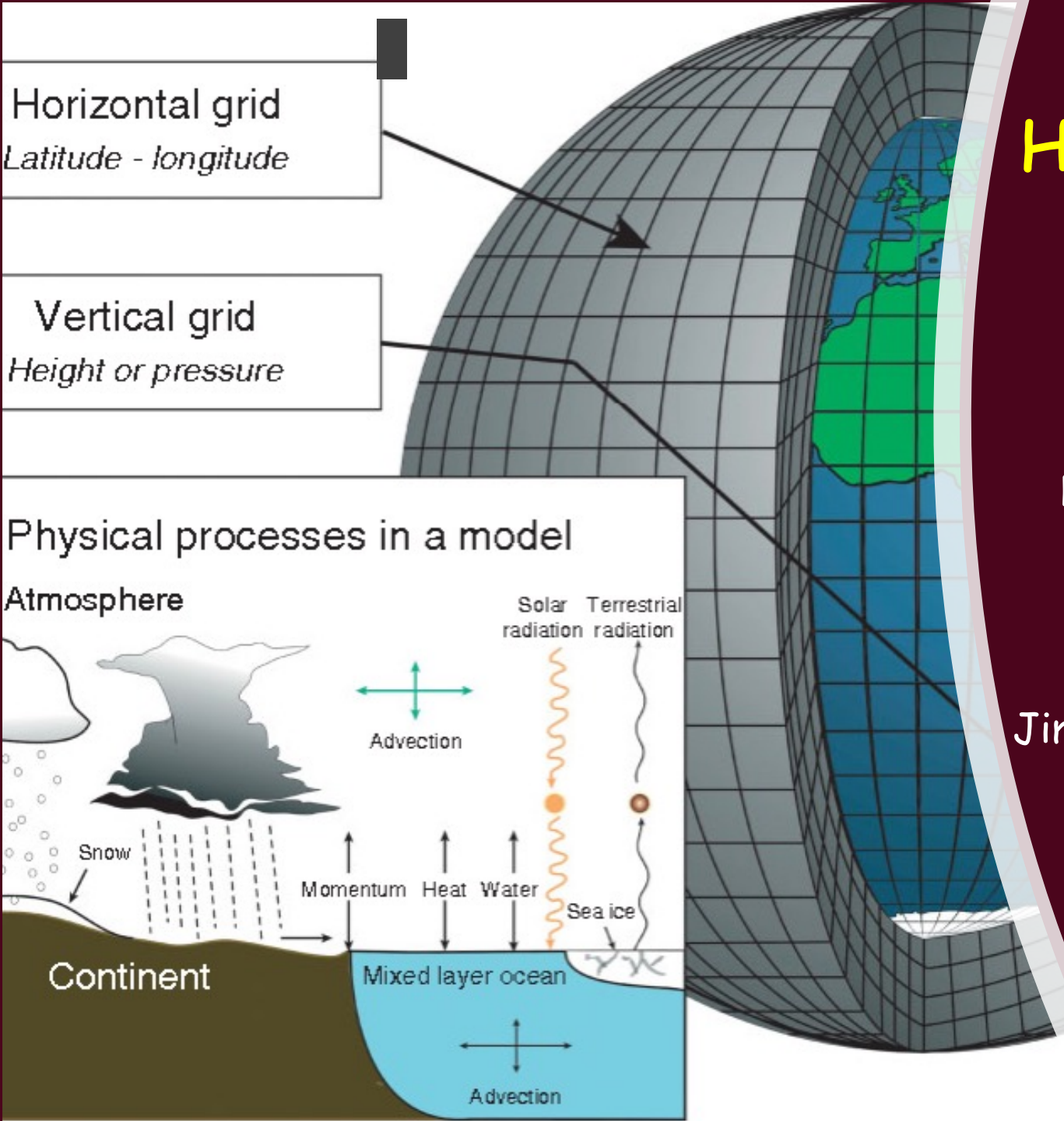


Benefits and Challenges of High-Resolution Global Climate Simulations and Prediction

Ping Chang

Department of Oceanography & Atmospheric Sciences, Texas A&M University

Special Thanks to

Jim Edwards and other colleagues at the National Center for Atmospheric Research (NCAR)

Frontera User Meeting

Texas Advanced Computing Center

University of Texas at Austin

August 4-5, 2022

Complexity of Climate System

To accurately simulate and predict climate change, an Earth system modeling approach is required to represent complex interactions among different components of the Earth system.

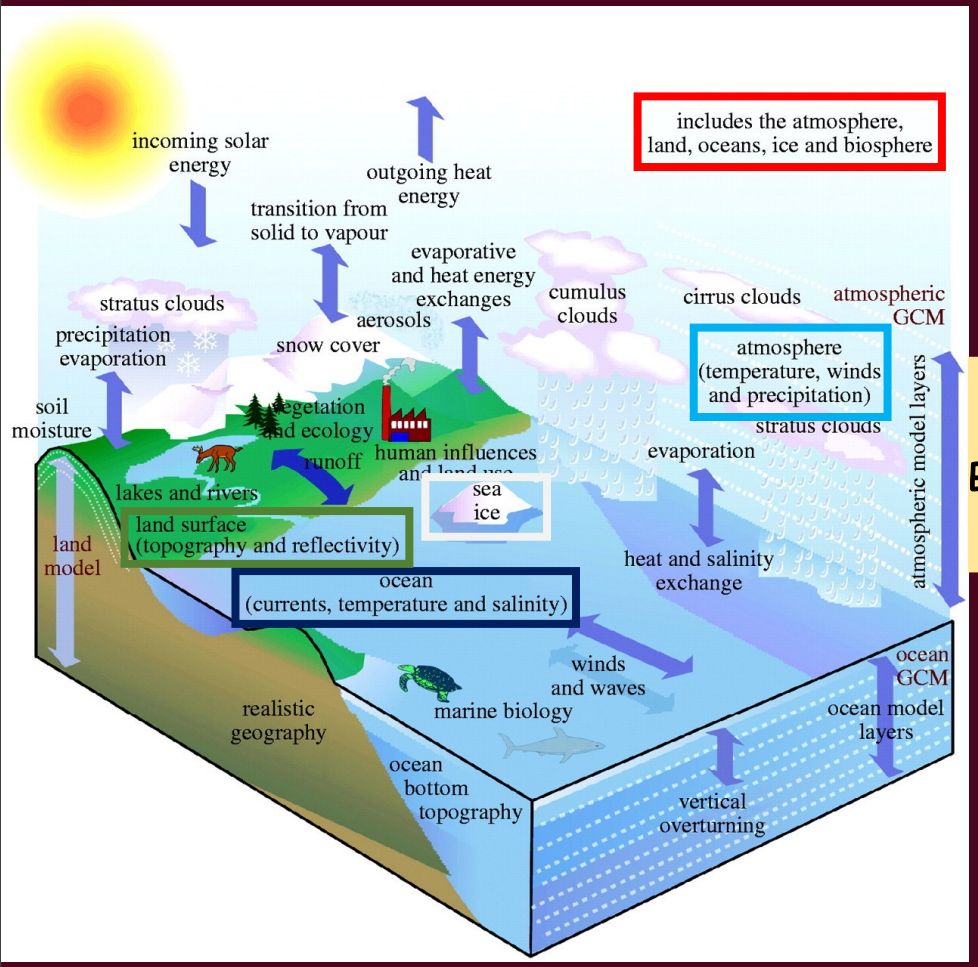
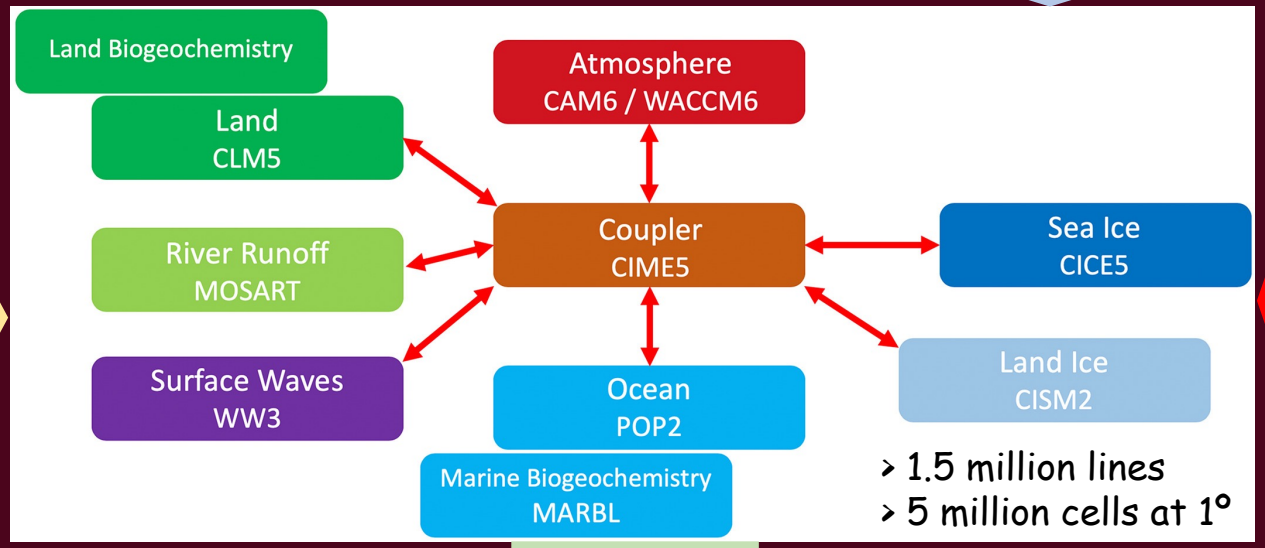


Figure source: Karl and Trenberth 2003

Model Building

Initial Condition

Community Earth System Model (CESM)



