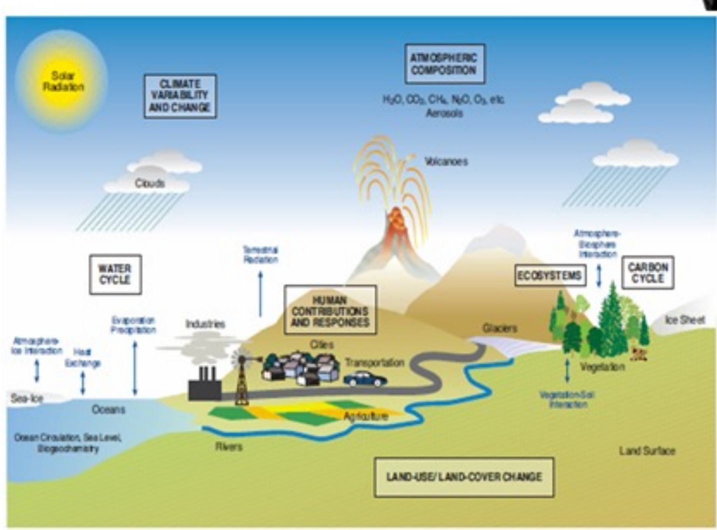
$$p = \rho RT$$

equation of state

- Non-linear fluid dynamics, turbulent in nature
- Presence of water makes things even harder
- Now carbon/nitrogen cycles, biogeochemistry, human behaviors, …

Global climate models (GCM)





- Resolution (dynamics)
- Sub-grid processes (physics)
- Physics parameterizations are the main source of uncertainty

Model implementation: Code run on giant supercomputers

The Cheyenne Supercomputer located in Cheyenne, Wyoming.


```
!-----------------------------------------------------------------------
! Calculate light absorption by the plant canopy
!-----------------------------------------------------------------------
      IF (CAN_RAD_MOD == 2) THEN
        CALL ALBPFT          (ROW_LENGTH*ROWS,LAND_PTS,                  &
     &                       LAND_INDEX,TILE_INDEX,TILE_PTS,ILAYERS,       &
     &                       ALBSOIL,COS_ZENITH_ANGLE,LAI,ALB_TYPE_DUMMY,  &
     &                       FAPAR_DIR,FAPAR_DIF,CAN_RAD_MOD)

      ENDIF


!-----------------------------------------------------------------------
! Loop over Plant Functional Types to calculate the available moisture
! and the values of canopy conductance, the carbon fluxes and the leaf
! turnover rate
!-----------------------------------------------------------------------
      DO N=1,NPFT

        IF (NTILES == 1) THEN
          DO L=1,LAND_PTS
            TSTAR(L) = TSTAR_TILE(L,1)
            Z0(L) = Z0_TILE(L,1)
          ENDDO
        ELSE
          DO L=1,LAND_PTS
            TSTAR(L) = TSTAR_TILE(L,N)
            Z0(L) = Z0_TILE(L,N)
          ENDDO
        ENDIF
```

A section of code from HadGEM2-ES (as used for CMIP5) in Fortran (a programming language).
Credit: Dr Chris Jones, Met Office Hadley Centre (via Carbon Brief)

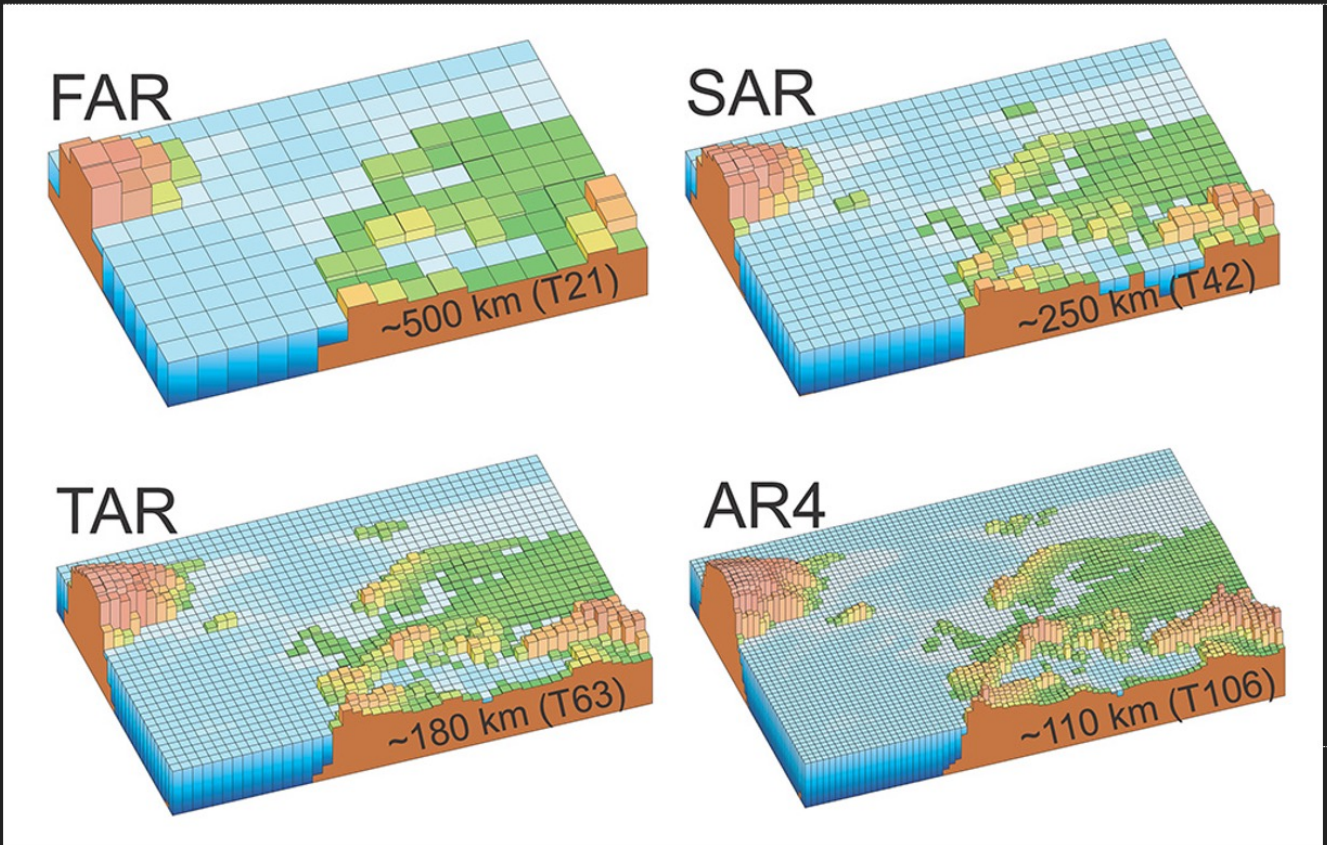
The first global climate model was developed at GFDL in the 1960s

Syukuro (Suki) Manabe

Suki with Joe Smagorinsky (R: GFDL's first Director) and Kirk Bryan (L: leader of ocean modeling) in 1969.

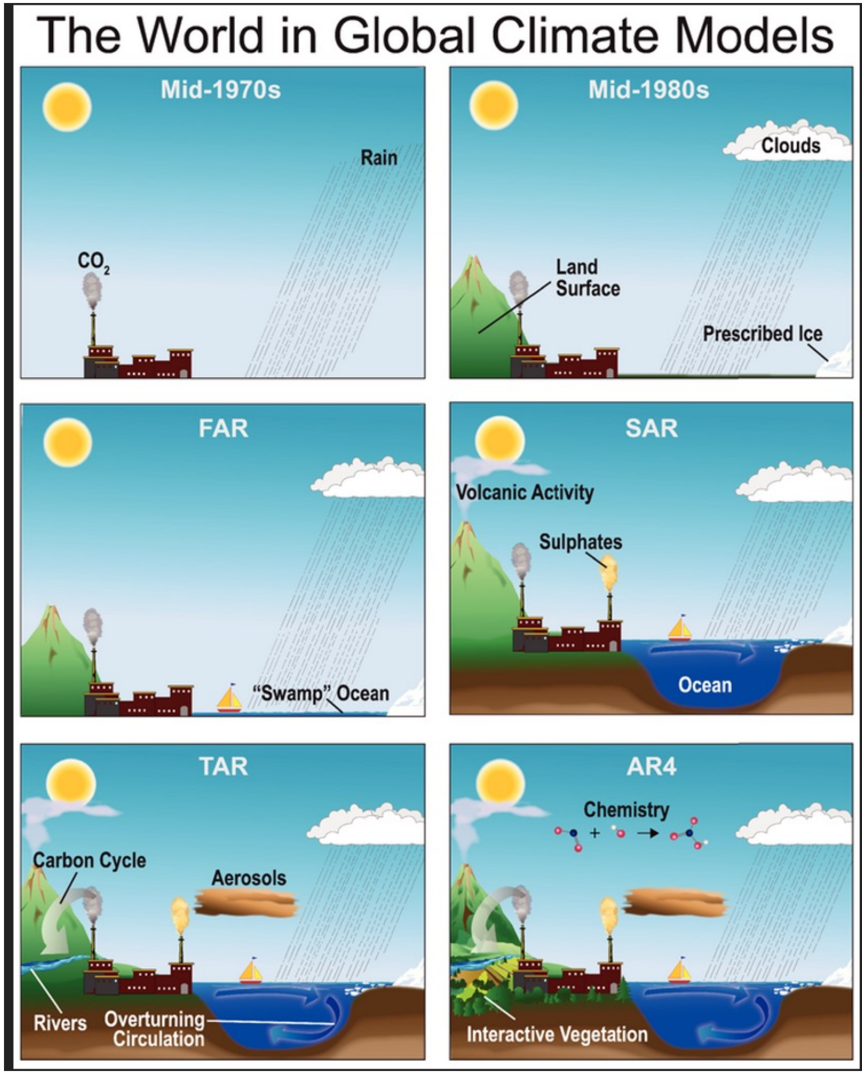
- Suki was honored with the Nobel Prize in Physics in 2021 "for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming"

Increasing spatial resolution of climate models used in the 1st four IPCC reports



First ("FAR") - 1990
Second ("SAR") - 1995
Third ("TAR") - 2001
Fourth ("AR4") - 2007

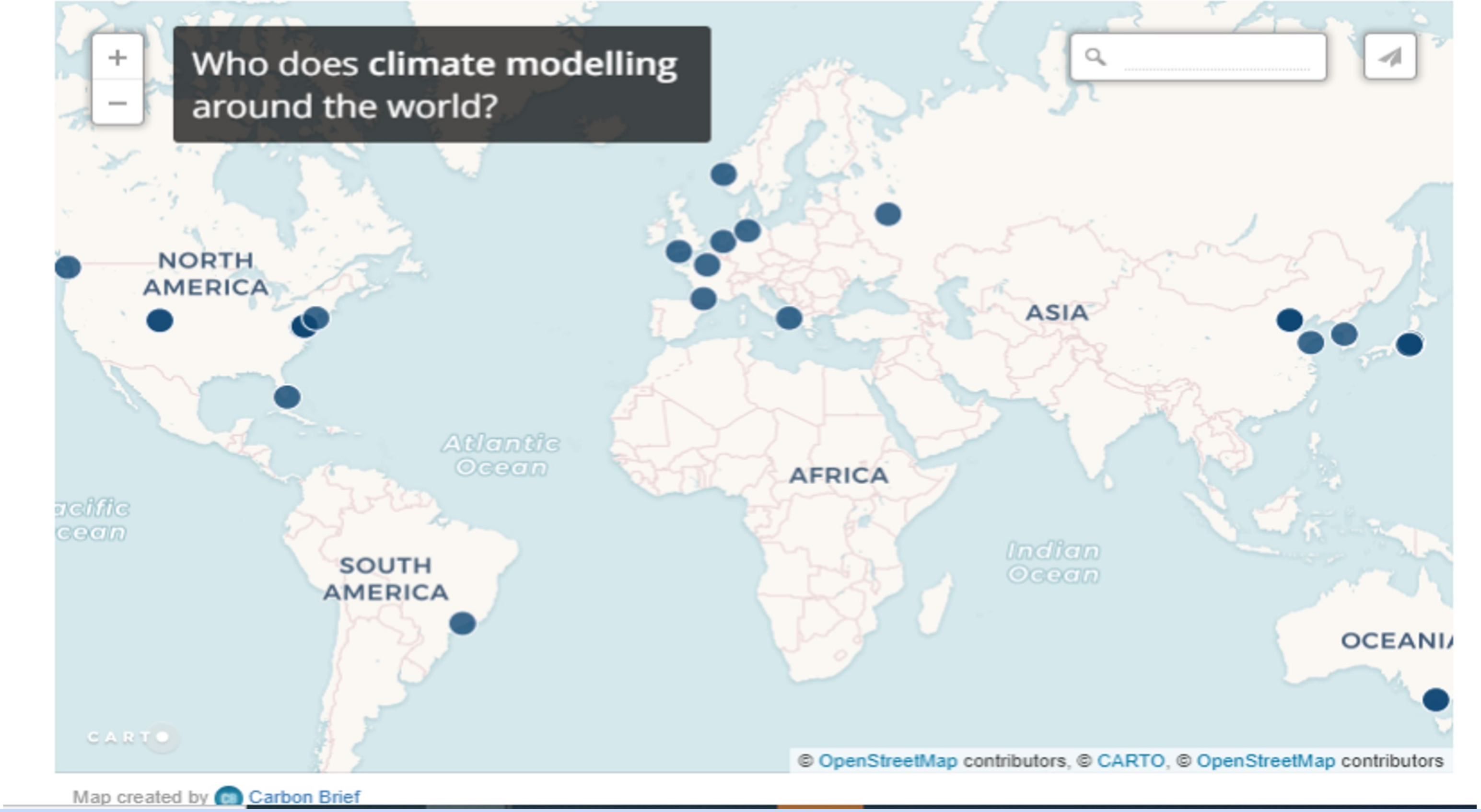
Source: IPCC AR4, Fig 1.2



More complete and complex representation of global climate processes

Illustration of the processes added to global climate models over the decades, from the mid-1970s, through the first four IPCC assessment reports.