> 1.5 million lines
> 5 million cells at 1°

https://nordicesmhub.github.io/containers/01-introduction/

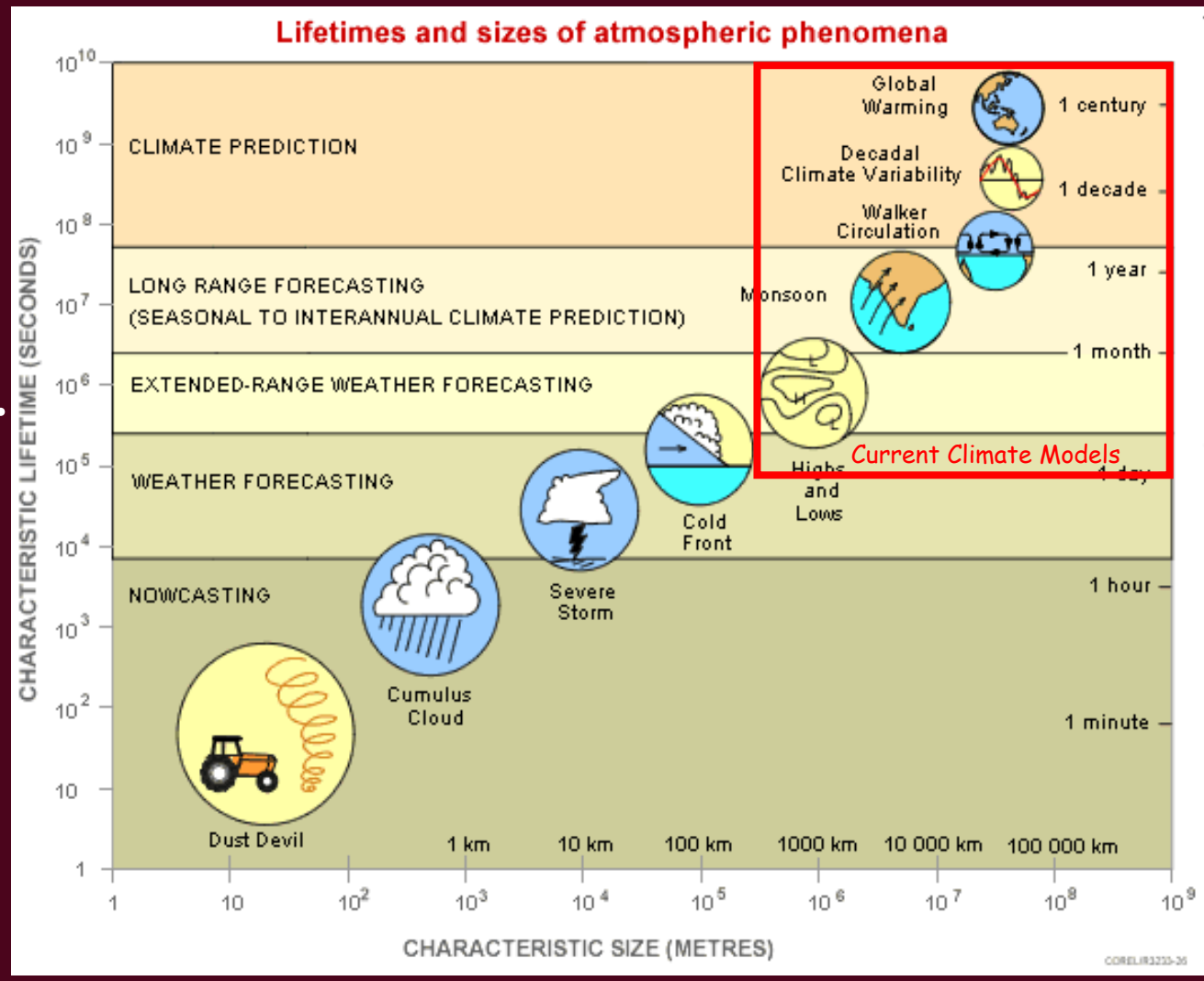
Climate Forcing: Past, Present, Future

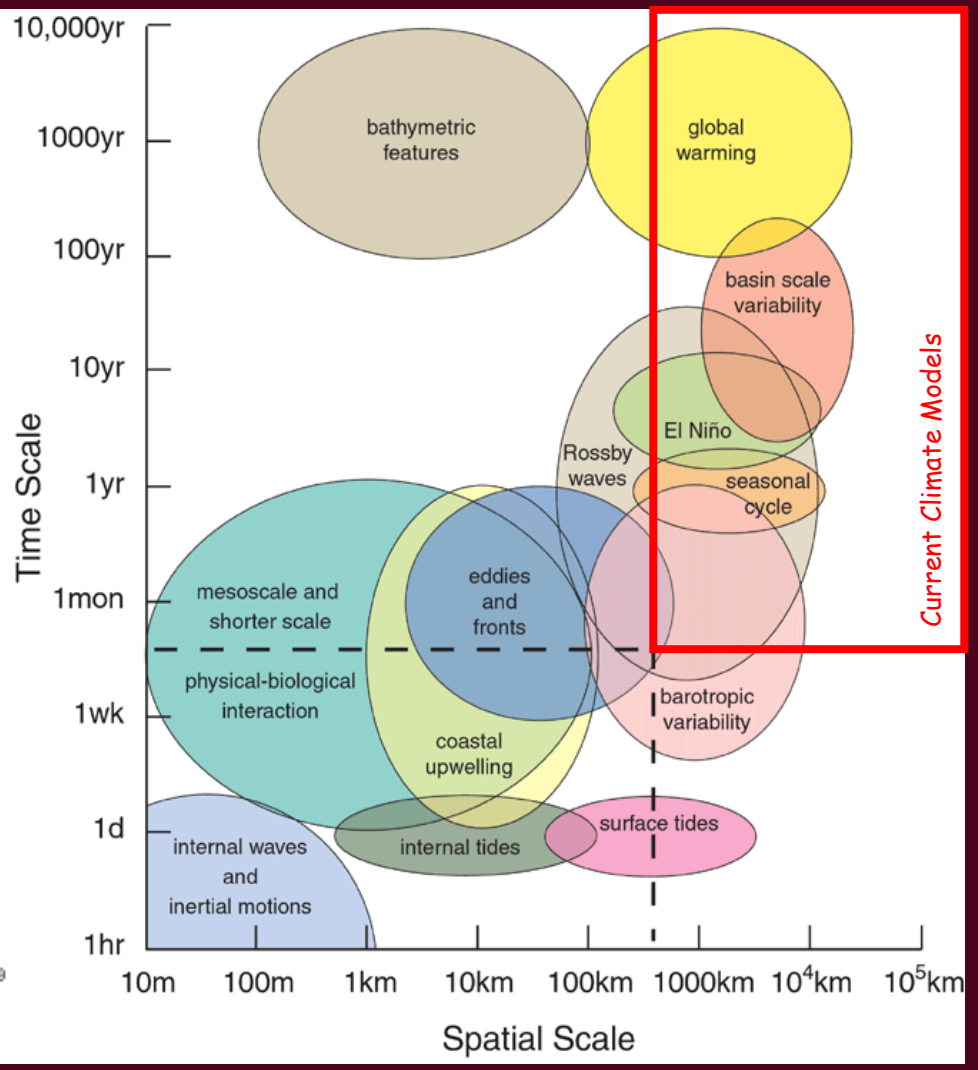
Climate Simulations

Intergovernmental Panel for Climate Change (IPCC) Assessment Report

Multi-scale Nature of Climate System

Atmosphere

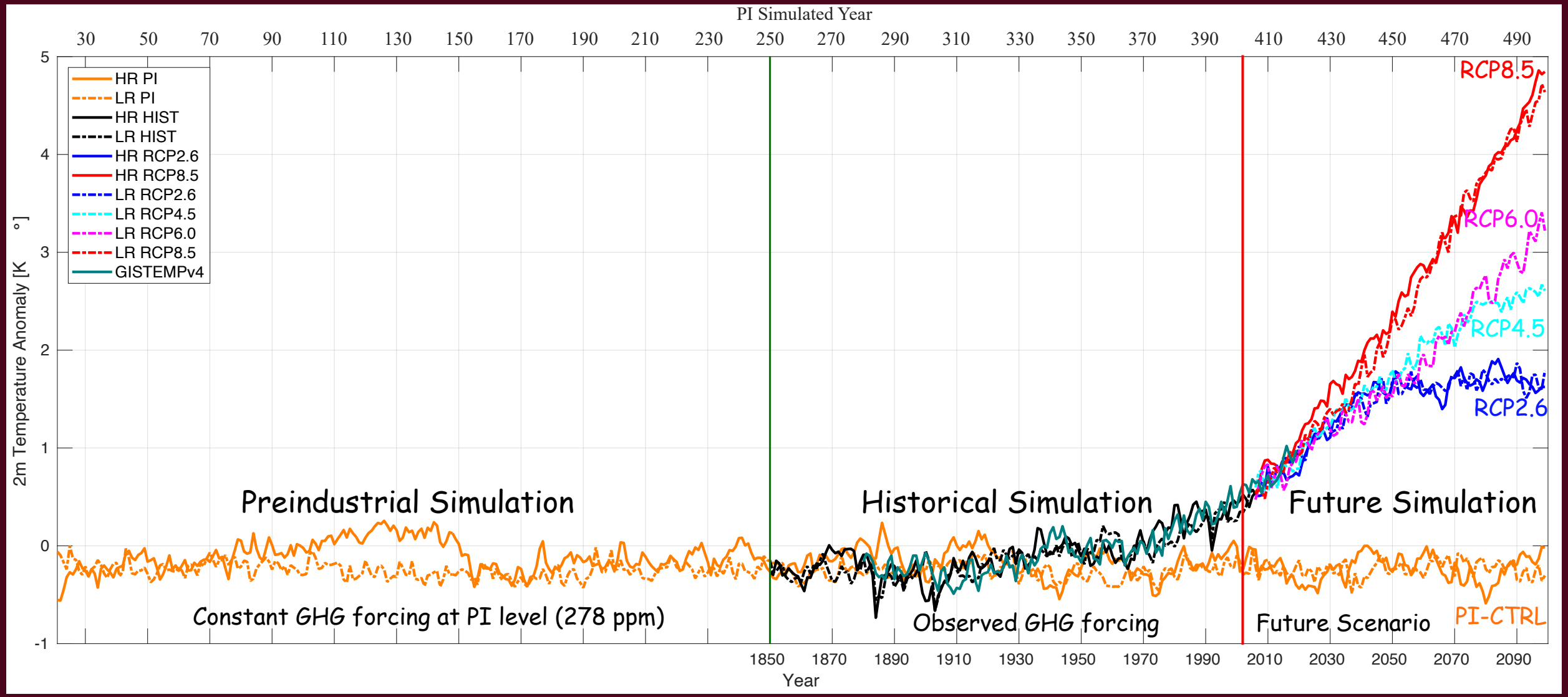




Ocean

https://ceoas.oregonstate.edu/file/webspacetimescalesgif

Long Time Scales of Climate Change



IPCC Climate Simulations

Coupled Model Intercomparison Project (CMIP):

- Ensemble of atmospheric model intercomparison project (AMIP) simulations (5-40 x 40 years ~200 years)
- Preindustrial control simulations (1850 climate forcing) (~1,000 years)
- Ensemble of 1850-2100 historical and future climate simulations under different emission scenarios (i.e. RCP/SSP1 2.6, RCP/SSP2 4.5 … RCP/SSP5 8.5) (5-40 x 250 years x 5 ~ 6,000 years)
- 1%/yr CO2 increase – transient climate sensitivity experiment (~150 years)
- Abrupt 4 x CO2 - equilibrium climate sensitivity experiment (~150 years)

Total simulation years:

~ 10,000 years

Computational Resources:

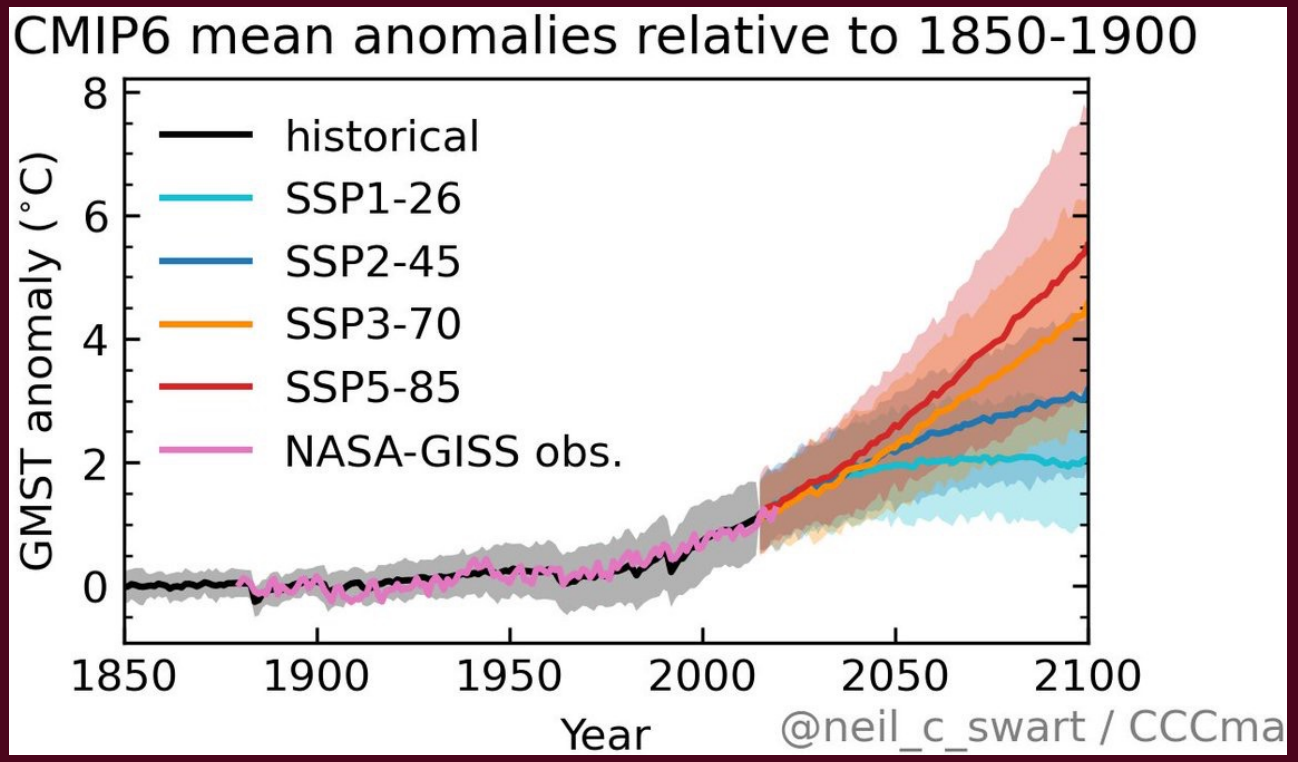
~ 100 million core hrs for IPCC-class Earth system model simulations with 1° (~100 km) atmosphere & ocean resolution

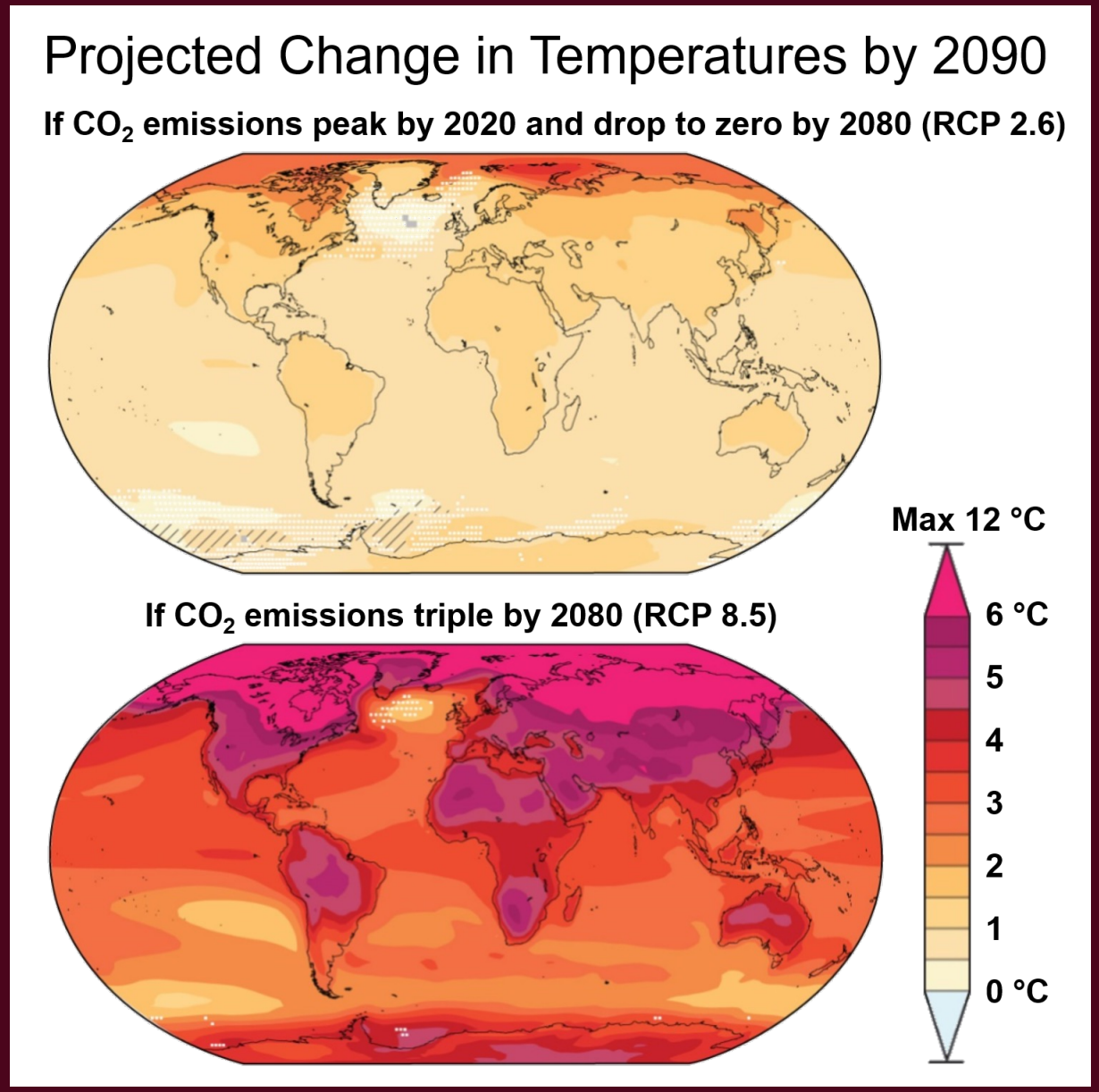
Participants for CMIP Phase 6 (2017-2020):

~ 33 models for CMIP6, from US, China, UK, Australia, Canada, Germany, Japan, India, Italy, France, Russia, South Korea, Brazil …

What are IPCC-Class Climate Models Capable of?

IPCC-Class climate models are capable of simulating and projecting 1) global-mean surface temperature (GMST) changes, 2) large-scale warming patterns, 3) large-scale weather pattern changes and 4) other large scale climate phenomena, such as El Niño-Southern Oscillation …

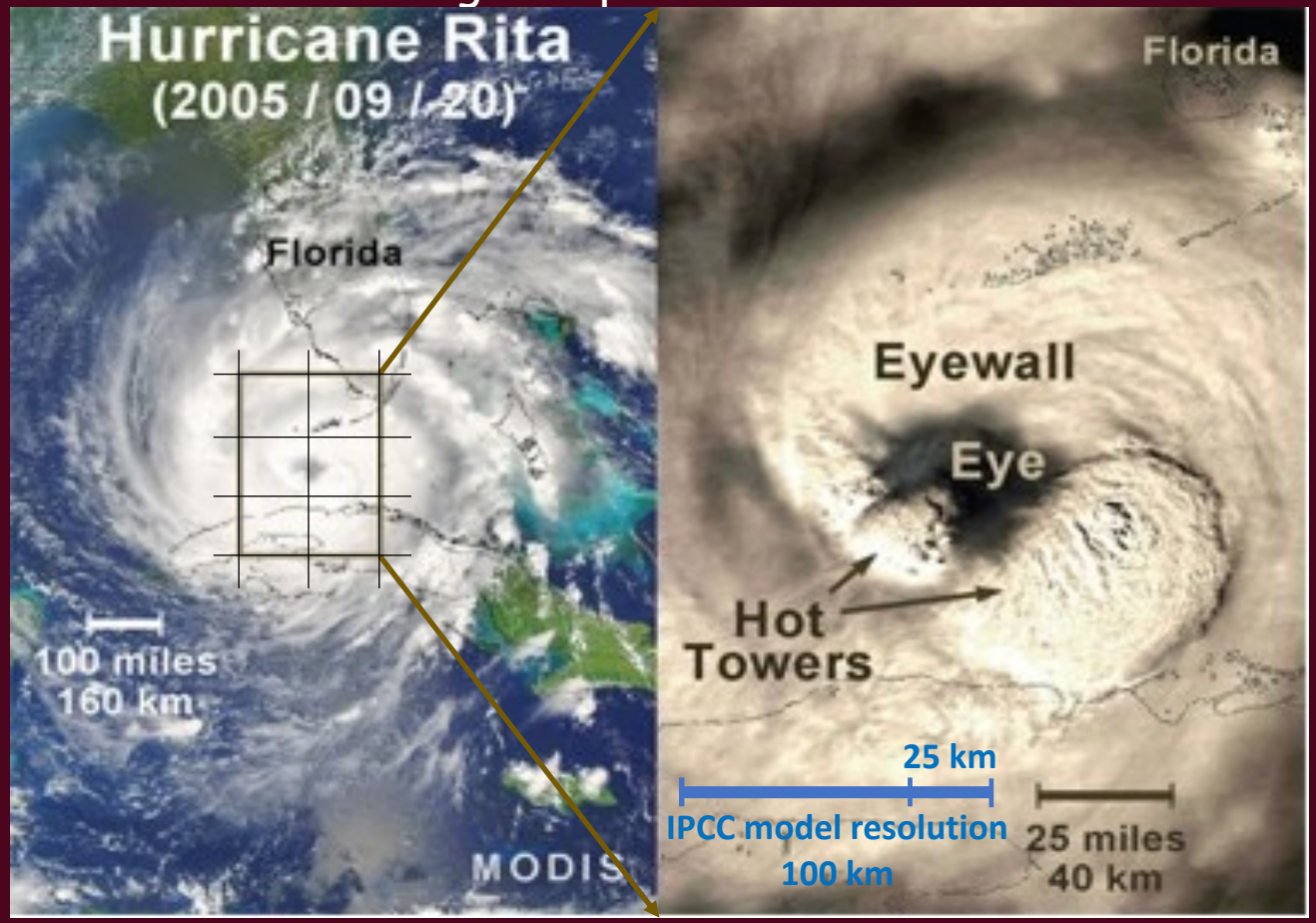




https://commons.wikimedia.org/wiki/File:Projected_Change_in_Temperatures_by_2090.png

What are the limitations of IPCC-Class Climate Models?

At ~100 km horizonal resolutions, IPCC-Class climate models lack capability of simulating and projecting changes in weather extremes, such as tropical cyclones, and changes in regional ocean environments, such as coastal sea-level rise, coastal upwelling, as well as many other small-scale regional phenomena …



https://www.nbcnews.com/id/wbna12818816

Hurricane Harvey Simulation

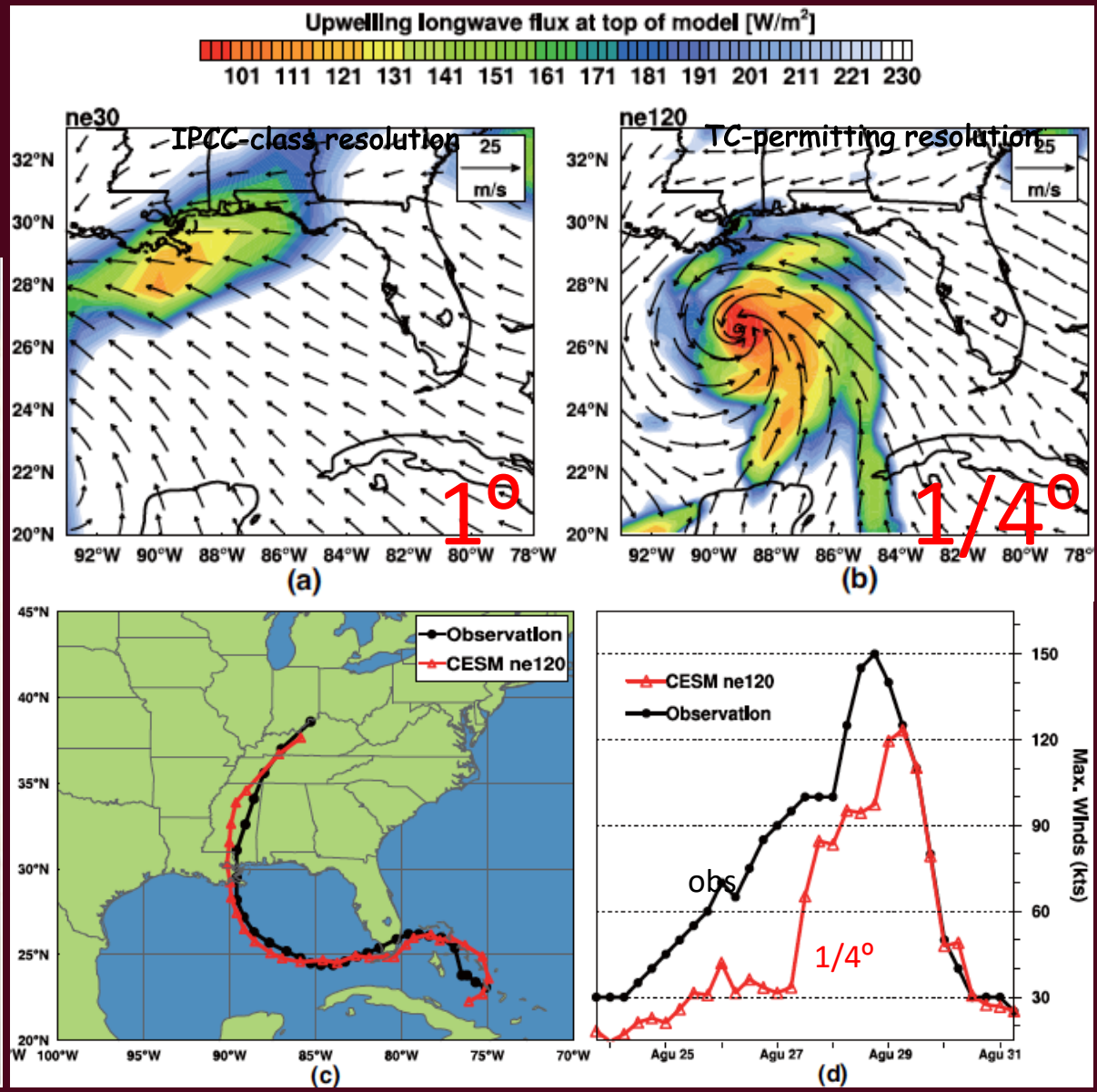
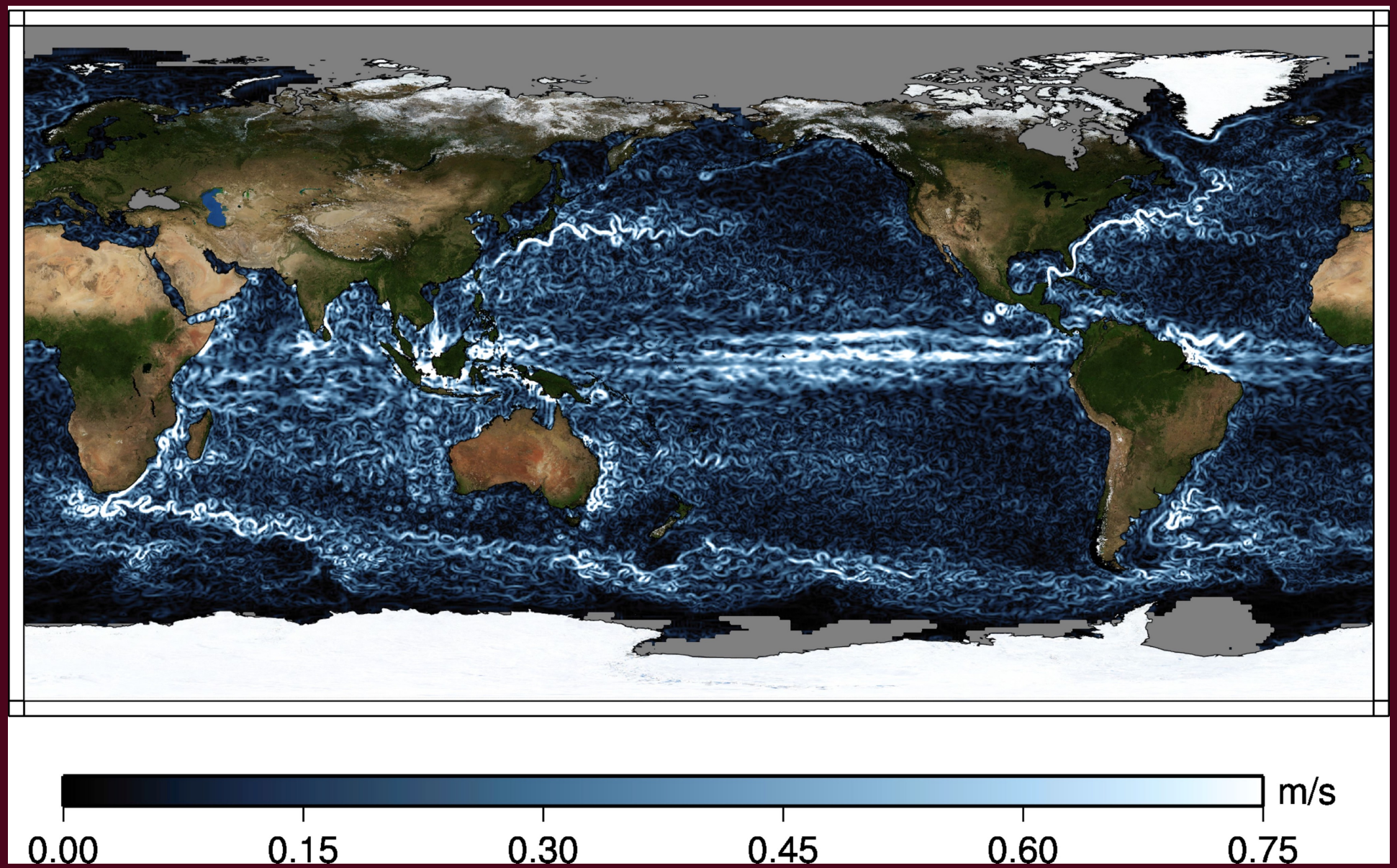


Figure Source: Fu et al. (2017)