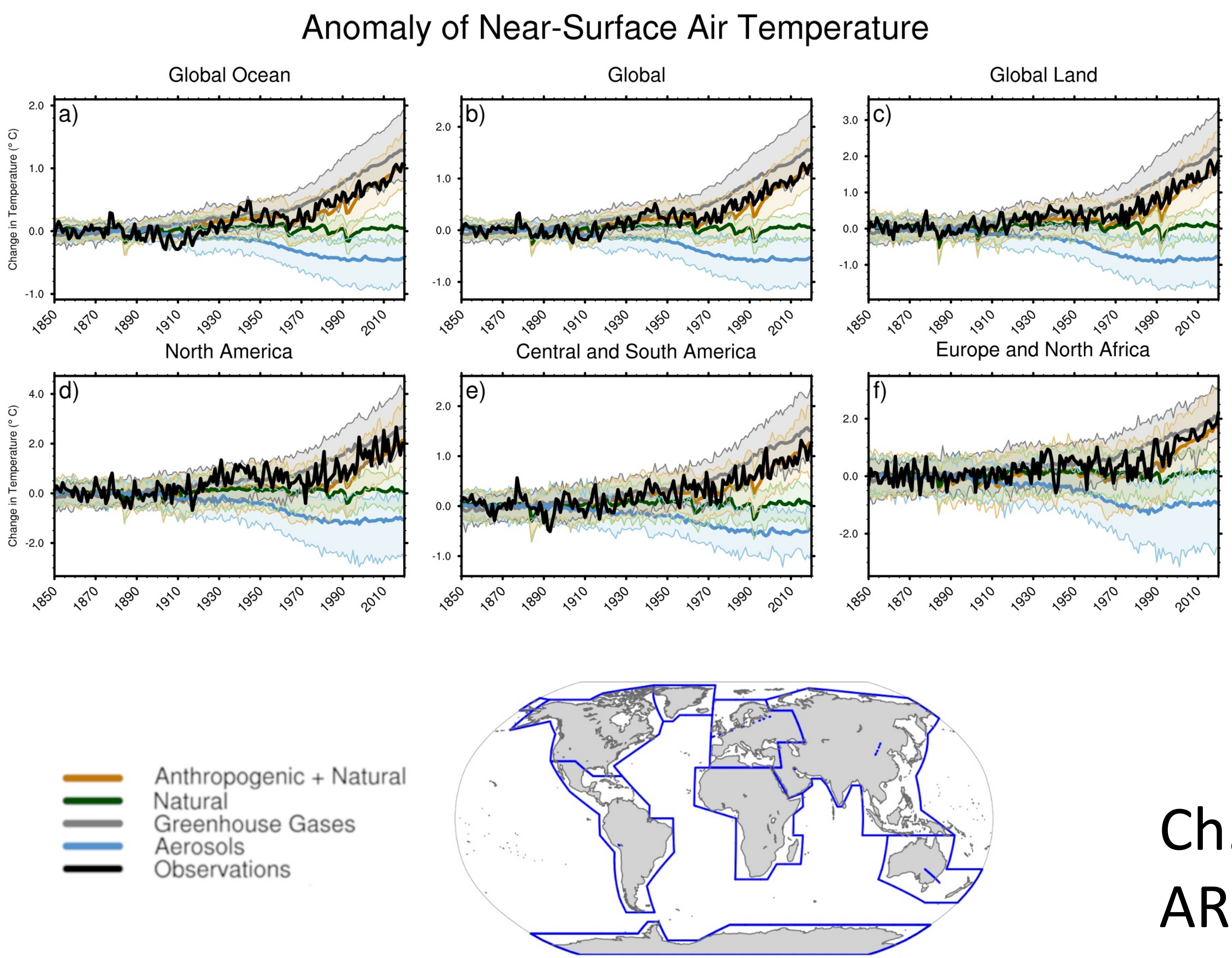
Source: IPCC AR4, Fig 1.2



Many climate models run by modeling centers around the world

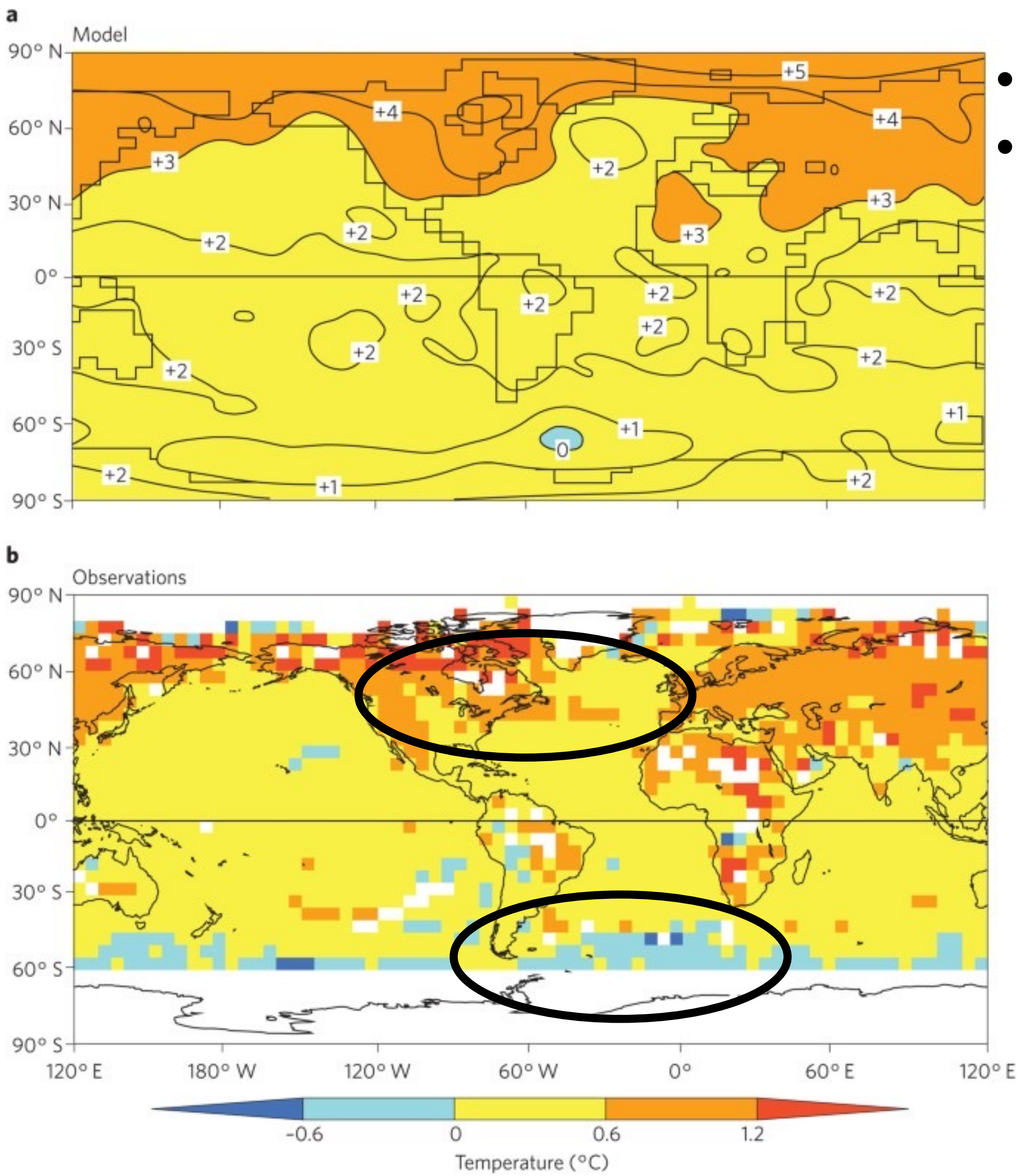
- Ability to compare results across models helps identify strengths & weaknesses, and improves confidence in predictions where all models agree
- But also presents a challenge of making sure that all models are running the same experiment so that we can effectively compare across models

Past success #1: Attributing human-induced warming



Ch. 3 of IPCC AR6

Past success #2: Predicting the warming pattern

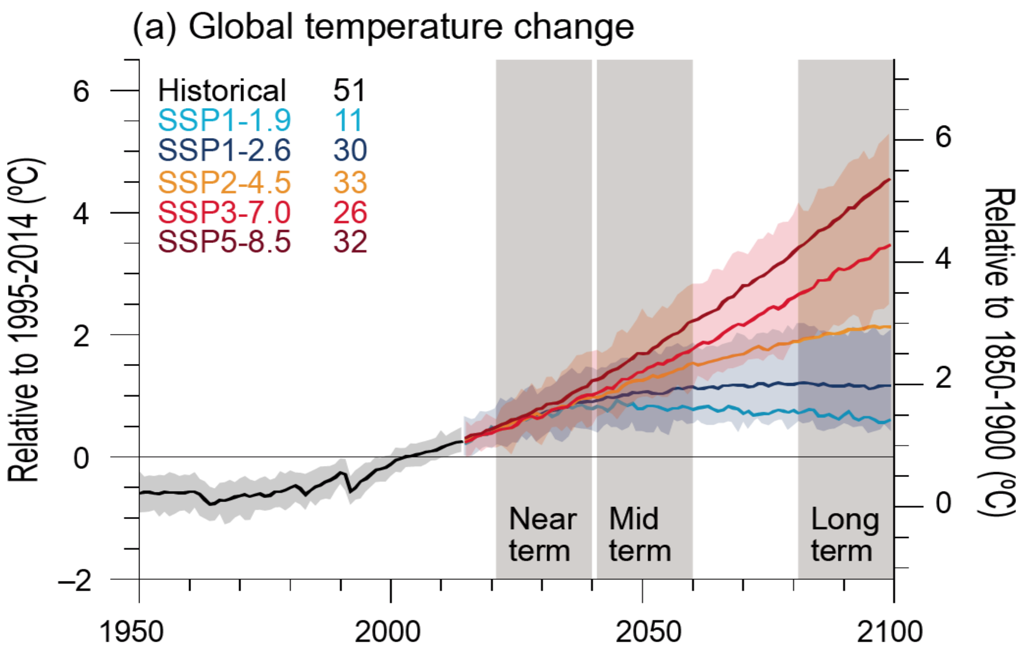


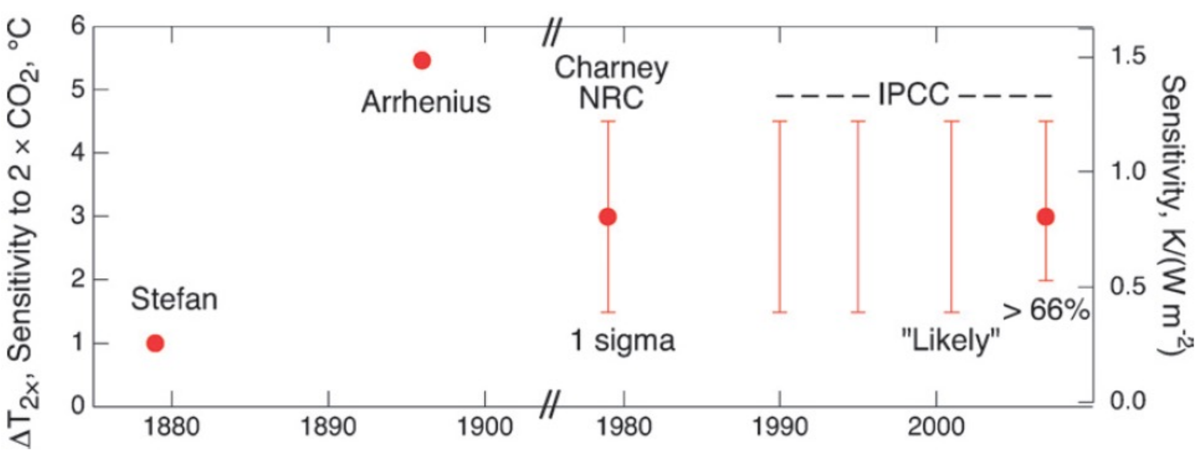
- Predicted in 1989
- Warming realized by the ~70th year (the time of doubling in the 1%-per-year simulation)

- Observed warming (1991-2015 minus 1961-1990)

Stouffer and Manabe, 2017

Ongoing challenge #1: large uncertainty in the future warming





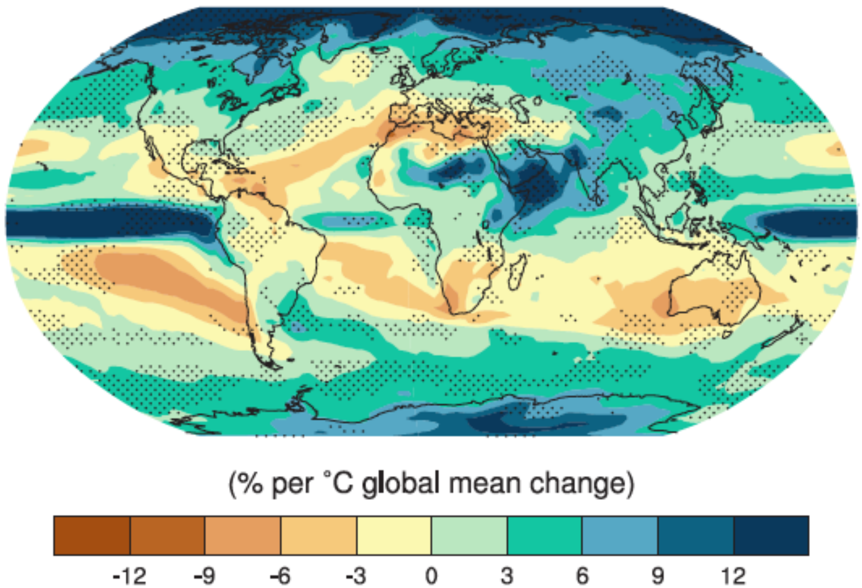
Ch. 4 of IPCC AR6

- λ likely between 1.5 and 4.5 K (IPCC AR5, or Intergovernmental Panel on Climate Change Fifth Assessment Report).
- Hinders projection of future surface temperature change.
- Rooted in poor simulation of clouds by global climate models (GCM).