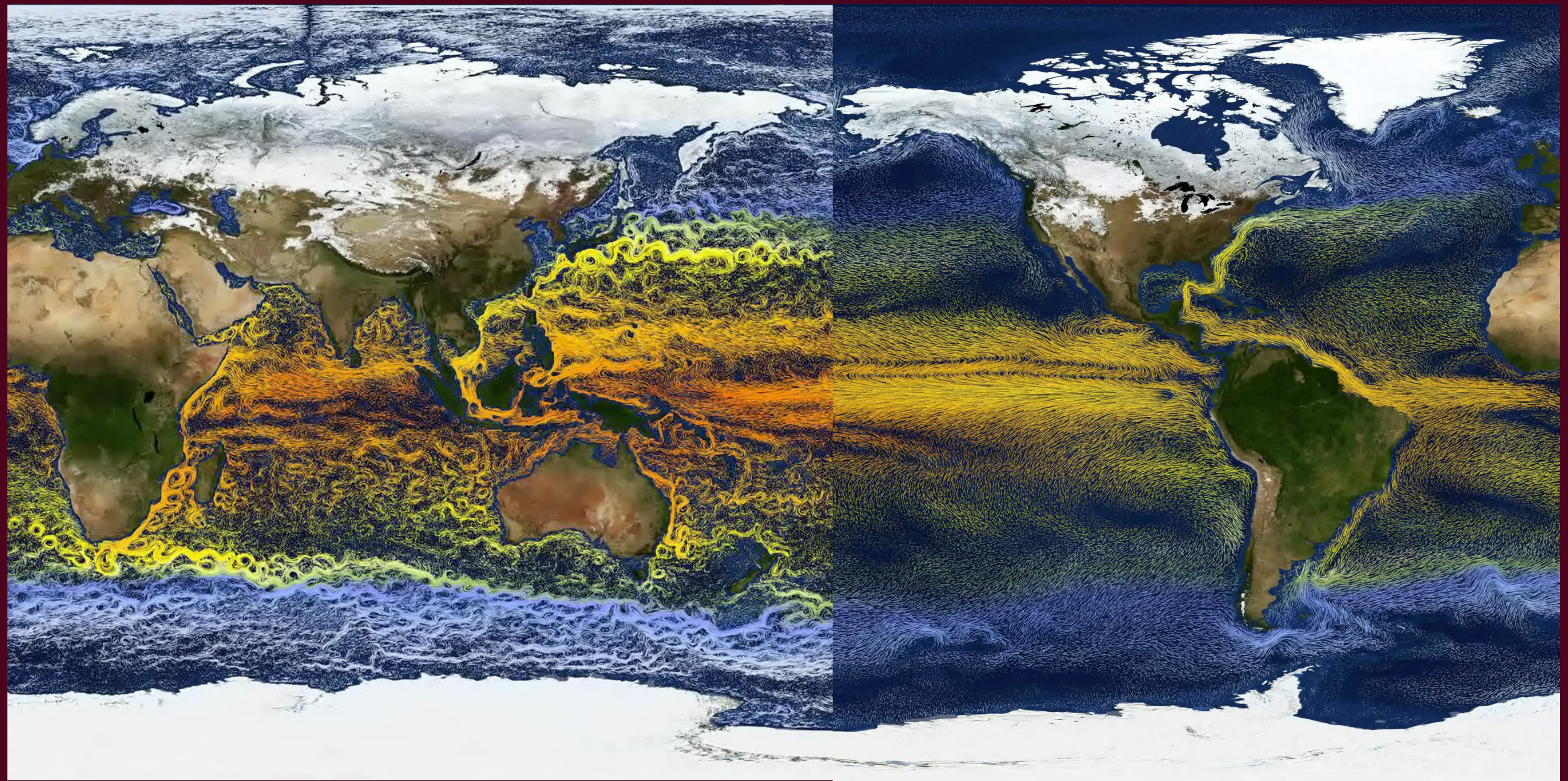
Satellite Observed Ocean Surface Currents
(12/31/2013)



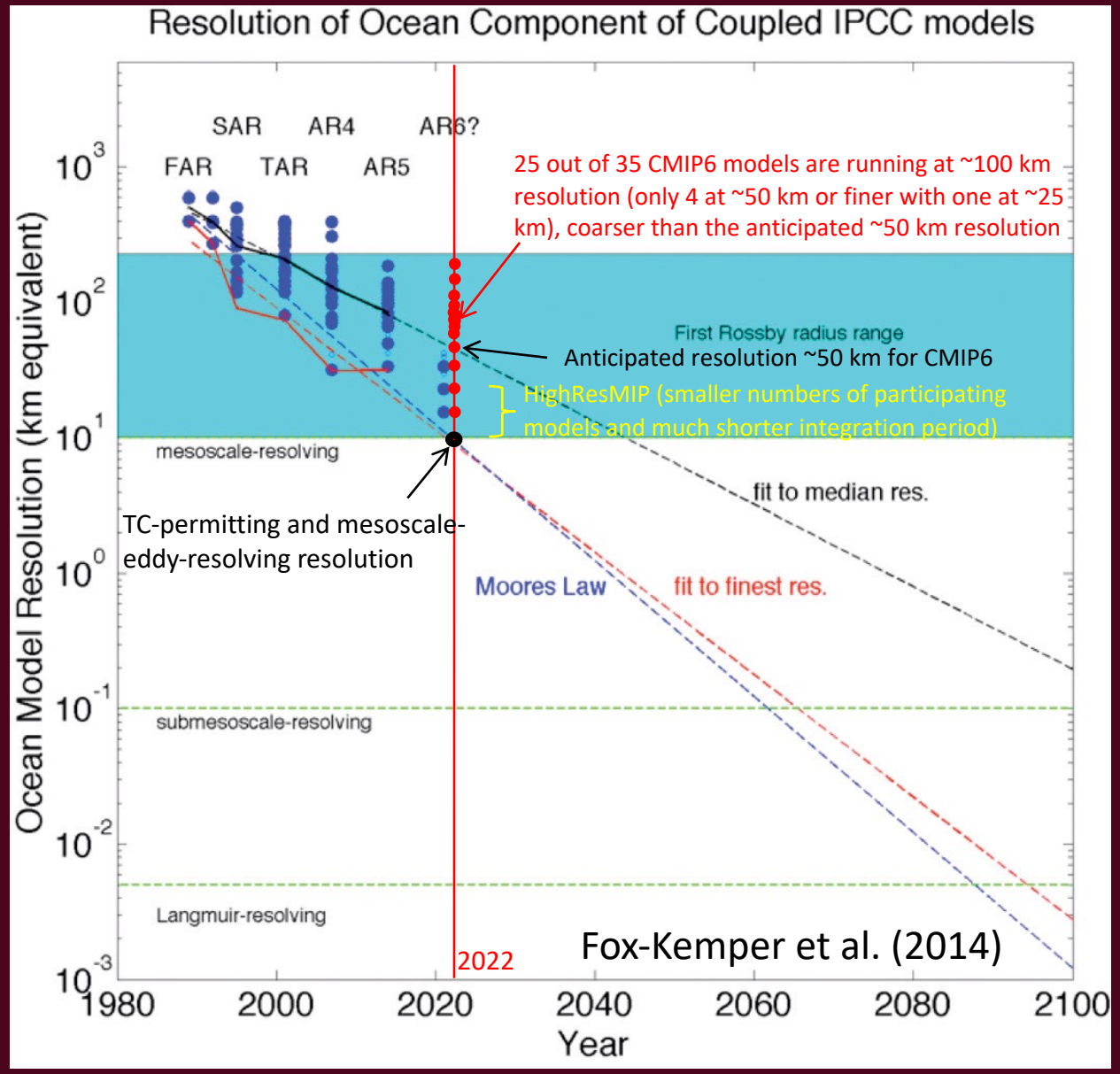
IPCC-Class vs. Eddy-Resolving Ocean Simulations

Mesoscale Eddy-Resolving (~10 km)

IPCC-Class (~100 km)



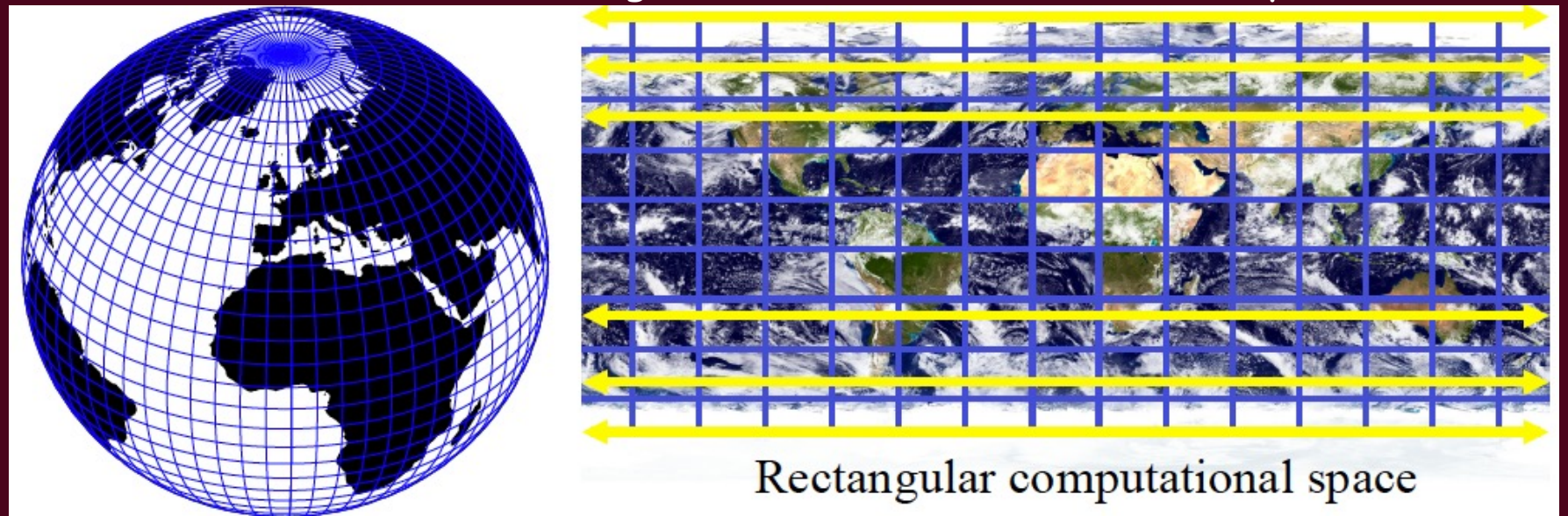
Moores Law for IPCC Climate Models



- A complete set of CMIP simulations at TC permitting (~25 km) atmosphere resolution and mesoscale-eddy-resolving (~10 km) ocean resolution (hereafter high-resolution) represents a major step forward in climate modeling community
- Our team (TAMU, NCAR and our international partners) is among the first to complete such a high-resolution set
- Completed simulations so far include
  - 1950-2005 AMIP simulations
  - 650 years of preindustrial climate simulation
  - Ensemble of 3 historical and future climate simulations (1850-2100) under RCP8.5 and one under RCP2.6
  - 1%/yr CO2 increase – transient climate sensitivity experiment (150 years)
  - Abrupt 4 x CO2 - equilibrium climate sensitivity experiment (150 years)
  - Ensemble of decadal prediction simulations

Transition from Low- to High-Resolution Models

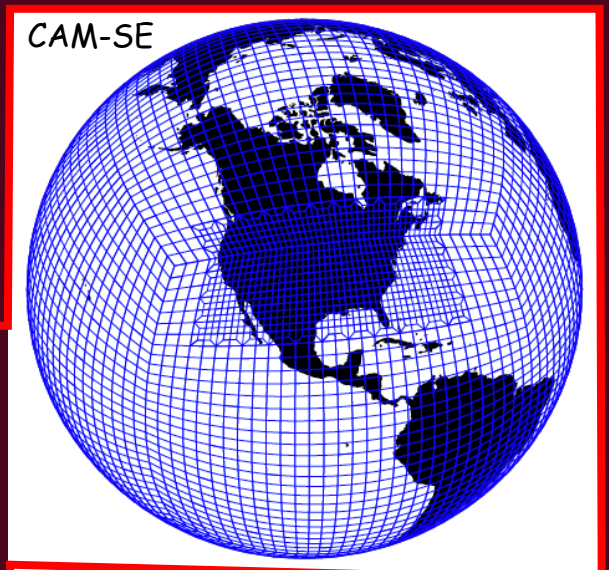
- In order to run high-resolution climate models efficiently, we need to reformulate the models for massively parallel computer architectures, such as Frontera
- For low-resolution CESM, the atmosphere model (CAM) is discretized on the traditional regular latitude-longitude grid:
  - CAM-EUL: Spherical harmonics based spectral transform method (dominated for over 40 years)
  - CAM-FV: Finite-volume method (the work-horse for CMIP5/6 simulations)
- These traditional numerical methods are not "trivially" amenable for massive parallel computer systems because they require non-local communication:
  - Legendre transform
  - "Polar filters" (due to convergence of the meridians near the poles)

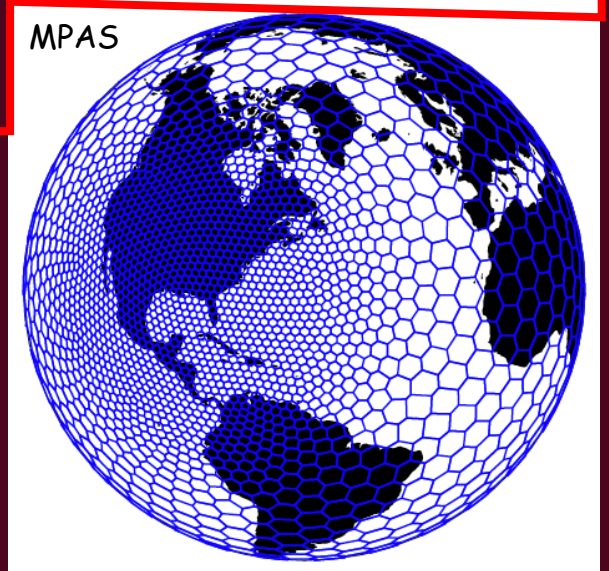


Peter Lauritzen: https://www.cesm.ucar.edu/events/tutorials/2019/files/Lecture2-lauritzen.pdf