Schwartz (2008)

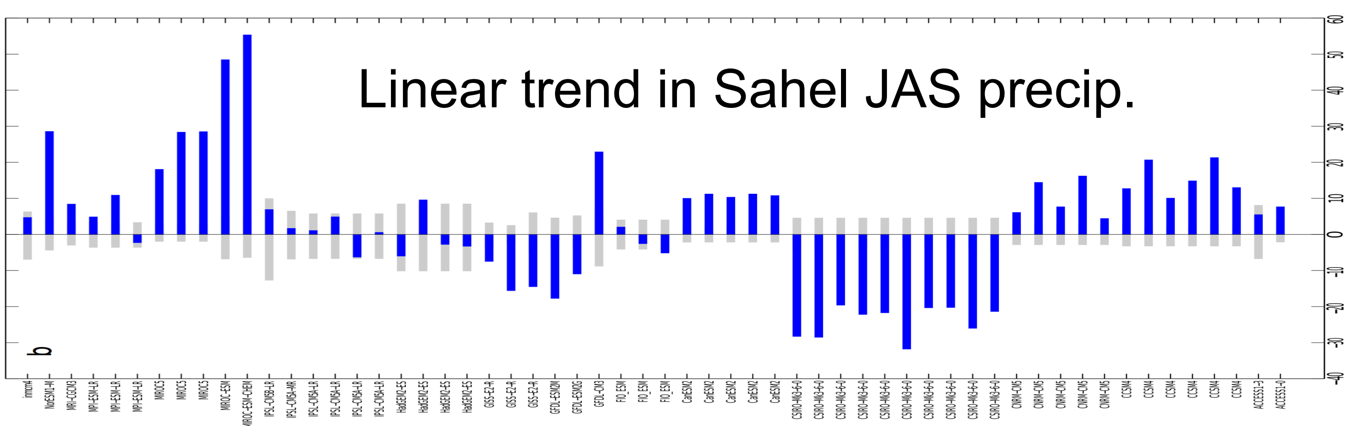
Ongoing challenge #2: large uncertainty in the future regional precipitation

Precip. scaled by global temp. (% °C^{-1})



Ch. 12 of IPCC AR5

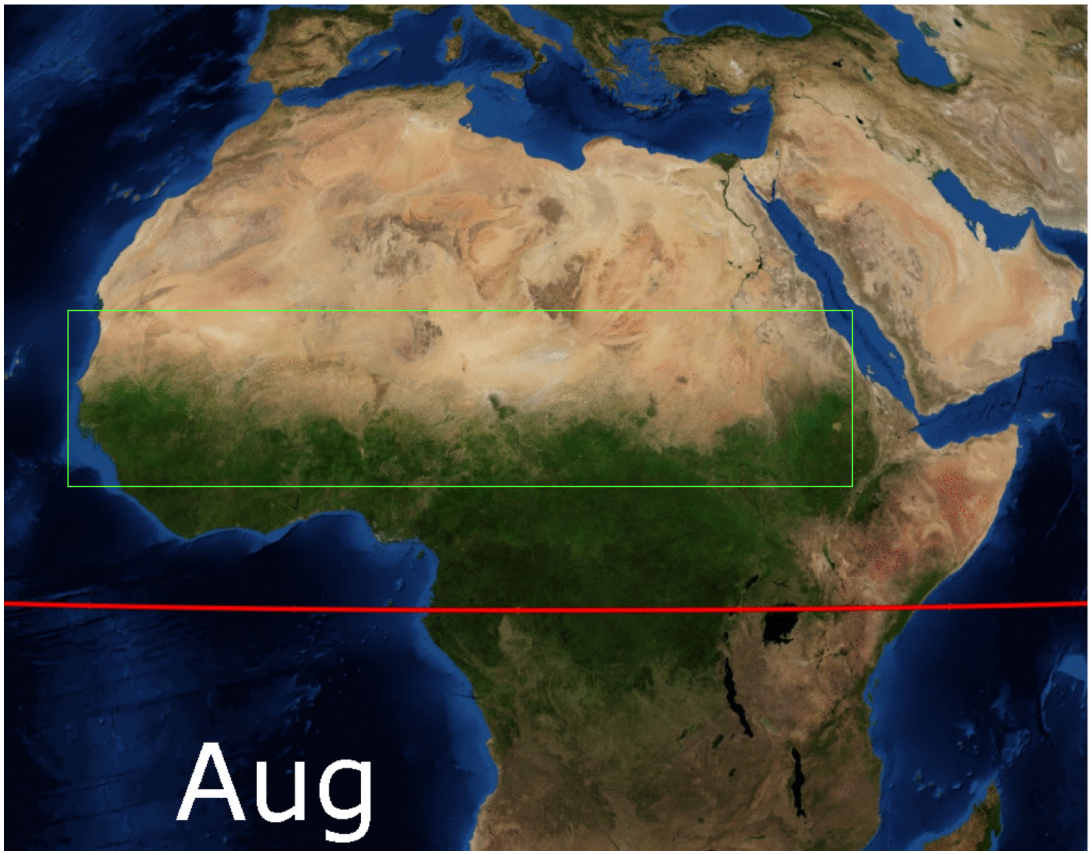
- Future scenarios: 2080-2099 minus 1986-2005.
- Stippling denotes where the results are robust.
- "Wet-get-wetter, dry-get-drier" does not work over the land.
- No sign of convergence from CMIP3 to CMIP5.



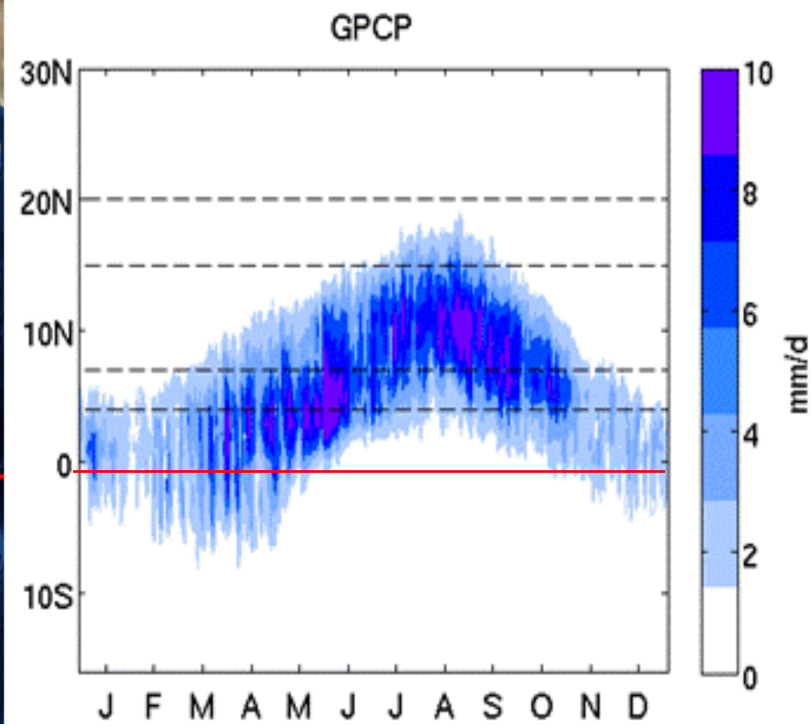
Biasutti (2013)

The Sahel: Transition between the Sahara and equatorial Africa

From the Arabic word “sahil”, which means “shore/coast.”

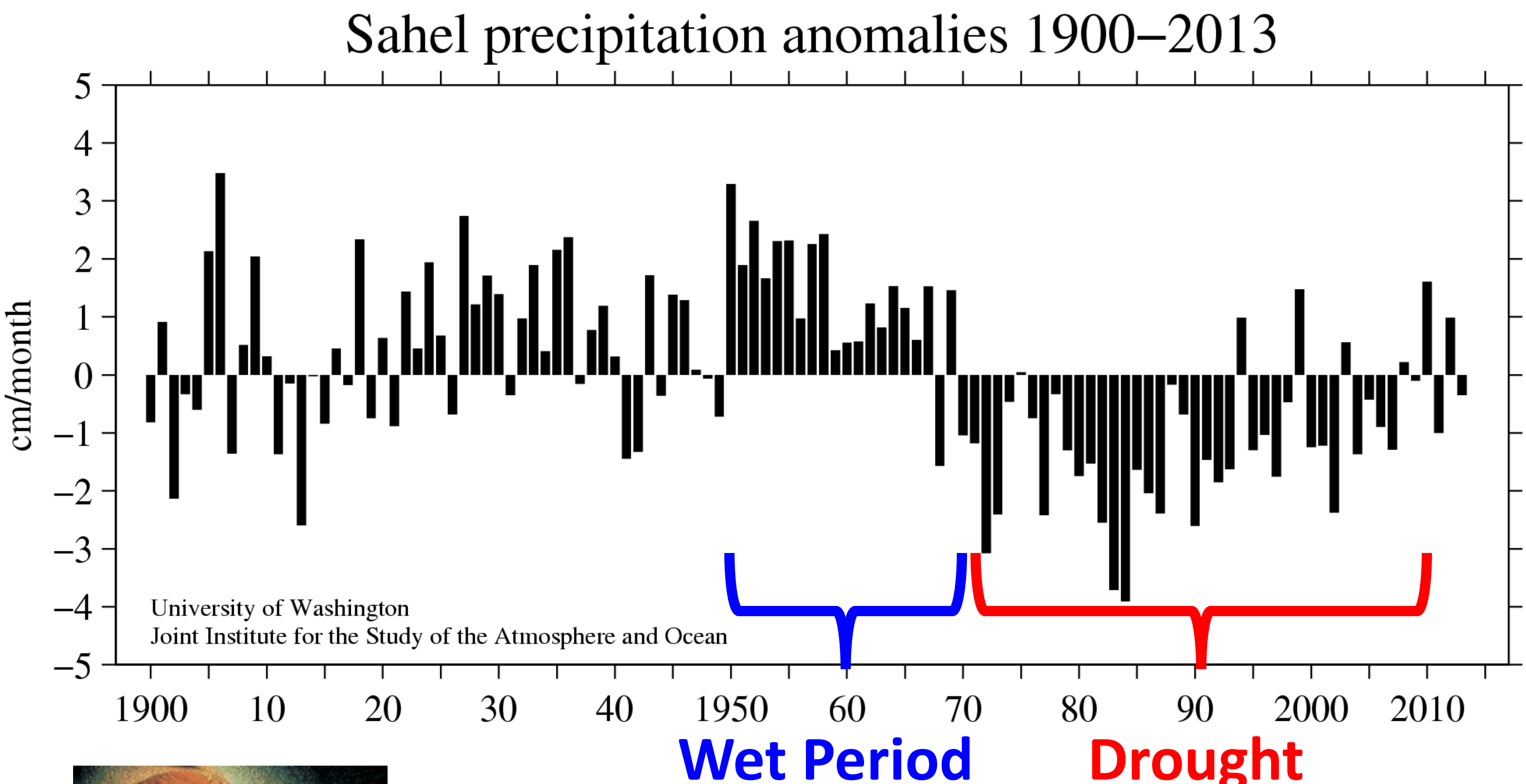


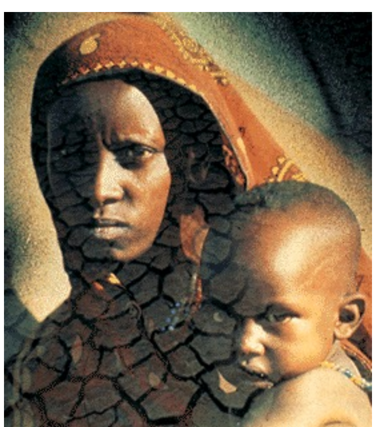
Precip. averaged over 15°W-10°E



10-20°N 18°W-40°E

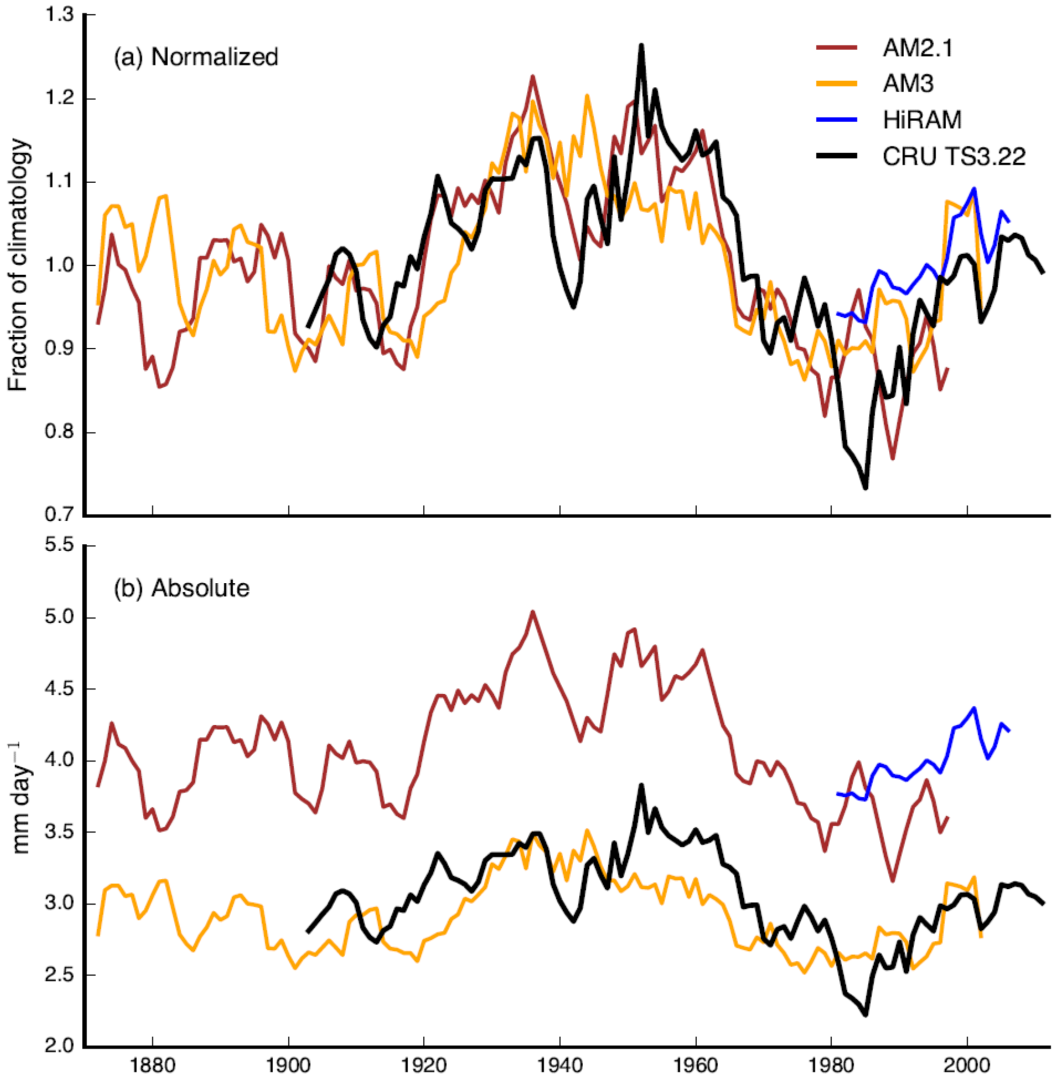
Large past variations in Sahel rainfall





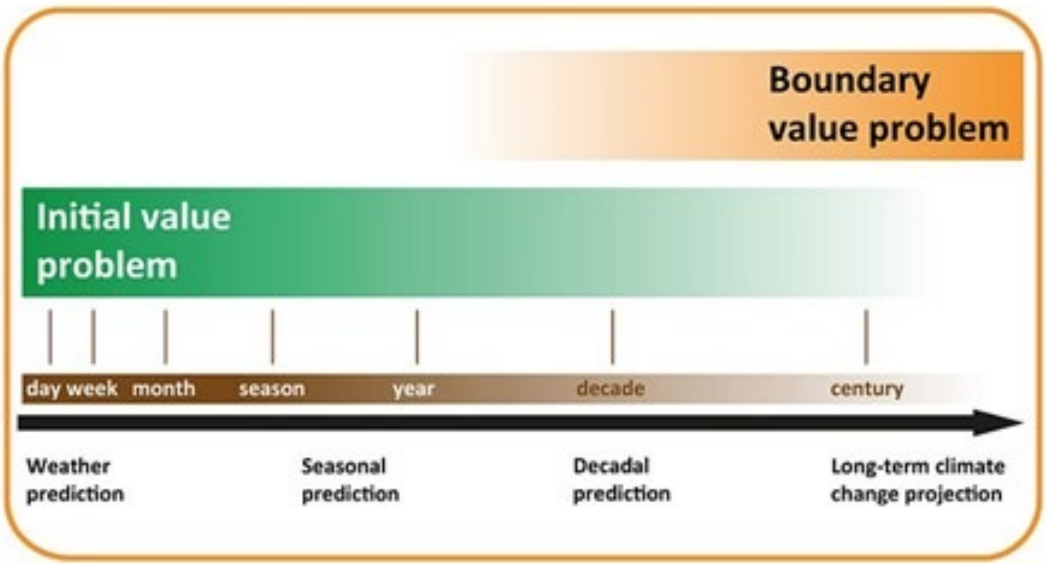
- Affected 20 countries, 150 million people;
- 30 million were in urgent need of food aid;
- 10 million refugees seeking food and water;
- 100,000 to 250,00 deaths …

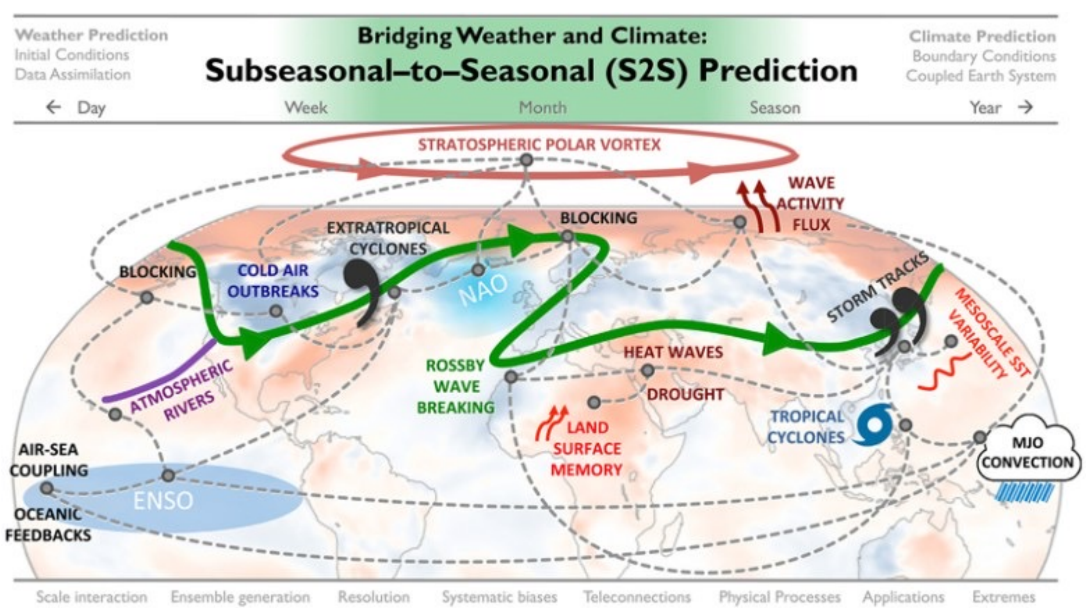
SST (sea surface temperature) is key to predicting regional precipitation



Time series of Sahel region-mean precipitation in the (thick black curve) CRU TS 3.22 observational dataset and in the AMIP simulations in (brown curve) AM2.1, (orange curve) AM3, and (blue curve) HiRAM, either (a) normalized by the time-mean precipitation (unitless) or (b) without normalization (mm day-1).

Future plan #1: Seasonal/decadal prediction





- Serving on a panel to advise NOAA on decadal prediction
- Advocating an international, coordinated effort to hindcast the observed “warming hiatus”
- Key to predicting regional climate
- Puerto Rico as an example

Model, simulations, and storm detection methods

Model (GFDL C192AM4, Zhao et al. 2018a,b, Zhao 2020, 2022)

- Atmospheric component of SPEAR-med, GFDL’s seasonal/decadal prediction model (Delworth et al., 2020)

Simulations (101-year)

- **Control**: C192AM4 forced by observed climatological SSTs
- **SPEAR-pattern M**: Assuming SPEAR pattern Mean will continue for the next 50 years
- **Observed-pattern:** Assuming observed pattern will continue for the next 50 years

Storm detection method (Zhao 2022)

- Atmospheric Rivers (Guan & Waliser 2015, Zhao 2020)
- Tropical Storms (Zhao et al. 2009, 2012)
- Mesoscale Convective Systems (Dong et al. 2020, Huang et al. 2018)

Paper accepted for publication in
Nature npj Climate and Atmospheric Science

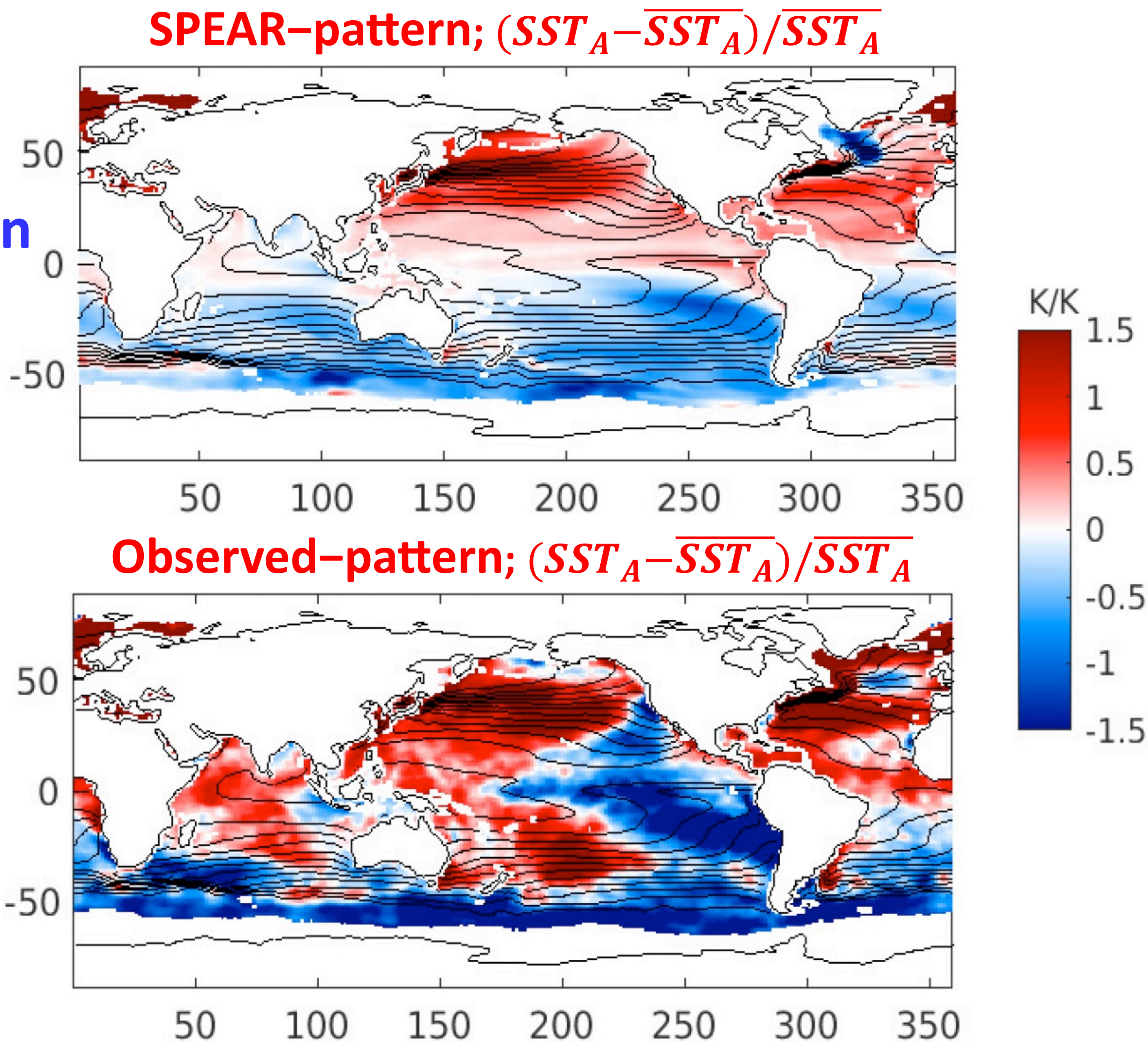
1979-2020 SST trend patterns in GFDL SPEAR & observation