Reformulation of CAM for massively parallel Computer Architectures

- Instead of the traditional regular latitude-longitude grid, we need 1) quasi-uniform grid and 2) local numerical method, and non-local communication is not required
- CAM-SE
  - Spectral element method
  - Discretized on cubed-sphere (uniform resolution or conforming mesh-refinement) and highly scalable
  - 1/4° "work-horse" for high-resolution CESM
- MPAS (Model for Prediction Across Scales)
  - Finite-volume unstructured
  - Centroidal Voronoi tessellation of the sphere
  - Fully compressible nonhydrostatic
  - Being integrated into CESM

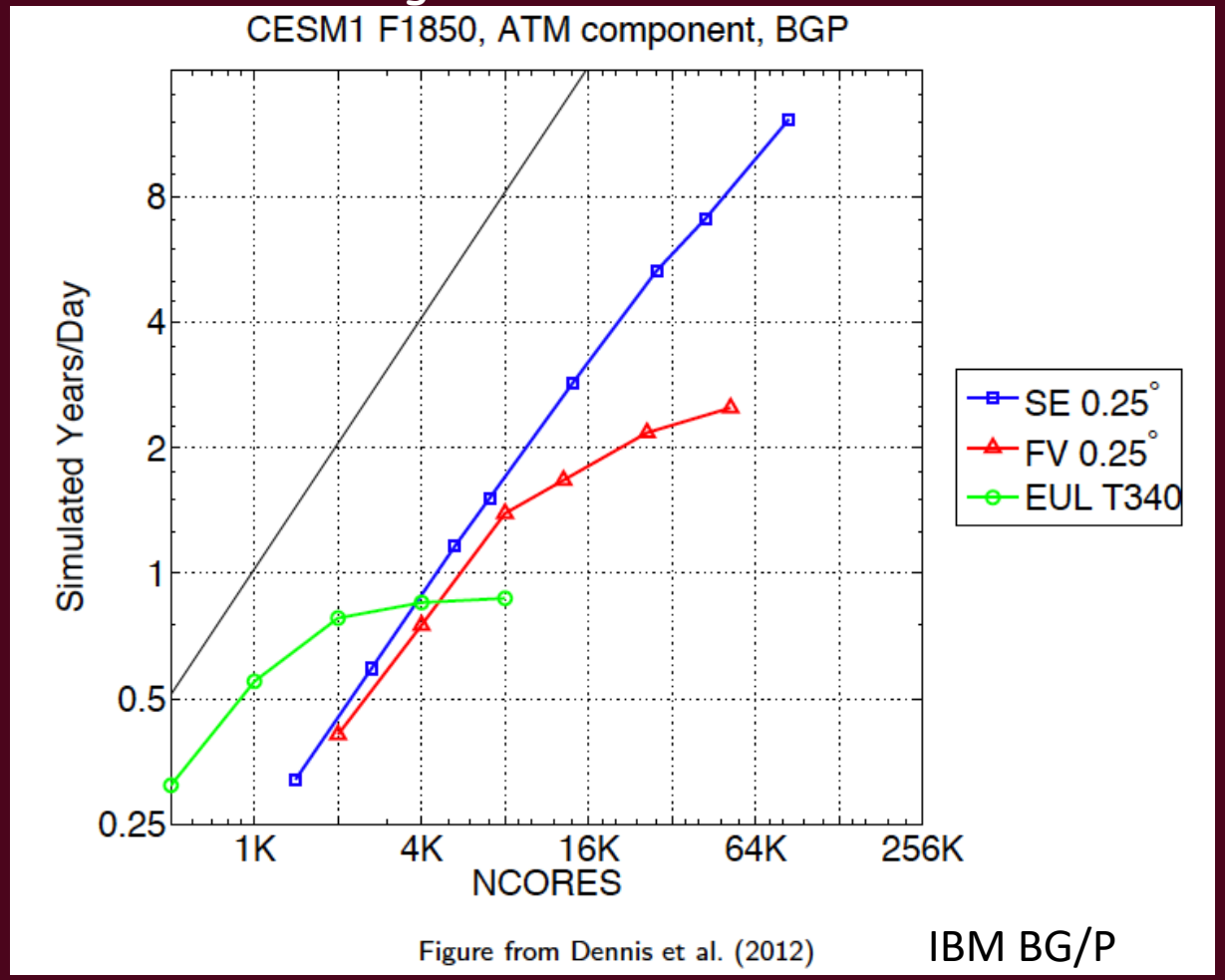




Peter Lauritzen: https://www.cesm.ucar.edu/events/tutorials/2019/files/Lecture2-lauritzen.pdf

CAM Scalability

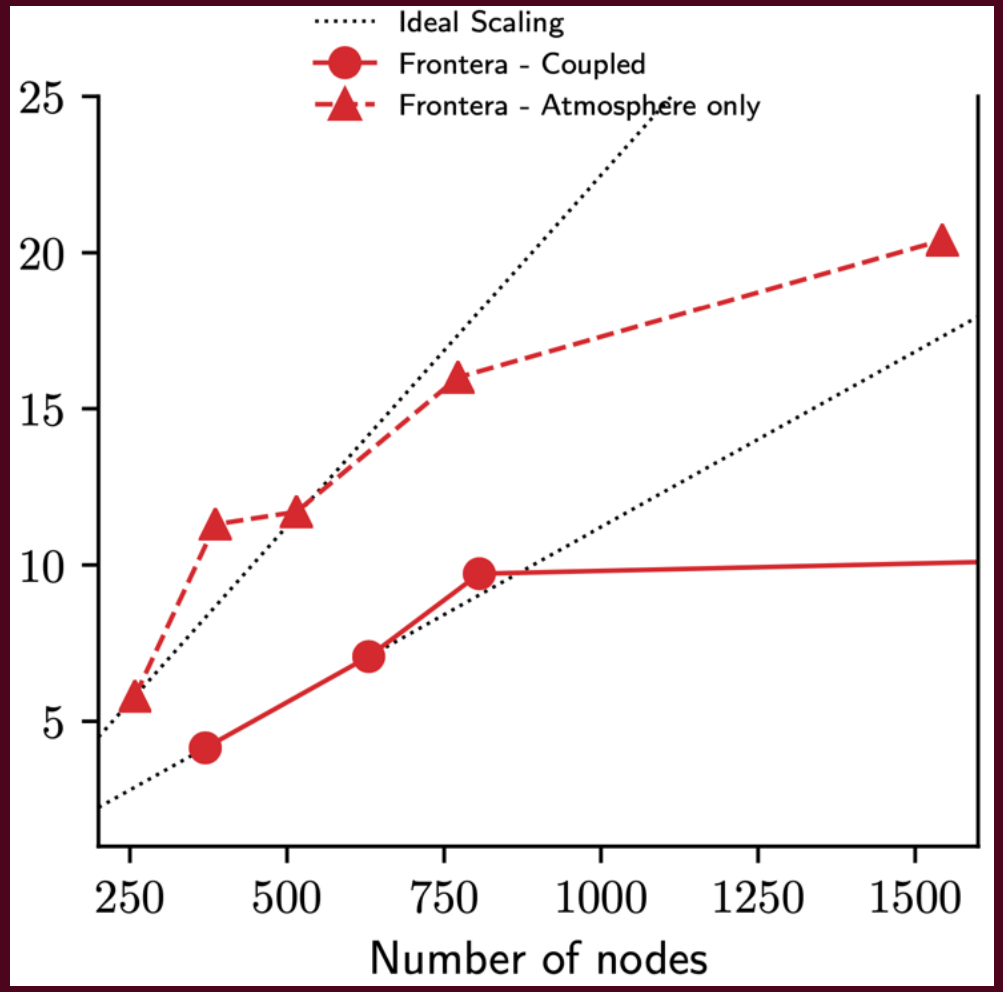
High-Resolution CAM



https://www.cesm.ucar.edu/events/tutorials/2019/files/Lecture2-lauritzen.pdf

- CAM-SE has superior scalability compared to CAM-FV and CAM-EUL
- CAM-SE is used for the high-resolution CESM simulations

High-Resolution CAM-SE on Frontera

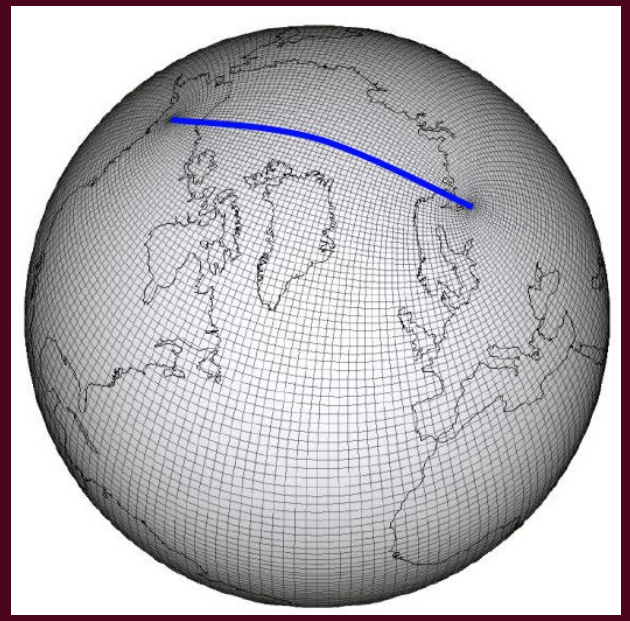


- CAM-SE achieves a benchmark of 20 simulation years per day on 1,500 Frontera nodes (84,000 cores)

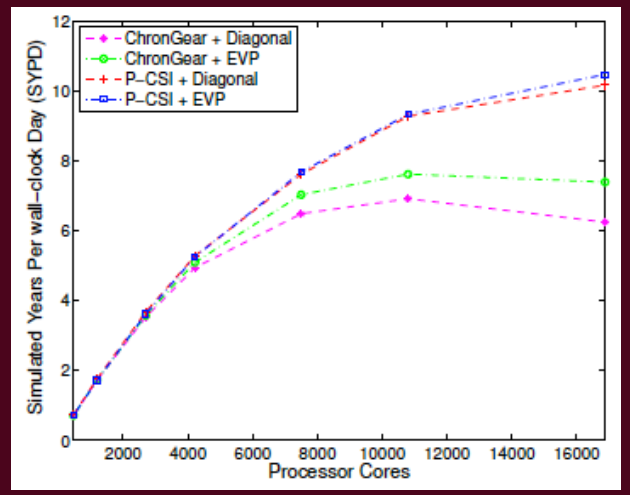
Ocean Component – POP2

- Finite difference code on Arakawa B-grid
- Vertical level- (z-) coordinate
- Horizontal orthogonal curvilinear tripole grid with displaced poles (two north poles on land) to avoid numerical instability
- Implicit free-surface method for barotropic mode, which requires solving an elliptic system of equations that scales poorly
- A preconditioned Chebyshev-type iterative method (P-CSI) is implemented to speed up the barotropic solver (Hu et al. 2015)
- CICE and POP2 Halo-update routines are optimized (Kim and Dennis, 2018)

Tripole Grid



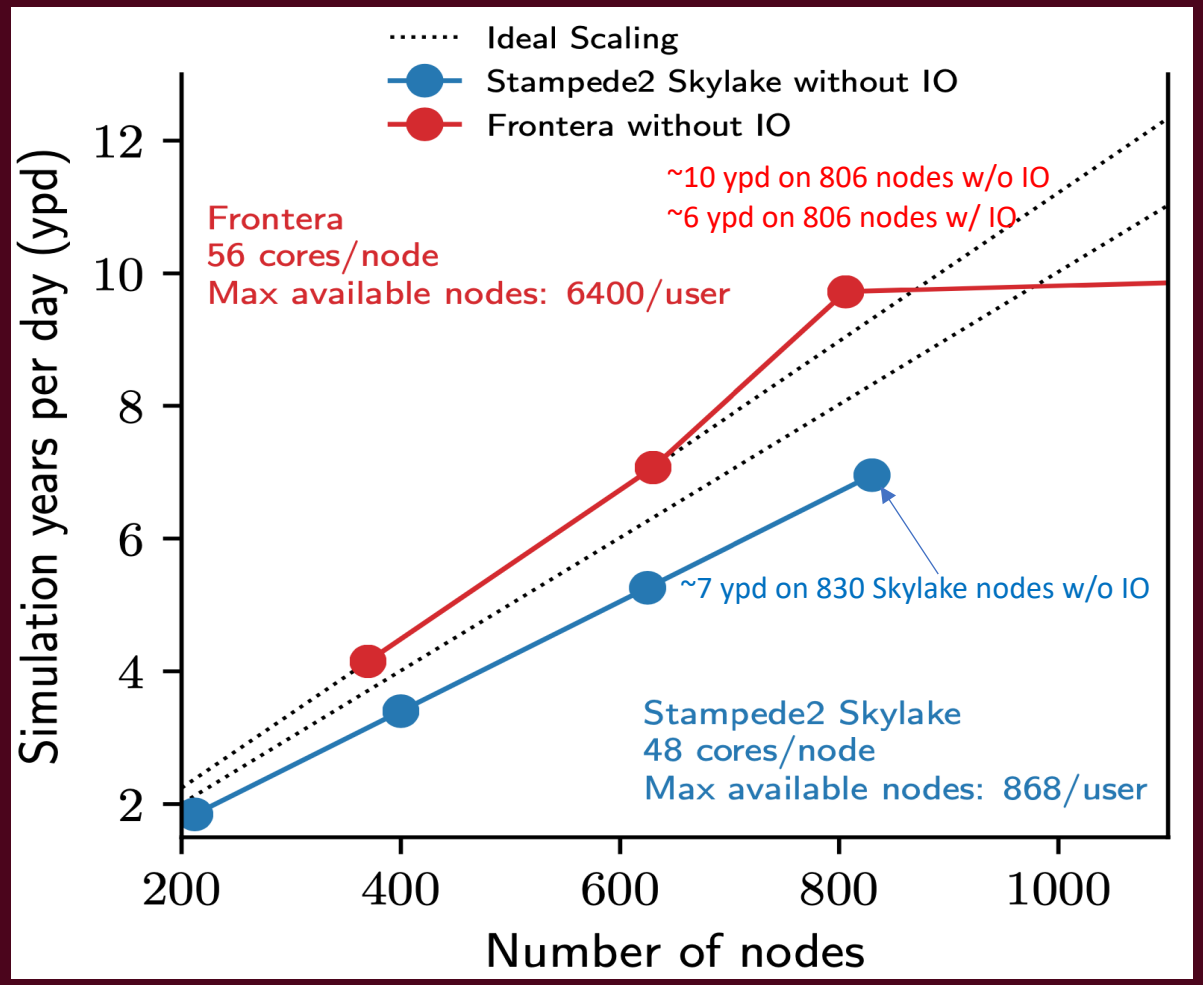
https://www.cesm.ucar.edu/events/workshops/ws.2018/presentations/sewg/kim.pdf