SPEAR LE ensemble mean

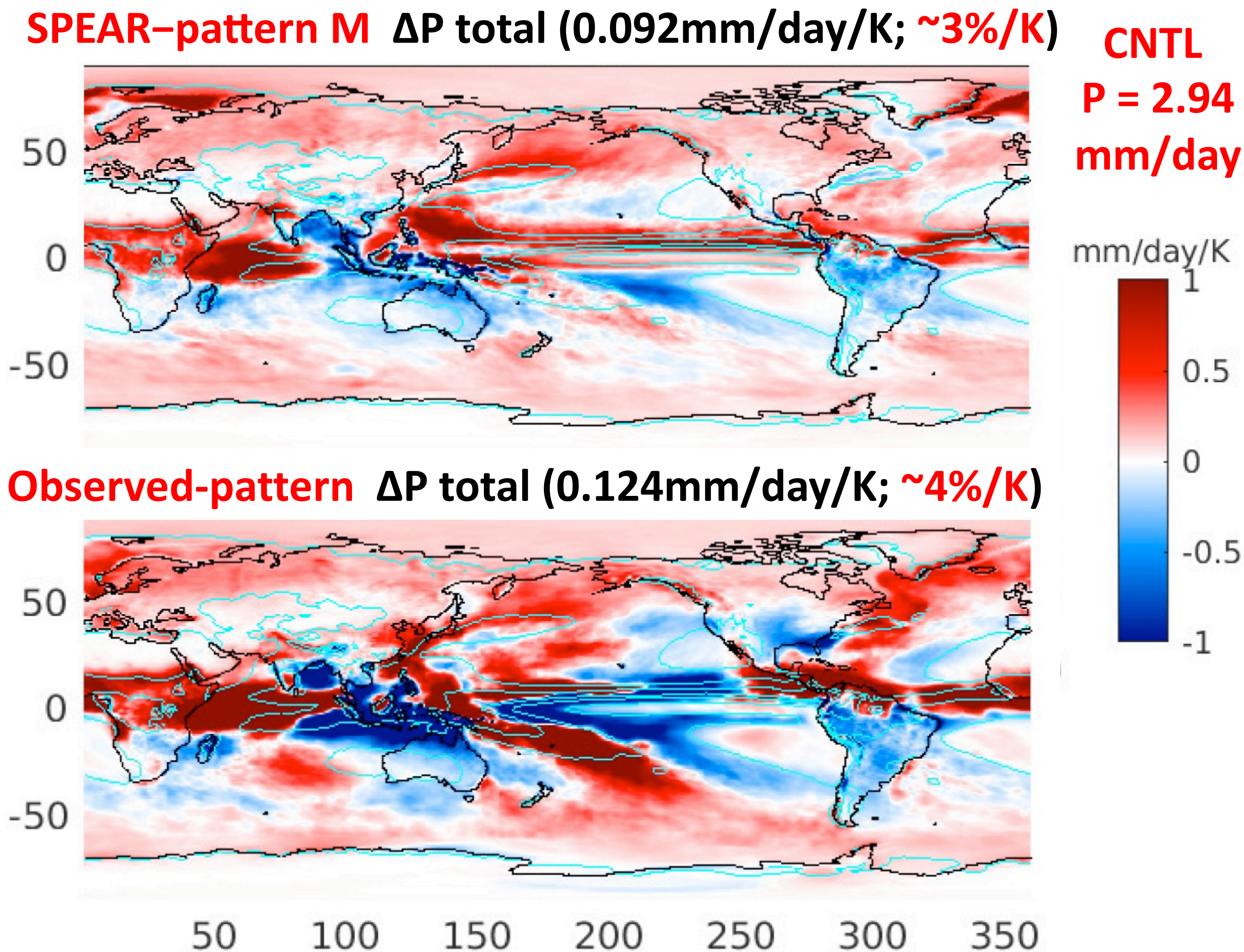
$\overline{SST_A}$ = 0.18 K/decade

HadISST

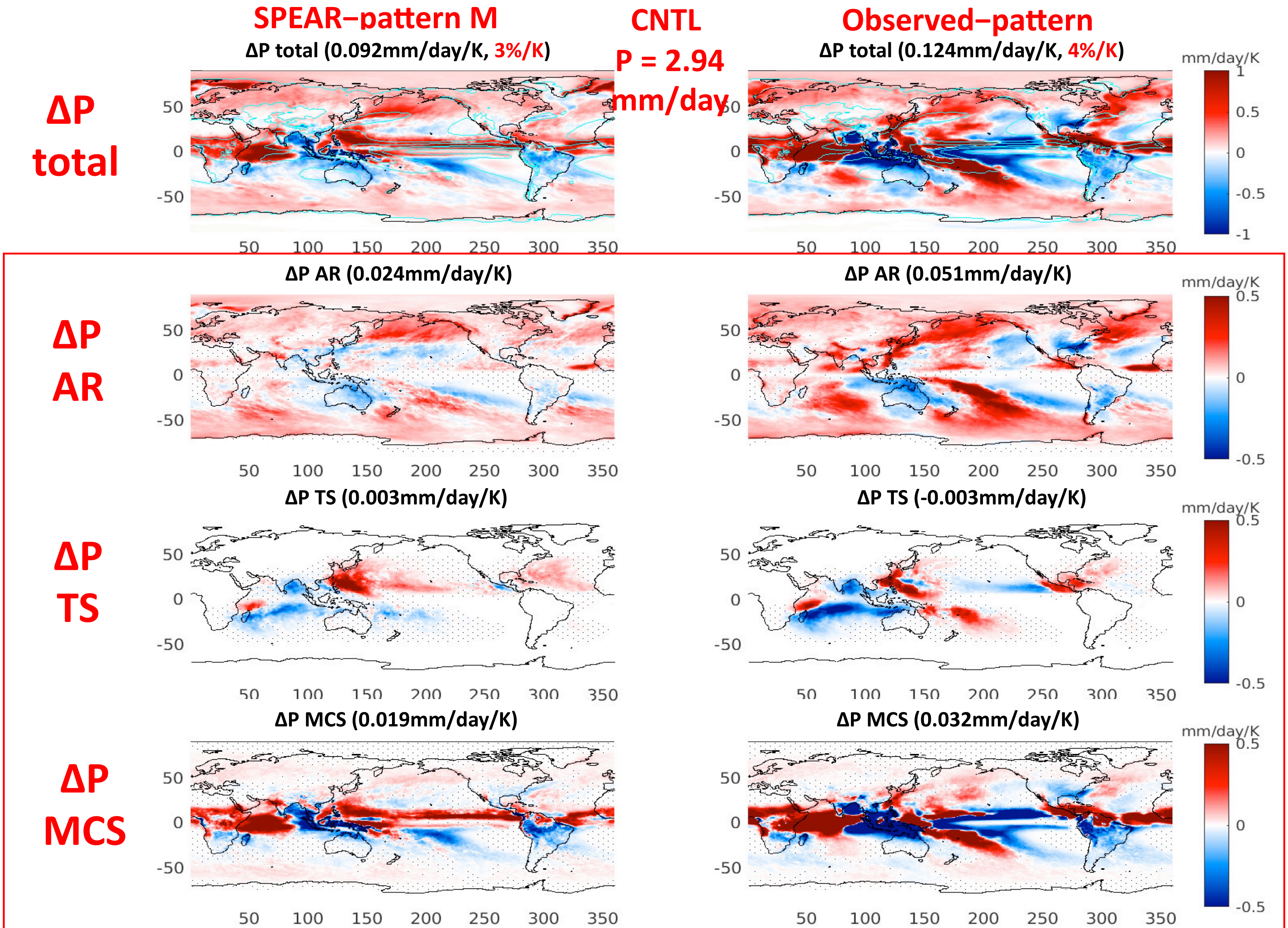
$\overline{SST_A}$ = 0.09 K/decade



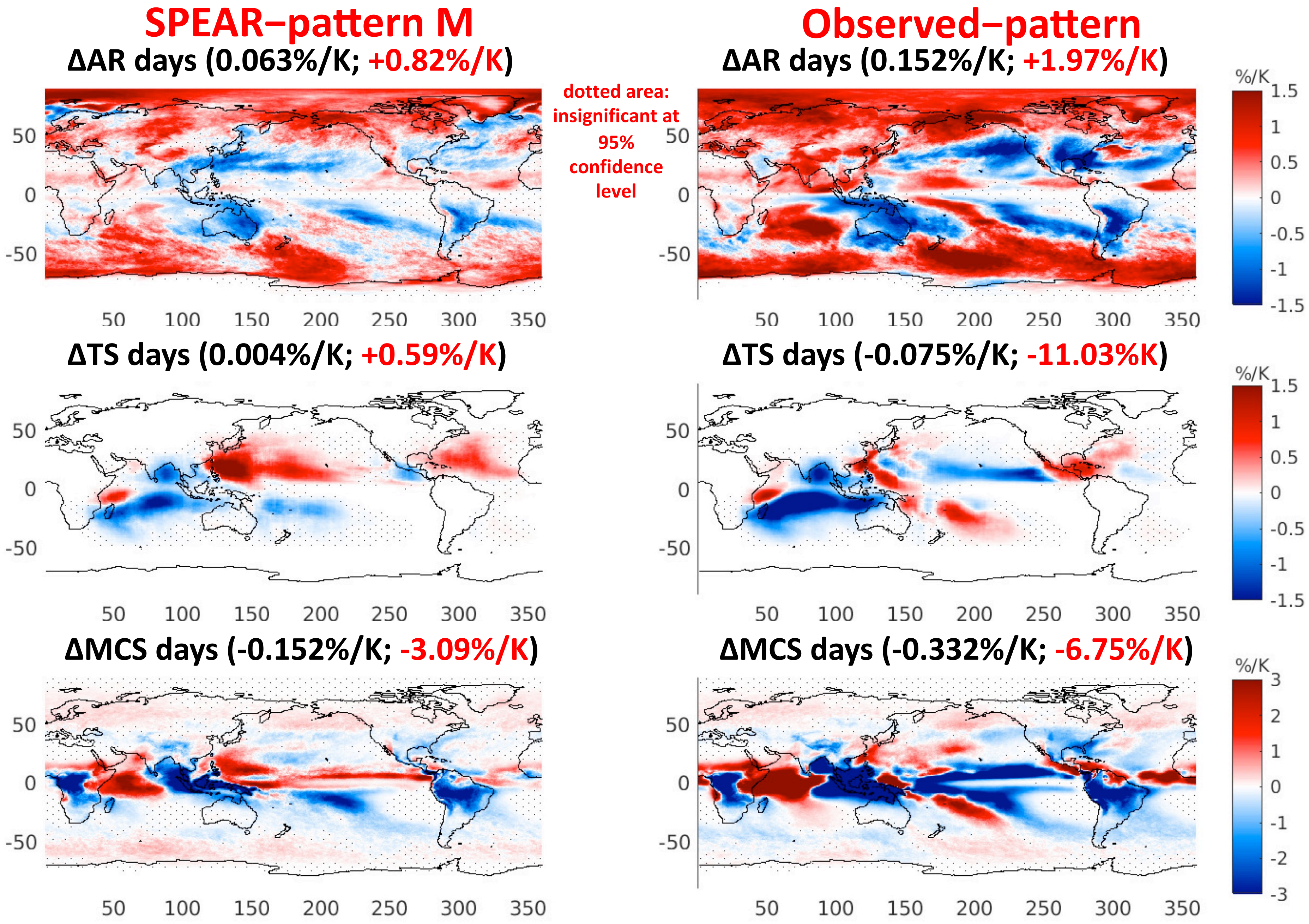
Change in annual precipitation: SPEAR vs observed pattern



Change in annual precipitation: SPEAR vs observed pattern



Future change in annual frequency of AR, TS and MCS days



Understanding Puerto Rico's Climate Challenges

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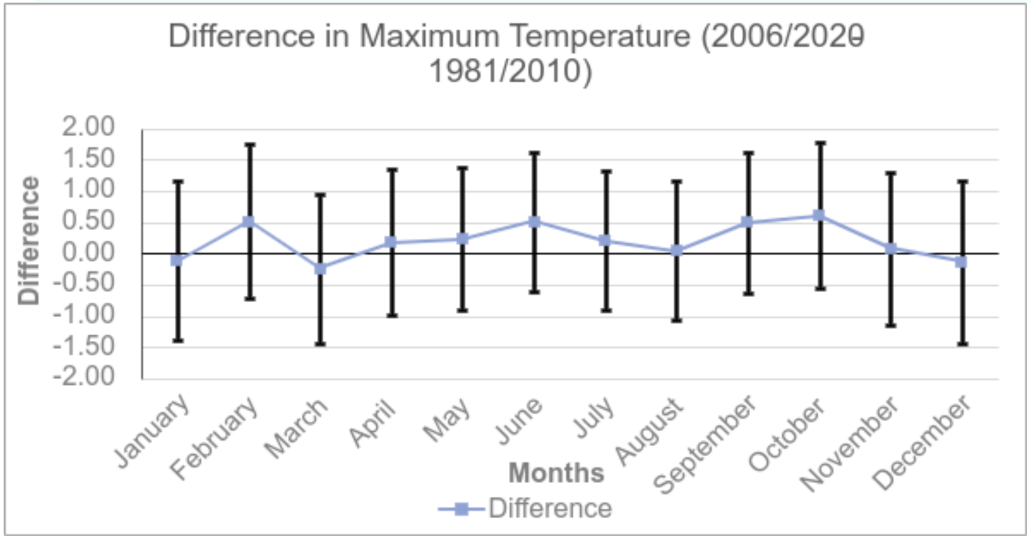
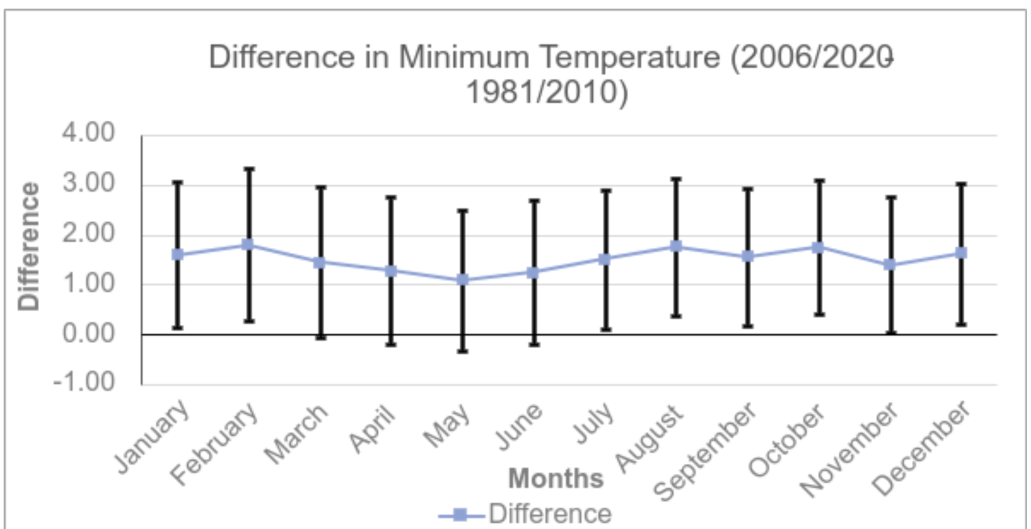
Puerto Rico Climate Office
University of Puerto Rico, Mayagüez

Oficina de Climatología de Puerto Rico

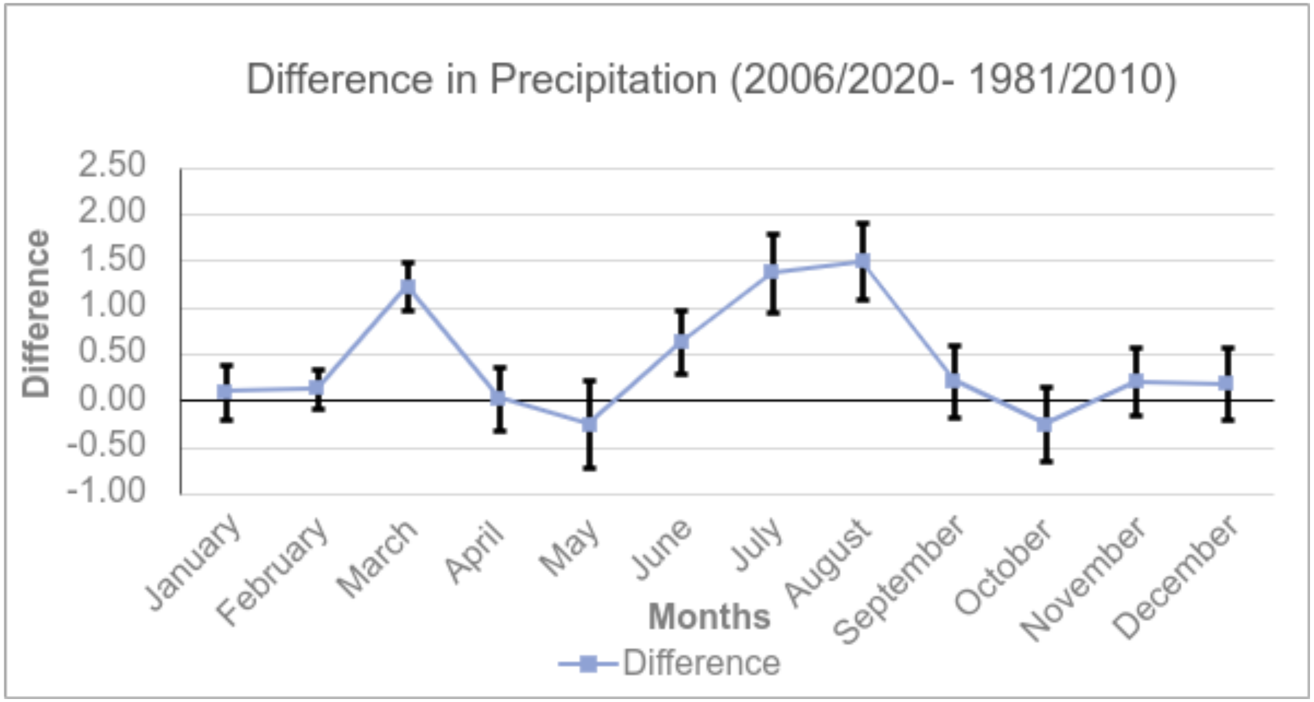
Island-wide Changes in T_{max} and T_{min} (2006-2020)-(1981-2010) Normals





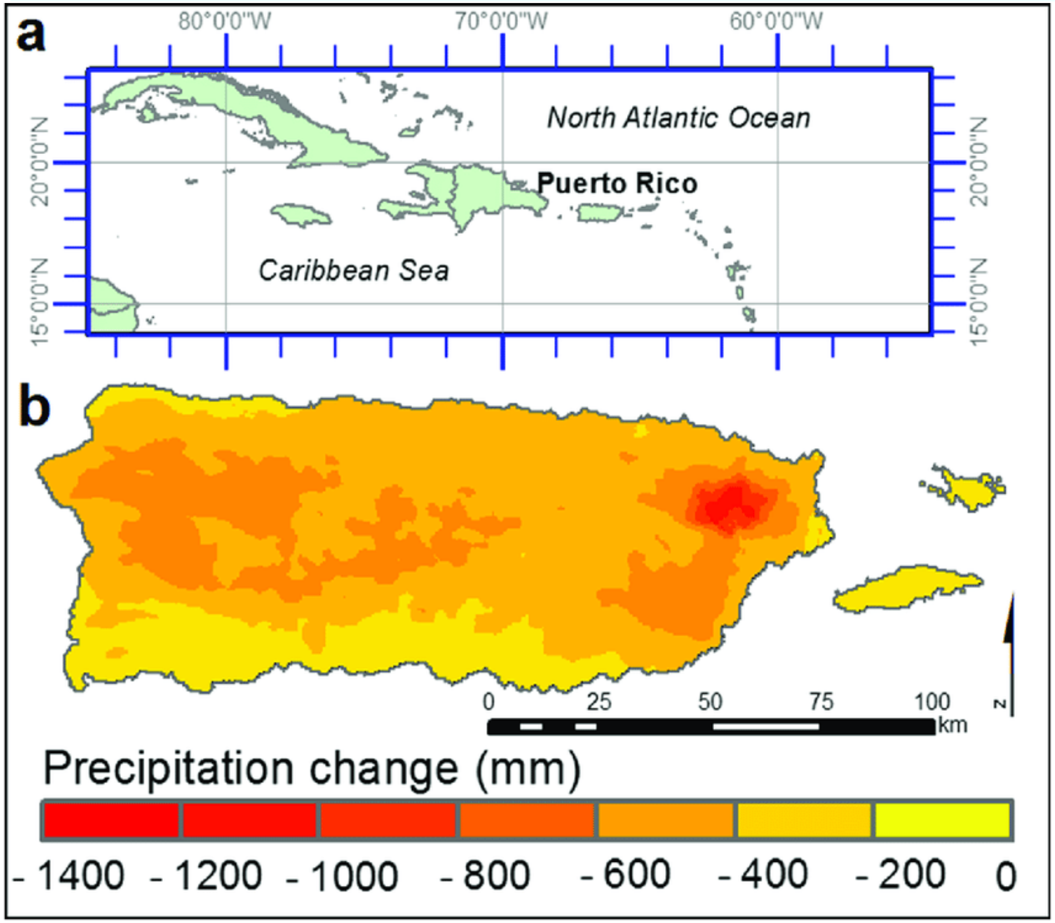
- Little warming during the day
- Pronounced warming at night
- Why?

Island-wide Changes in Rainfall (2006-2020)-(1981-2010) Normals



- Modest increase in precipitation
- Which kept day-time temperature in check

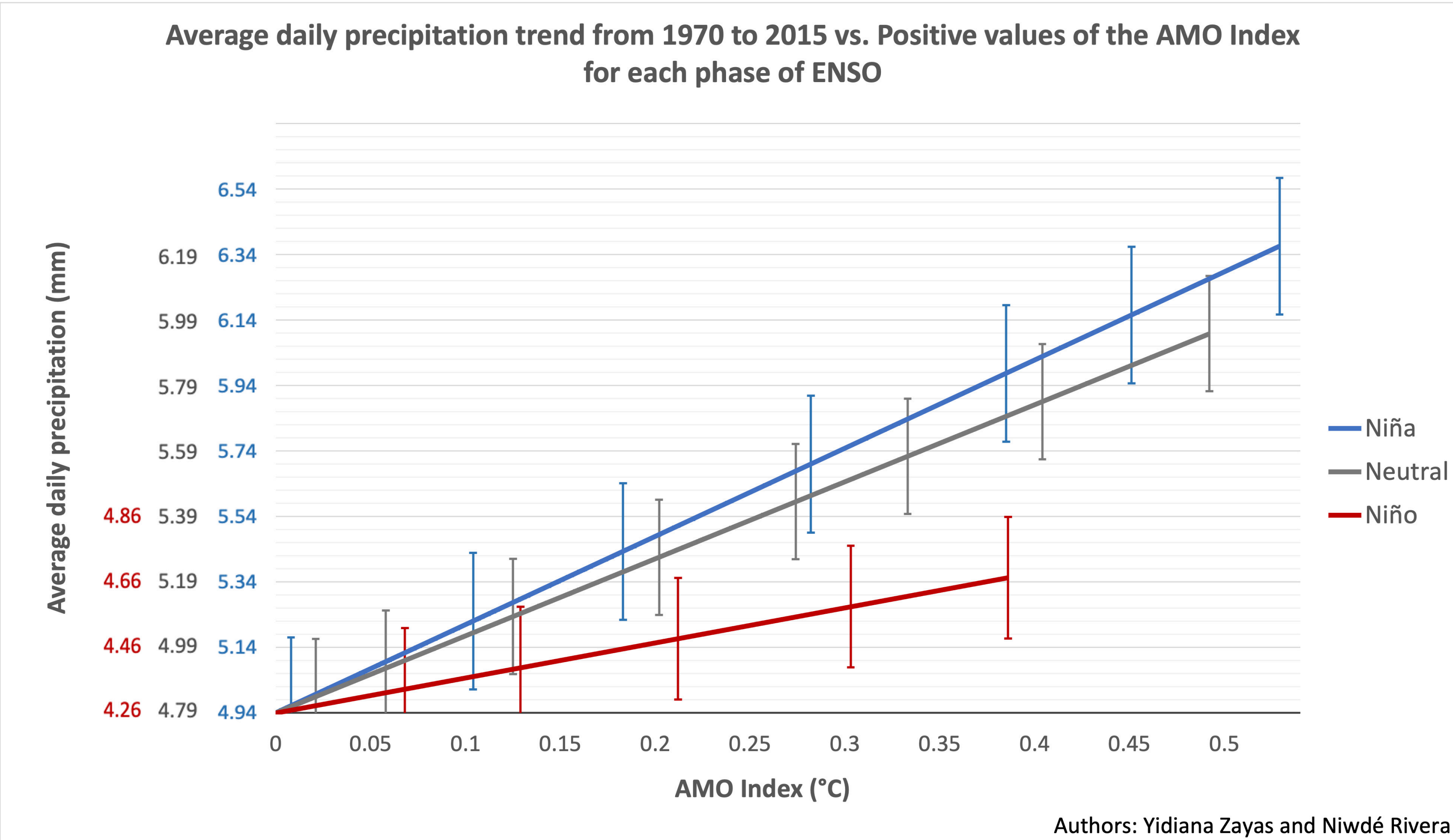
Precipitation Outlook



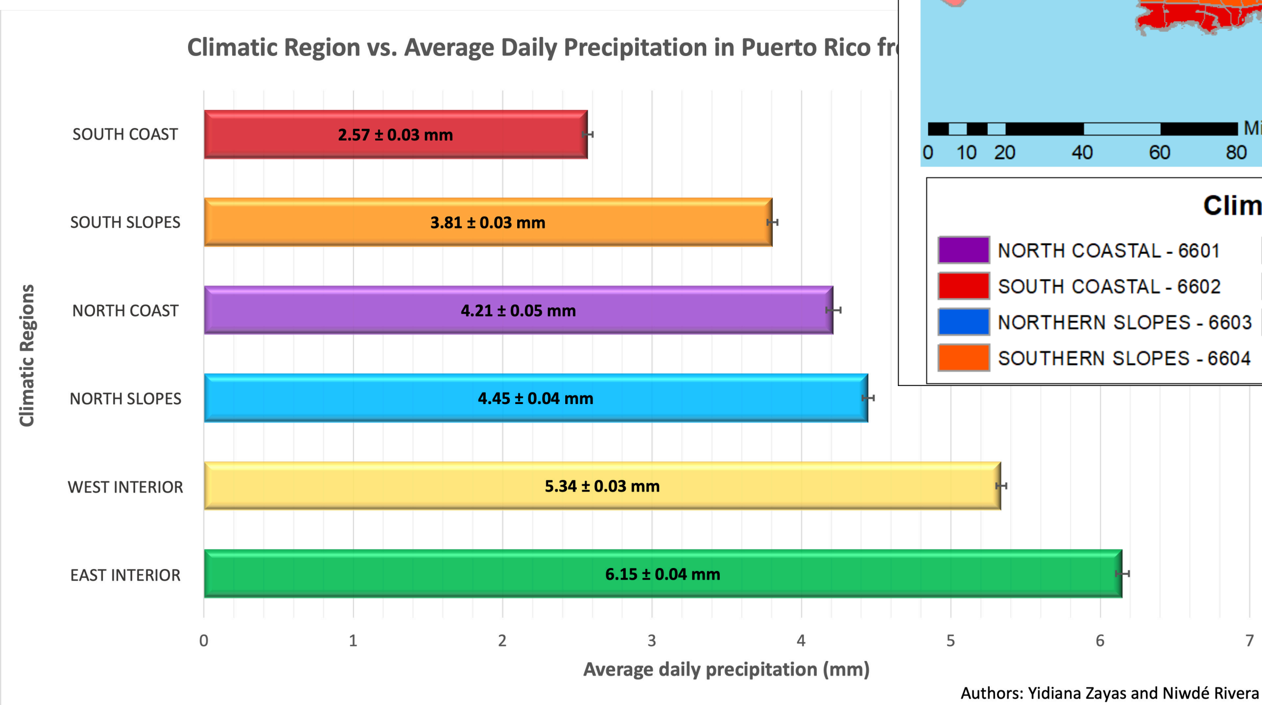
Precipitation decline between the 1960-1990 and the 2071-2099 periods under the high emission scenario (Henareh Khalyani et al. 2016)

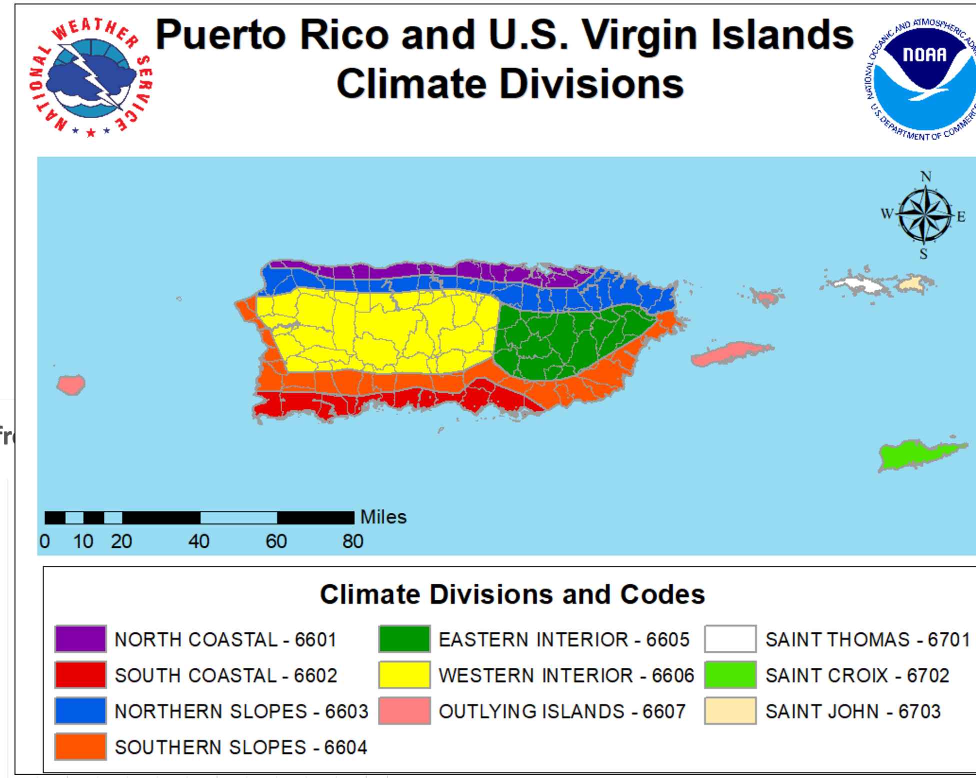
- Why is precipitation projected to decrease?
- Hypothesis: caused by different SST patterns (Niño in the past and Niña in the future)
- Consistent with observations
- Implications for climate adaption?

Precipitation and AMO



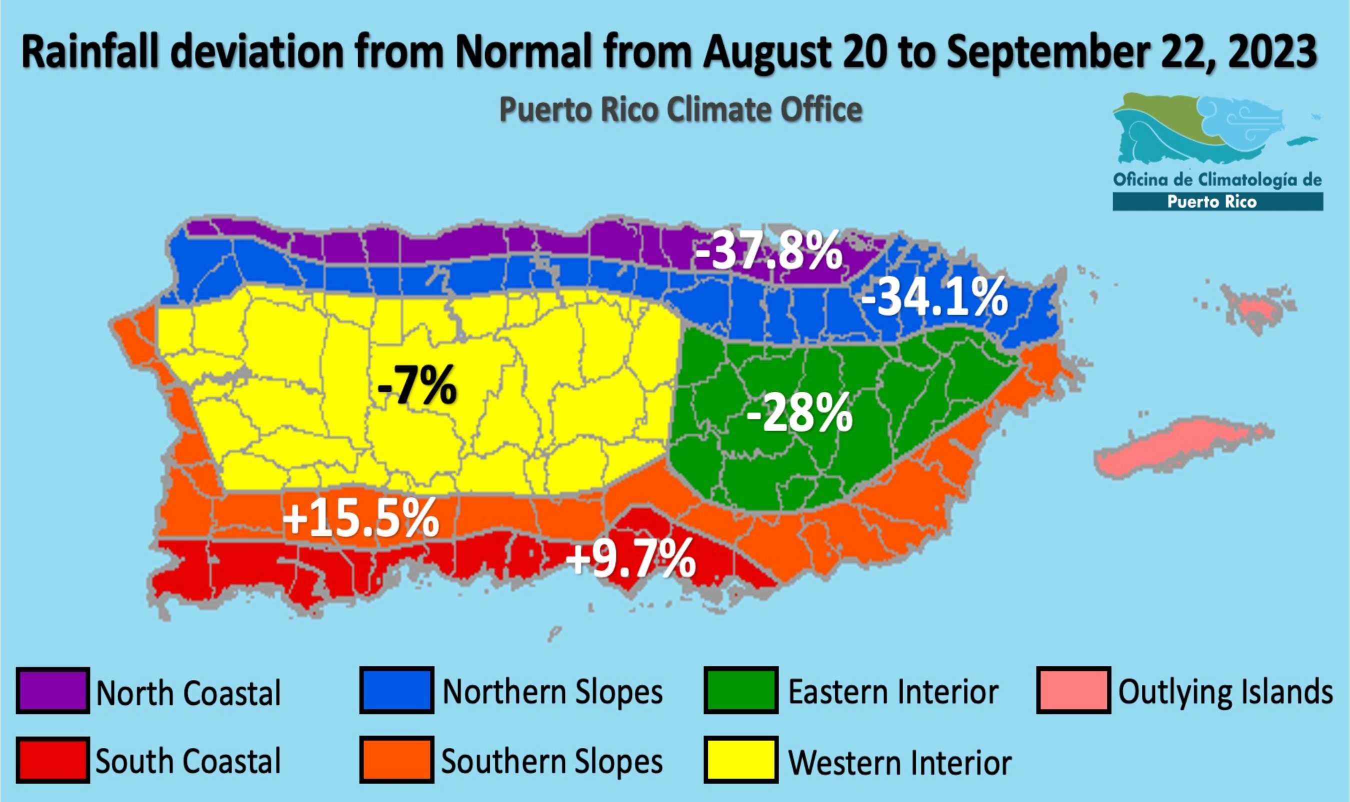
Mean Rainfall per Climate Zone (1991-2020 Normals)