Hu et al. (2015)

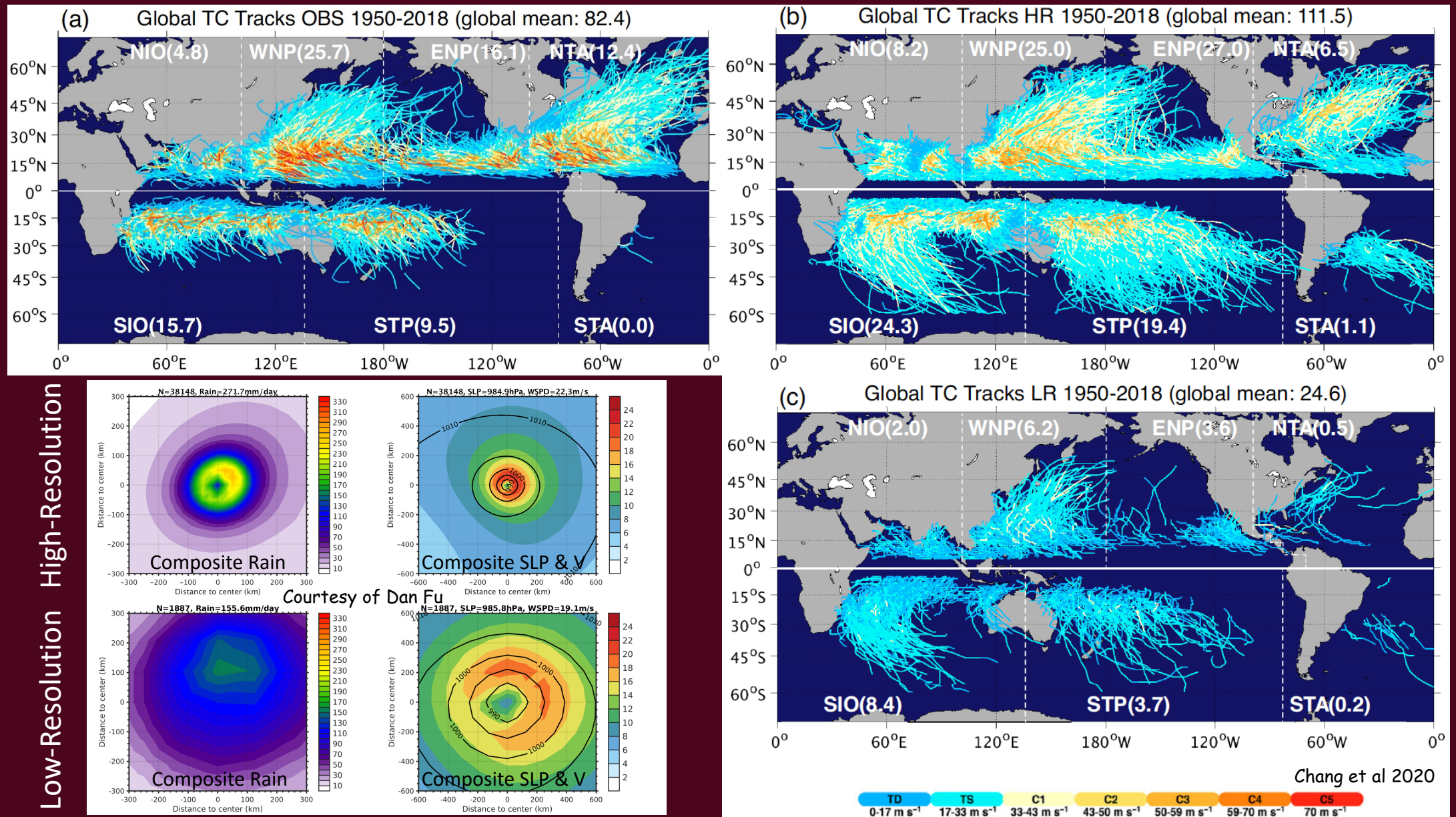
CESM Scalability

High-Resolution CESM on TACC Systems

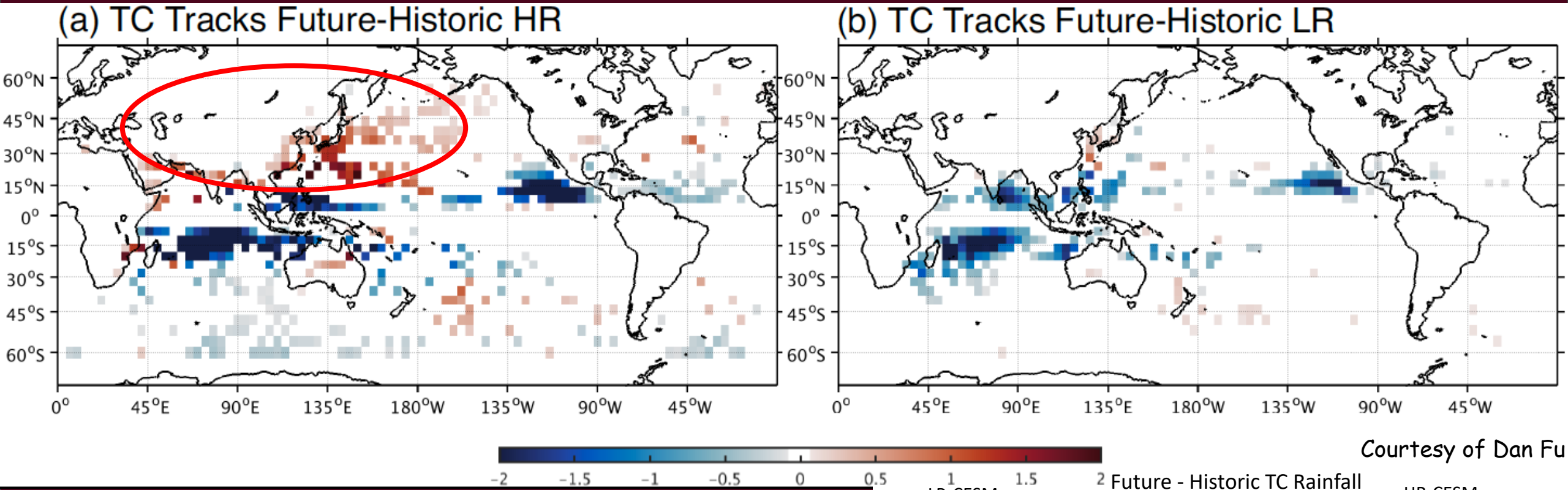


- High-resolution CESM shows an excellent scalability up to ~800 nodes (~45,000 cores) on Frontera
- POP2 does not scale beyond 800 nodes
- High-frequency IO significantly deteriorates the CESM performance (by~40%)
- 6 ypd performance on Frontera is among the best that we have seen for this class of climate models on any HPCs
- High-resolution CESM is ~92 times more costly than standard CESM

Global Tropical Cyclones

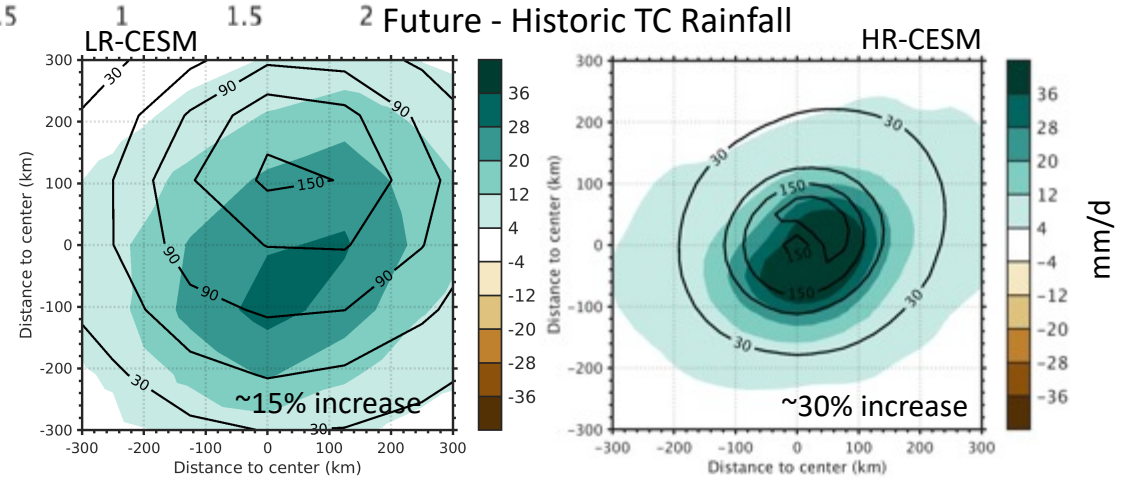


Projected Tropical Cyclones Changes



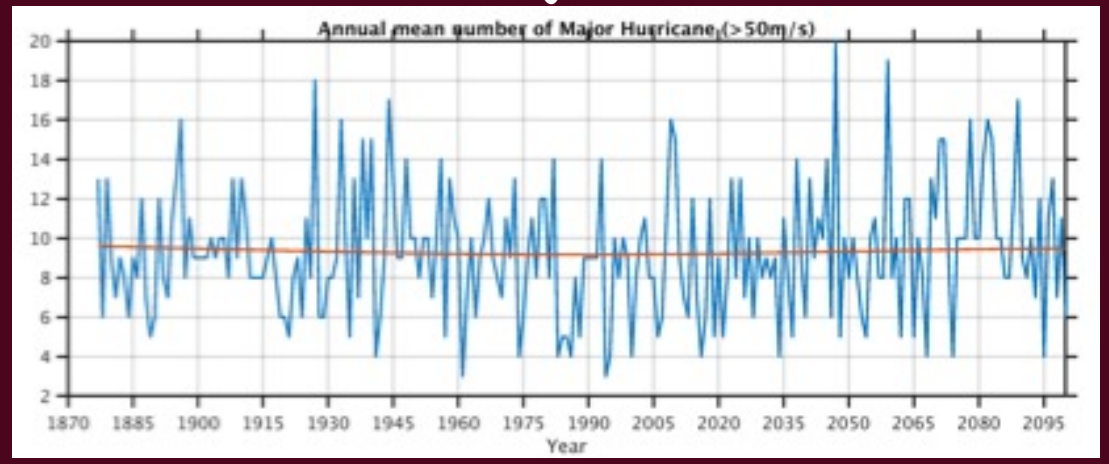
Courtesy of Dan Fu

- Projected TC change in HR-CESM simulations shows an increase in TC activity in the Northwestern Pacific and India Subcontinent, but LR-CESM simulations do not project such an increase
- HR-CESM simulations also project a 30% increase in TC-induced extreme rainfall compared to 15% increase in LR-CESM

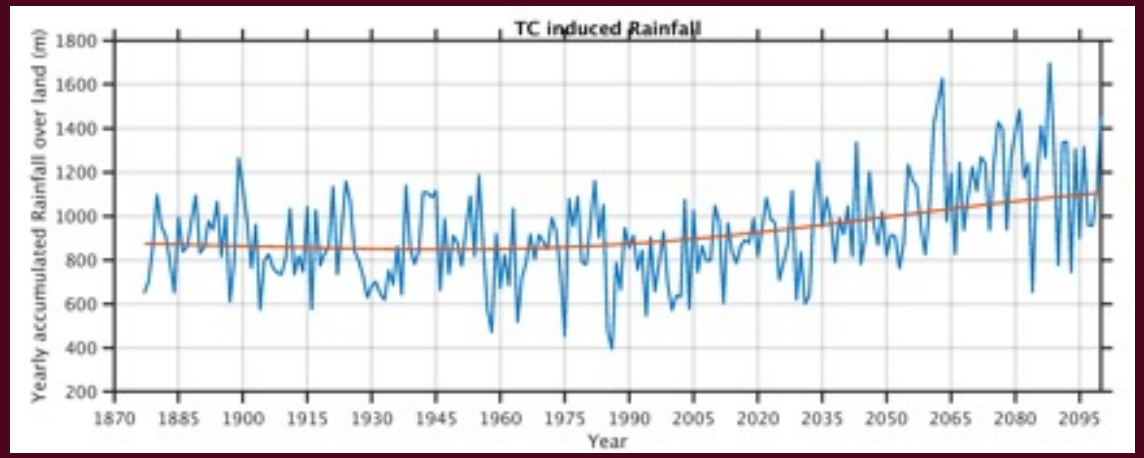


Future Projection of TC-rainfall over Land

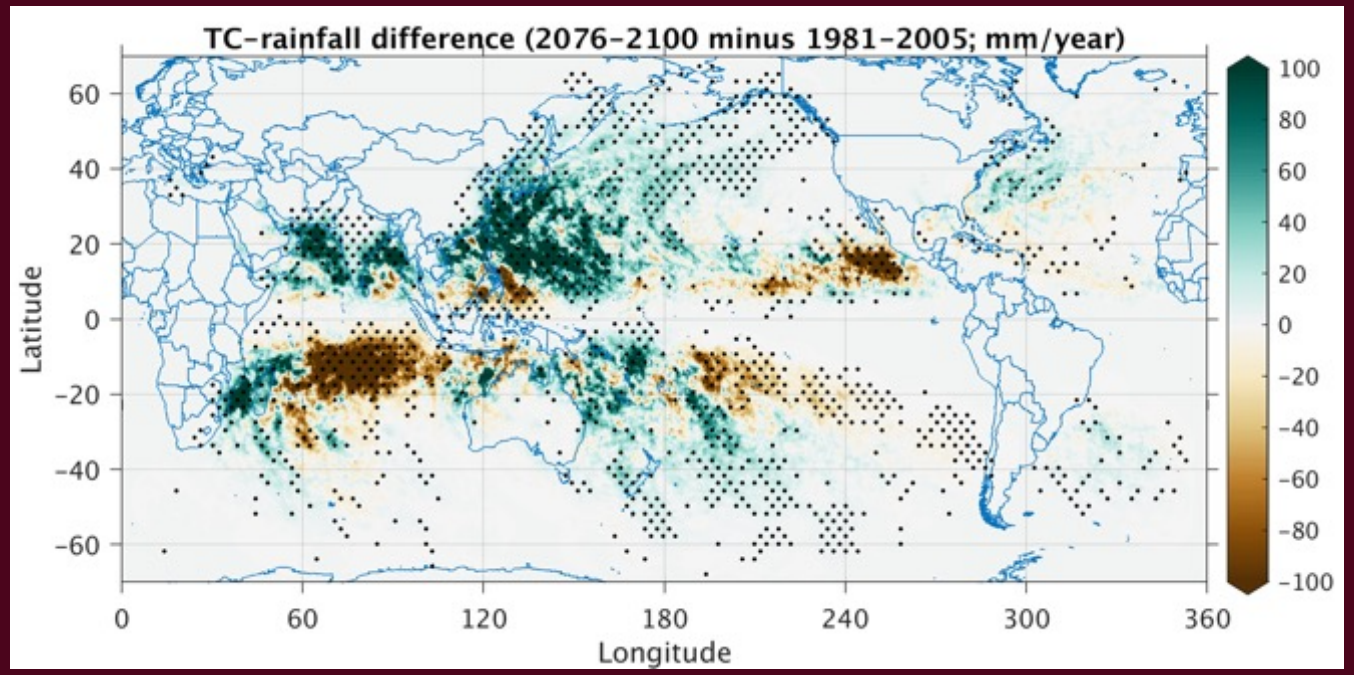
Number of Major Hurricane



Accumulated TC-rainfall over land

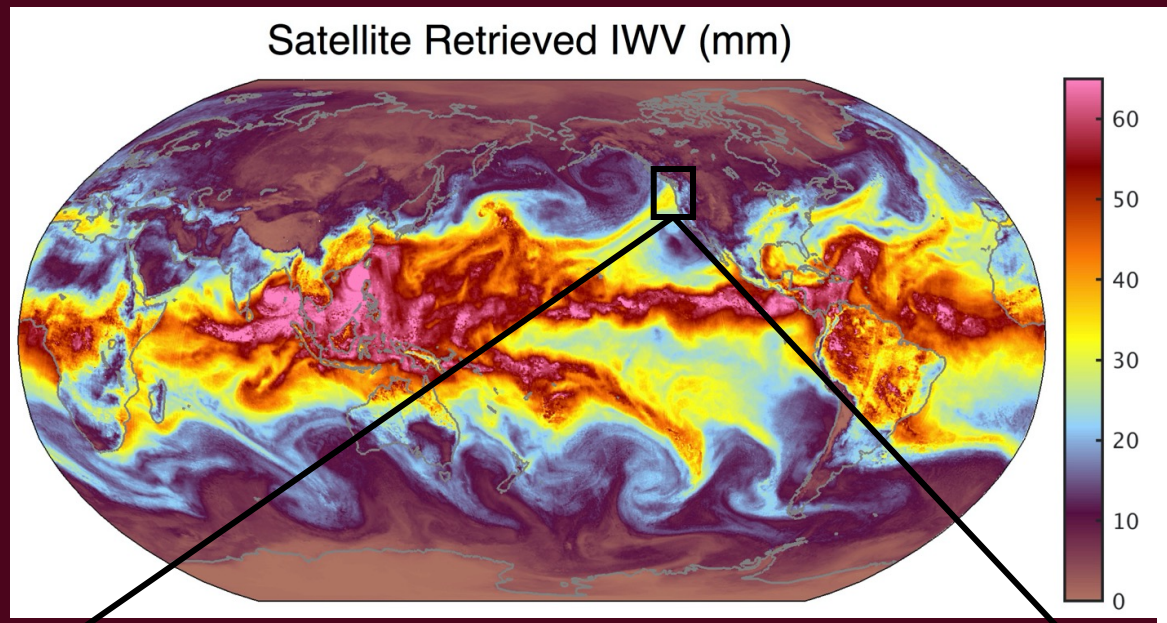


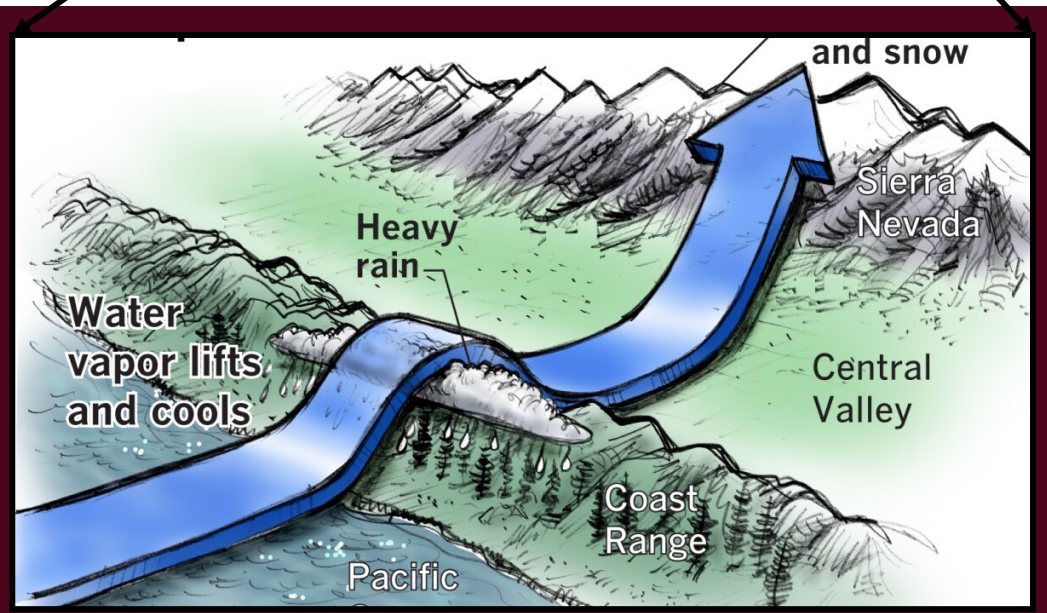
Future minus Historical Period

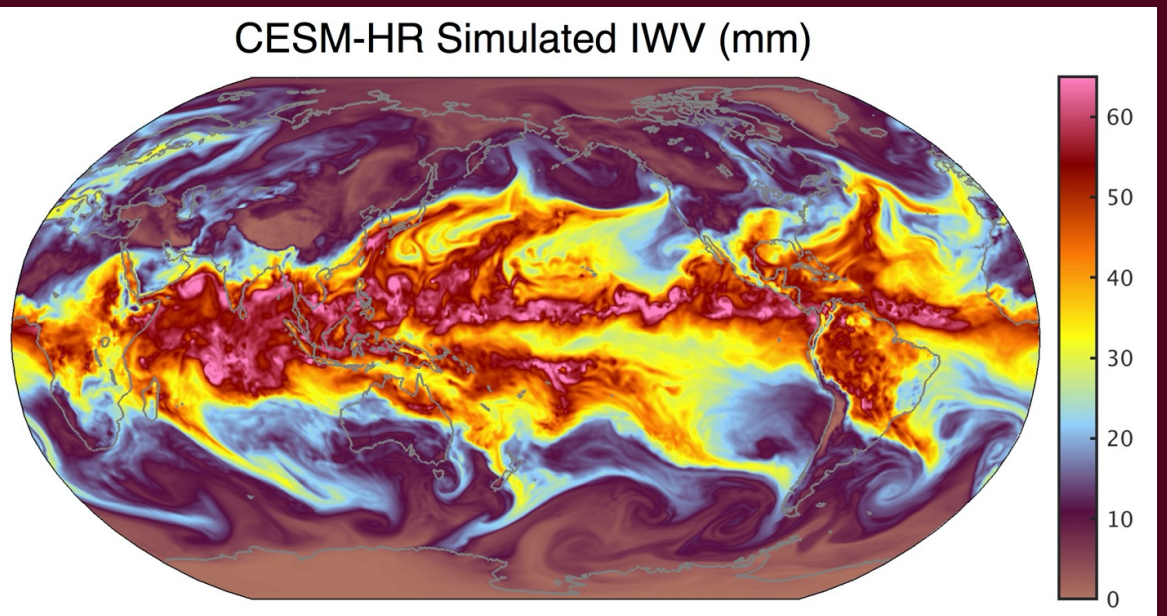


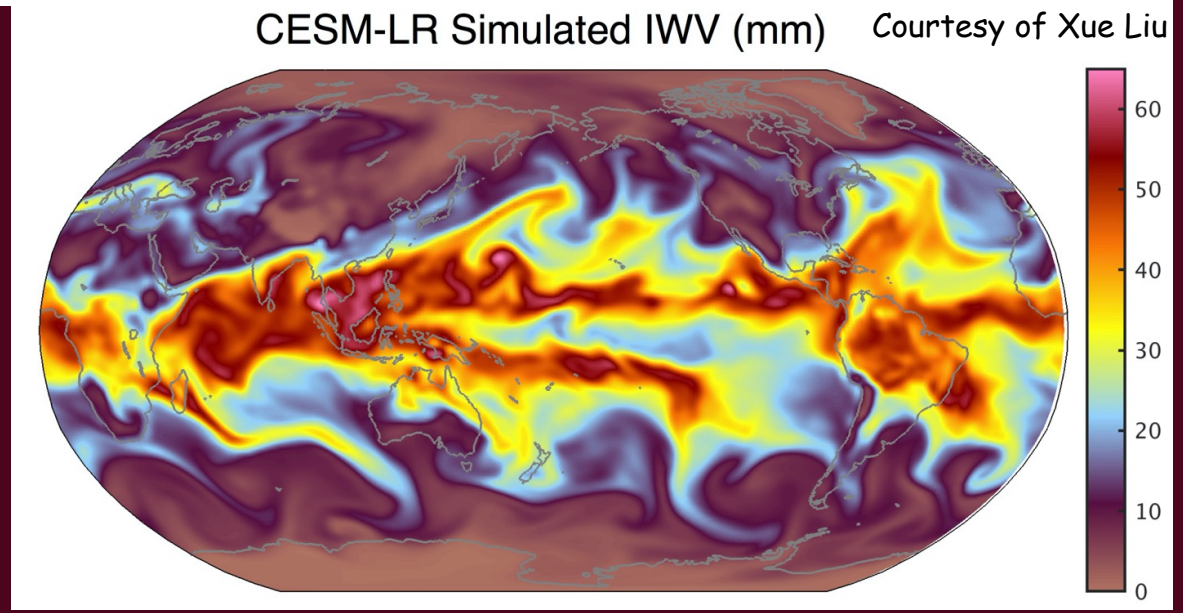
Courtesy of Dan Fu

Atmospheric Rivers





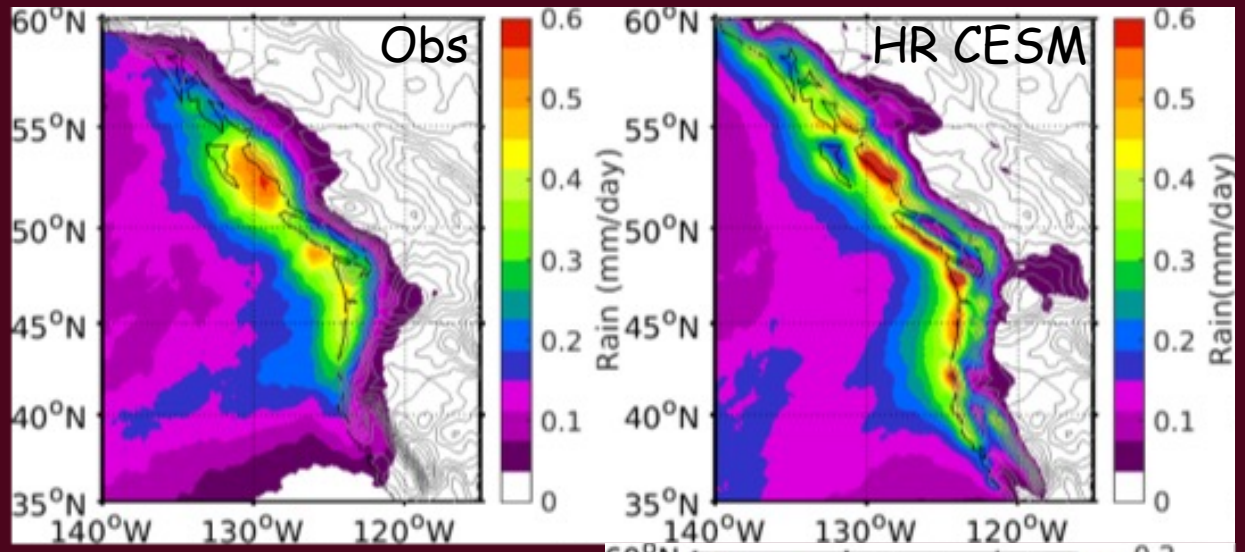


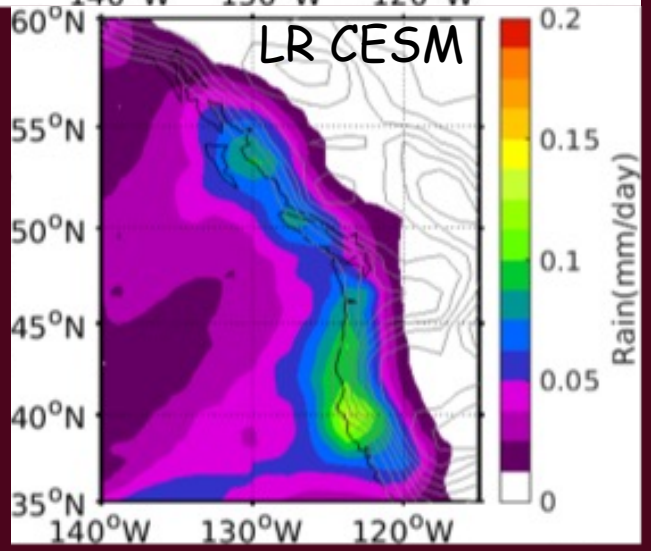


Courtesy of Xue Liu

Atmospheric River Induced Precipitation