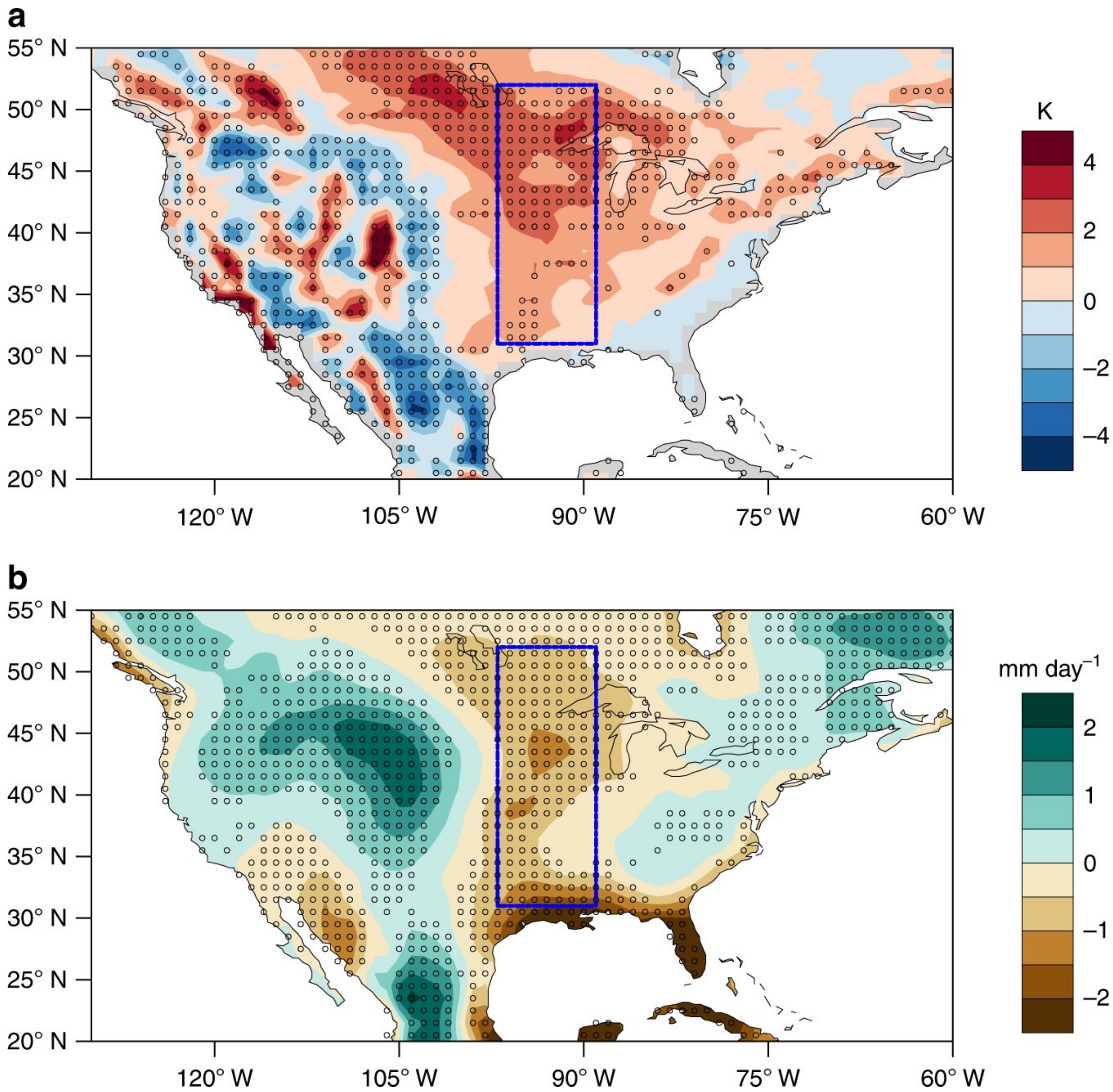
Rainfall Deviation from Normal

August – September



- Hypothesis: drying in 2023 due to Niño in 2023
- Regional wetting: importance of terrains -> downscaling and bias correction

Future plan #2: Bias correction



Geographical biases of temperature and precipitation in CMIP5 models. **a** Multi-model mean of temperature biases and **b** precipitation biases in summer during 1979–2005 from 19 CMIP5 historical simulations. Regions where at least two thirds of the models (i.e., 13 out of 19 CMIP5 models) agree on the sign of the difference are marked with black circles. The blue rectangle (31–52° N, 262–271° E) indicates the central U.S. Lin et al. (2017)

Linking climate modeling to crop modeling

Table 1: Variable names and definitions for the DLEM and CESM2 models. All variables are daily aggregates.

DLEM Variable Name	DLEM Long Name	CESM2 Variable Name	CESM2 Long Name	Units
dswrf	Down going shortwave radiation	FSA	Absorbed solar radiation	W/m^2
pr	Precipitation	PRECC	Convective precipitation rate (liq + ice)	mm/day
Tavg	Average temperature	TS	Surface temperature (radiative)	°C
Tmin	Minimum temperature	TSMX	Maximum surface temperature over output period	°C
Tmax	Maximum temperature	TXMN	Minimum surface temperature over output period	°C

Commonly used bias correction methods

For temperature

$$\widehat{\text{Bias}} = \bar{x} - \overline{obs}\ (eq.1)$$

$$x_i' = x_i - \widehat{\text{Bias}}\ (eq.2)$$

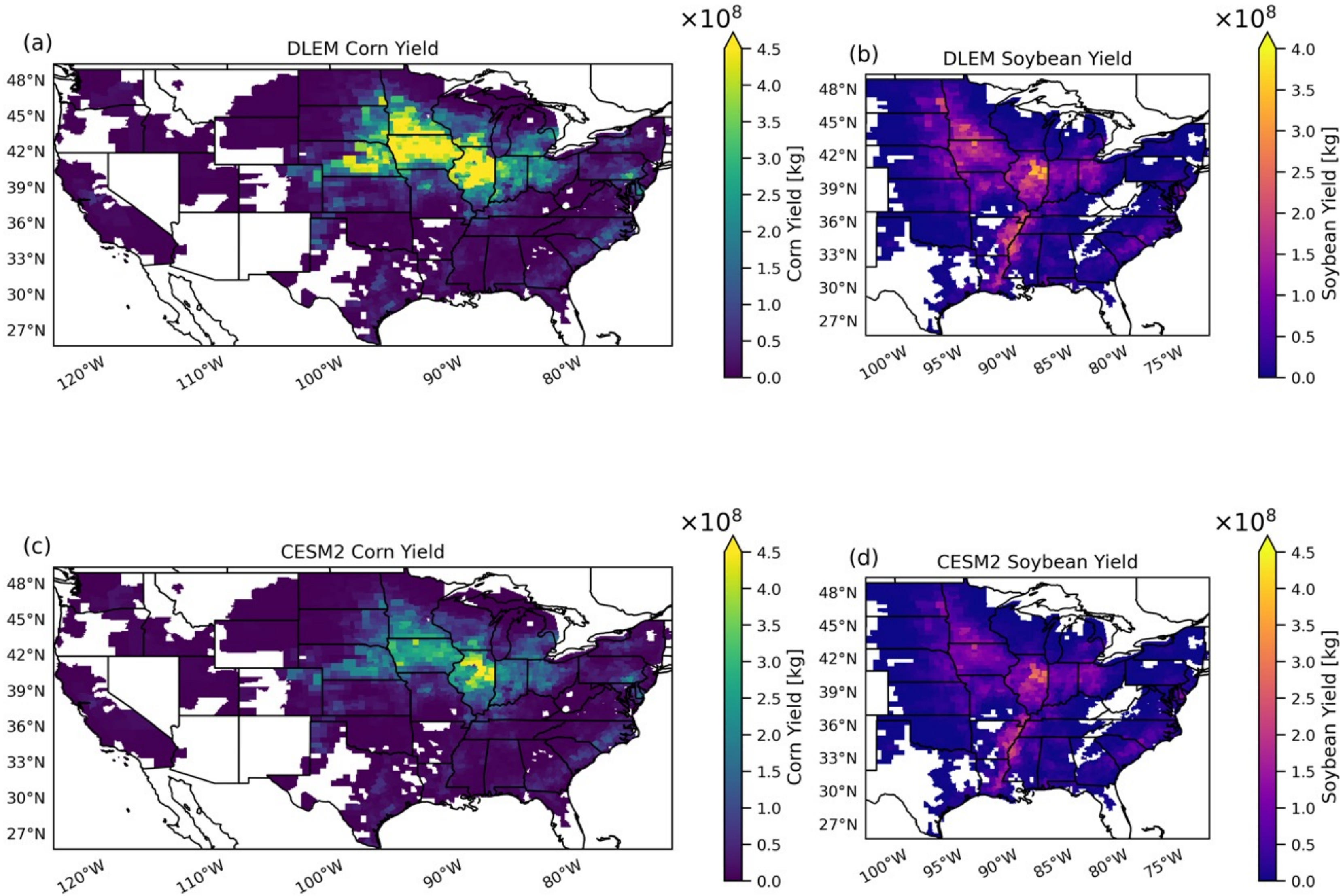
For precipitation/radiative fluxes

$$\widehat{\text{Rel.Bias}} = \overline{obs}/\bar{x}\ (eq.3)$$

$$x_i' = x_i \times \widehat{\text{Rel.Bias}}\ (eq.4)$$

Lack of physical consistency!

Predicted corn/soybean yield



UPRM's Meteorology Program

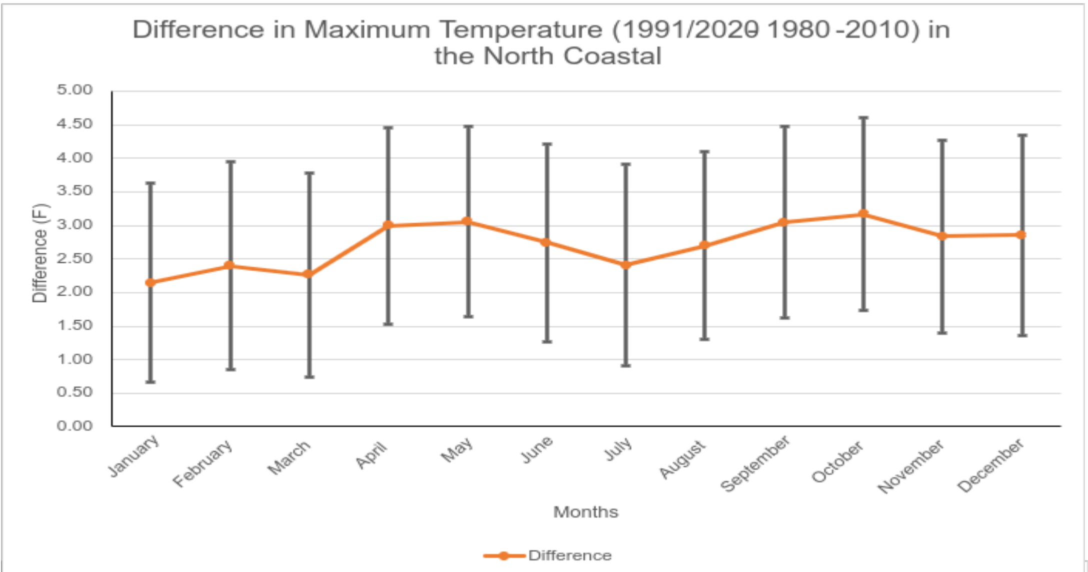
- **Some key achievments of our graduates**

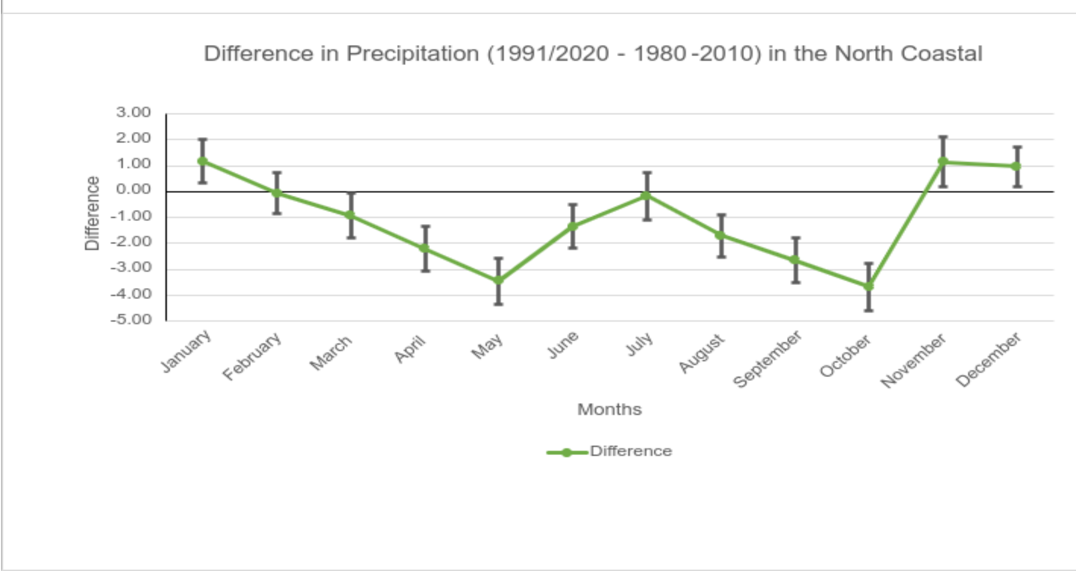
- NOAA and National Weather Service
  - Weather Forecast Office - San Juan: 7 graduates (3 female)
  - Weather Forecast Office - Texas: 4 y California: 2 (5 female)
  - National Hurricane Center: 2* PhDs (2 female)
  - National Climatic Data Center: 1 PhD (1 female)
  - National Center for Atmospheric Research: 3 PhDs (3 female)
- Graduates in Academia and National Centers
  - **Ángel Adames, PhD : Assistant Professor U. of Wisconsin, Madison**
  - Mayra Oyola, PhD: Assistant Professor U. of Wisconsin, Madison
  - Yaitza Luna, PhD: American Meteorological Society and NASA Program Manager
  - Diamilet Perez, PhD: MIT graduate, Florida International University, Postdoctoral Associate
- Students in Ms/PhD programs: 12 (9 female)

Going forward

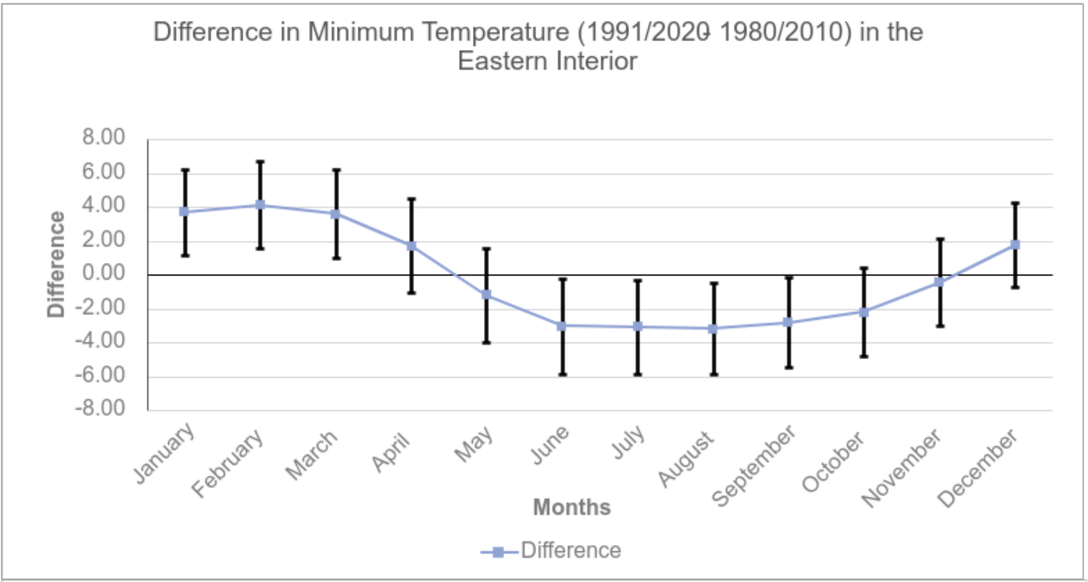
- Creation of a data science core for impact research
- Based on the latest physical climate science and seasonal/decadal predictions
- Use physic-informed ML for bias correction
- Explore societal impacts such as sea level rise, coastal flooding, hurricanes, extreme events, droughts/floods, food security, greenhouse emissions, mental health, etc.
- **Excited to work with the climate adaption community in Puerto Rico!**

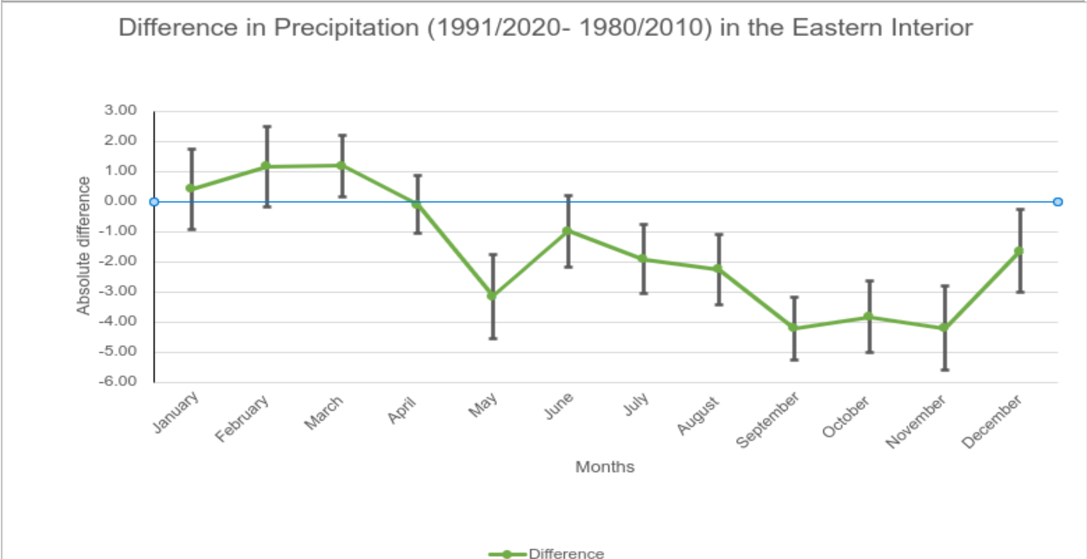
North Coast Changes in T_{max} and Prcp (1991-2020)-(1981-2010) Normals





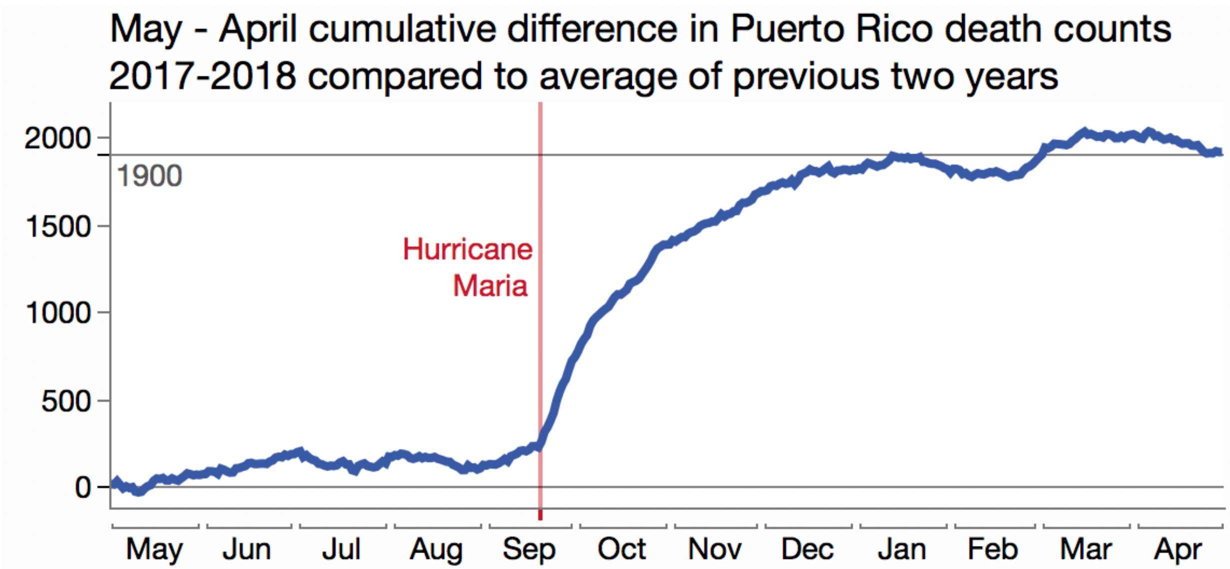
Eastern Int Changes in T_{min} and Prcp (1991-2020)-(1981-2010) Normals

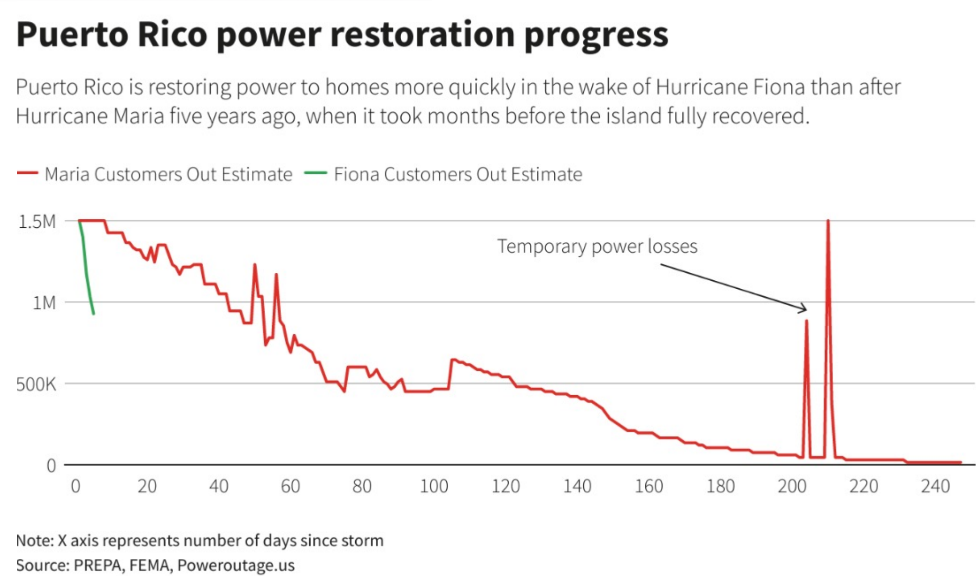




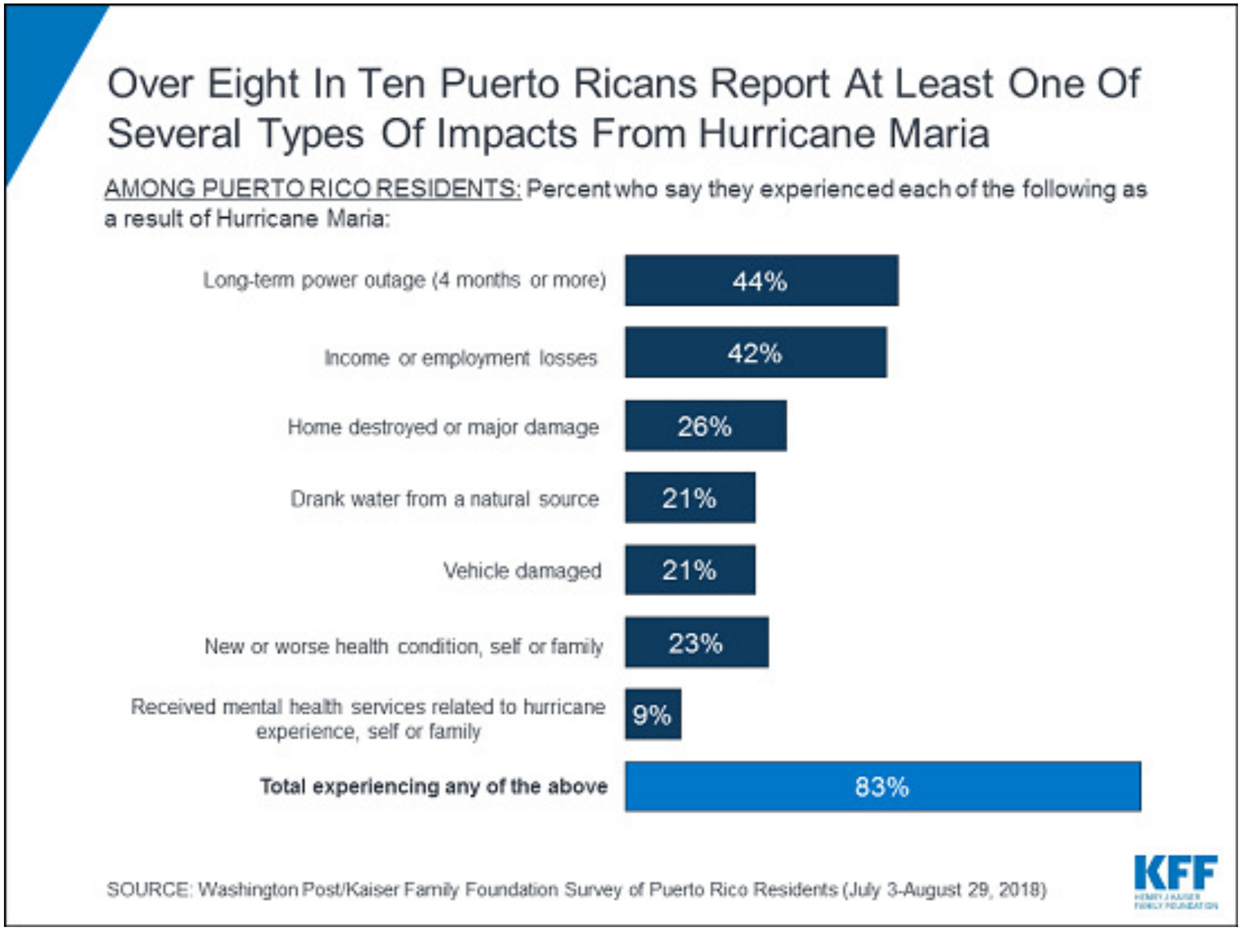
Coastal Erosion and Hurricanes

Hurricane María Outcomes





Hurricane María Outcomes



Coastal Erosion and Hurricanes

Antes del Huracán María

el Condominio Sol y Playa tenía piscina
en el mismo lugar donde van a reconstruirla

A sample of adaptation challenges

- Coastal erosion/sea-level rise
  - Comprehensive Coastal Law
  - Improve enforcement regarding coastal development
  - Long-term strategy for coastal community residents

- Heat Waves
  - Incorporate passive cooling and thermal insulation into building codes
  - Urban planning to reduce the heat-island effect
  - Urban reforestation – emphasize cooling power of trees
  - (200 l/day = 35,000 Btu/hr during daylight hours)

  - Droughts
    - Rain capture where ever possible
    - Protection of watersheds, reduction of run-off rain
    - Effective, continuous removal of sedimentation in reservoirs
    - Reduce water distribution losses. It is now ~ 57.7% (312 mgd)

Relative biases