Representation of Orography in Climate Models



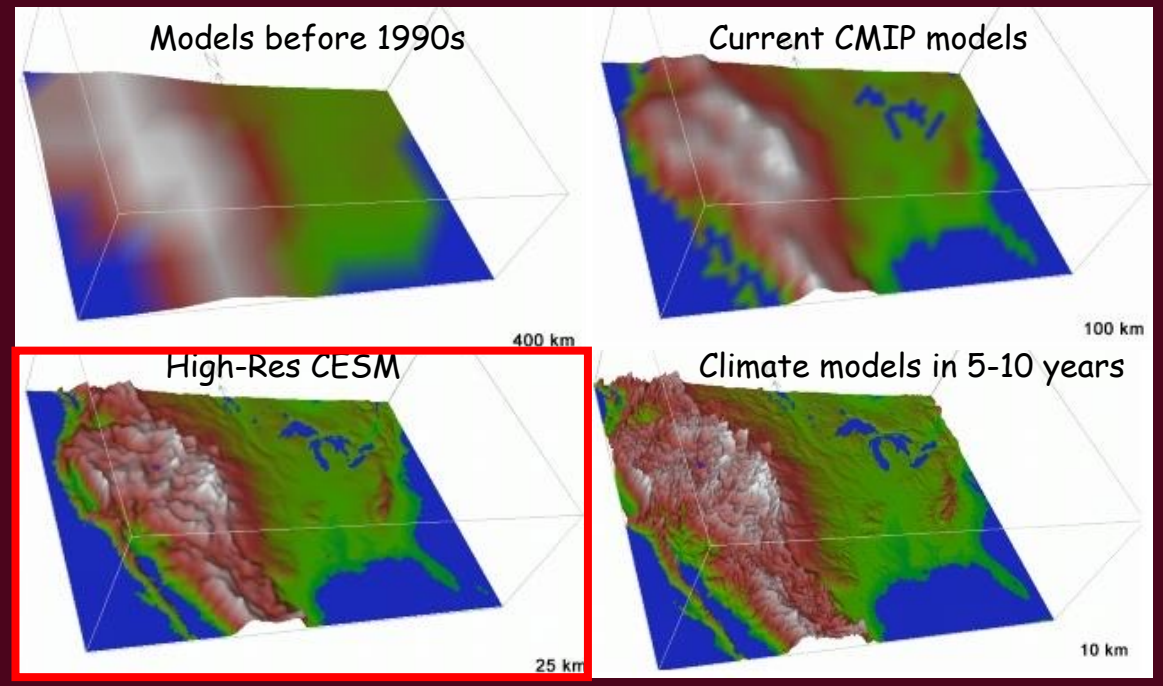


The underestimated precipitation in low-resolution CESM is likely caused by

- weak atmospheric rivers
- poorly represented orography

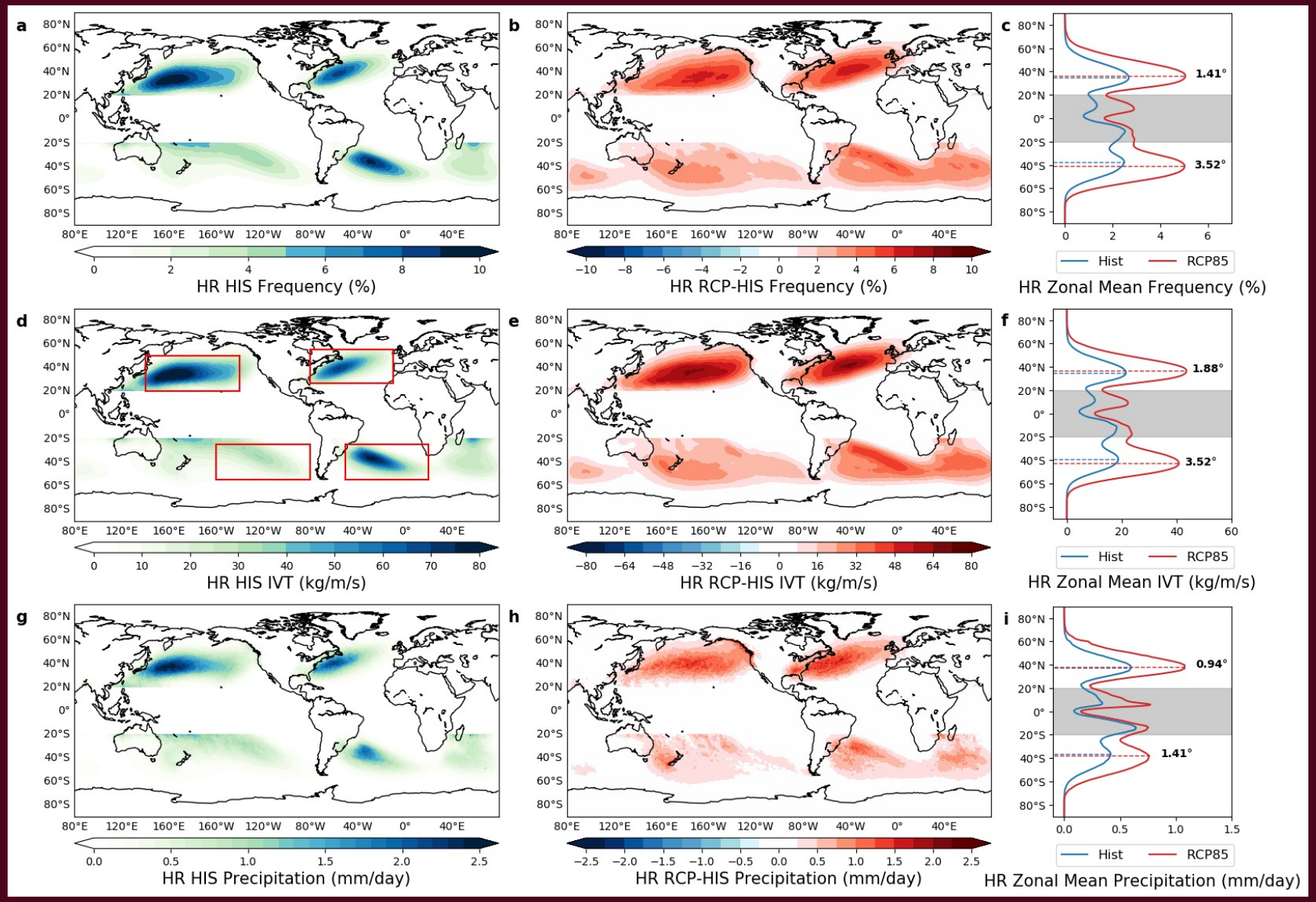
Courtesy of Xue Liu

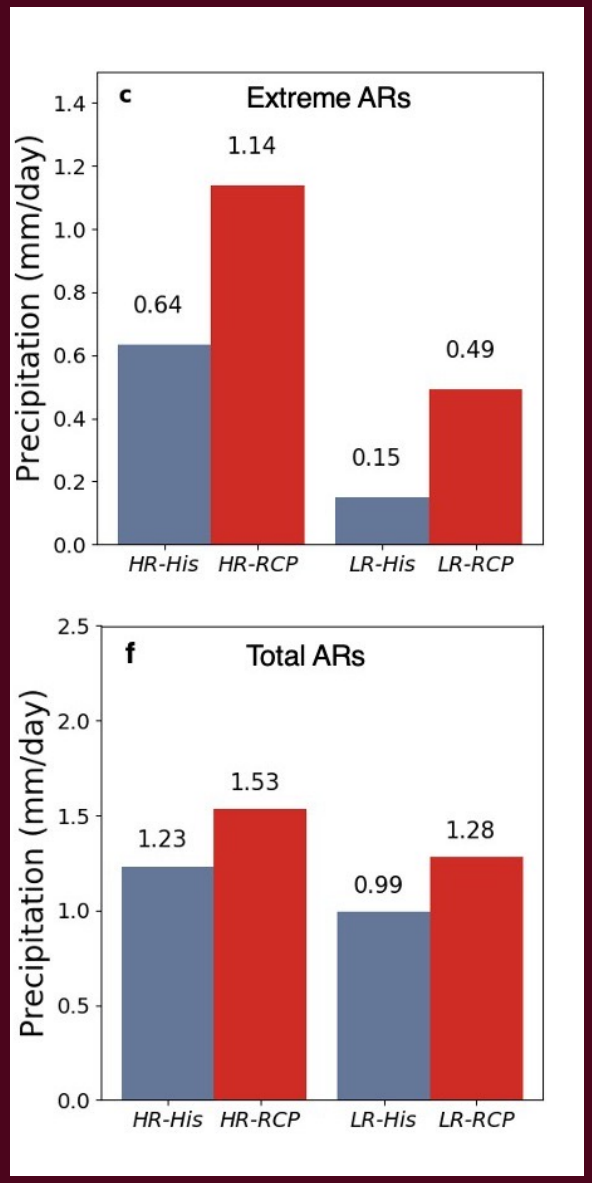
Representation of Orography in Climate Models



https://www.realclimate.org/index.php/archives/2007/05/climate-models-local-climate/

Projected Future Changes in Atmospheric Rivers

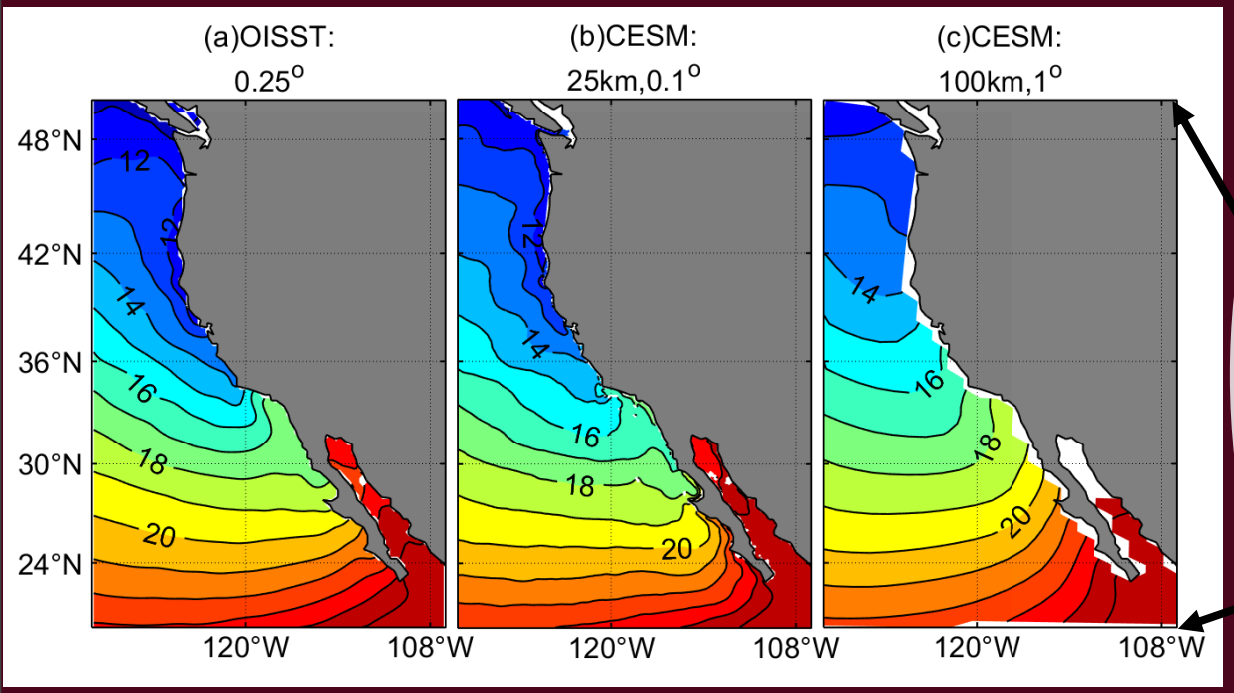


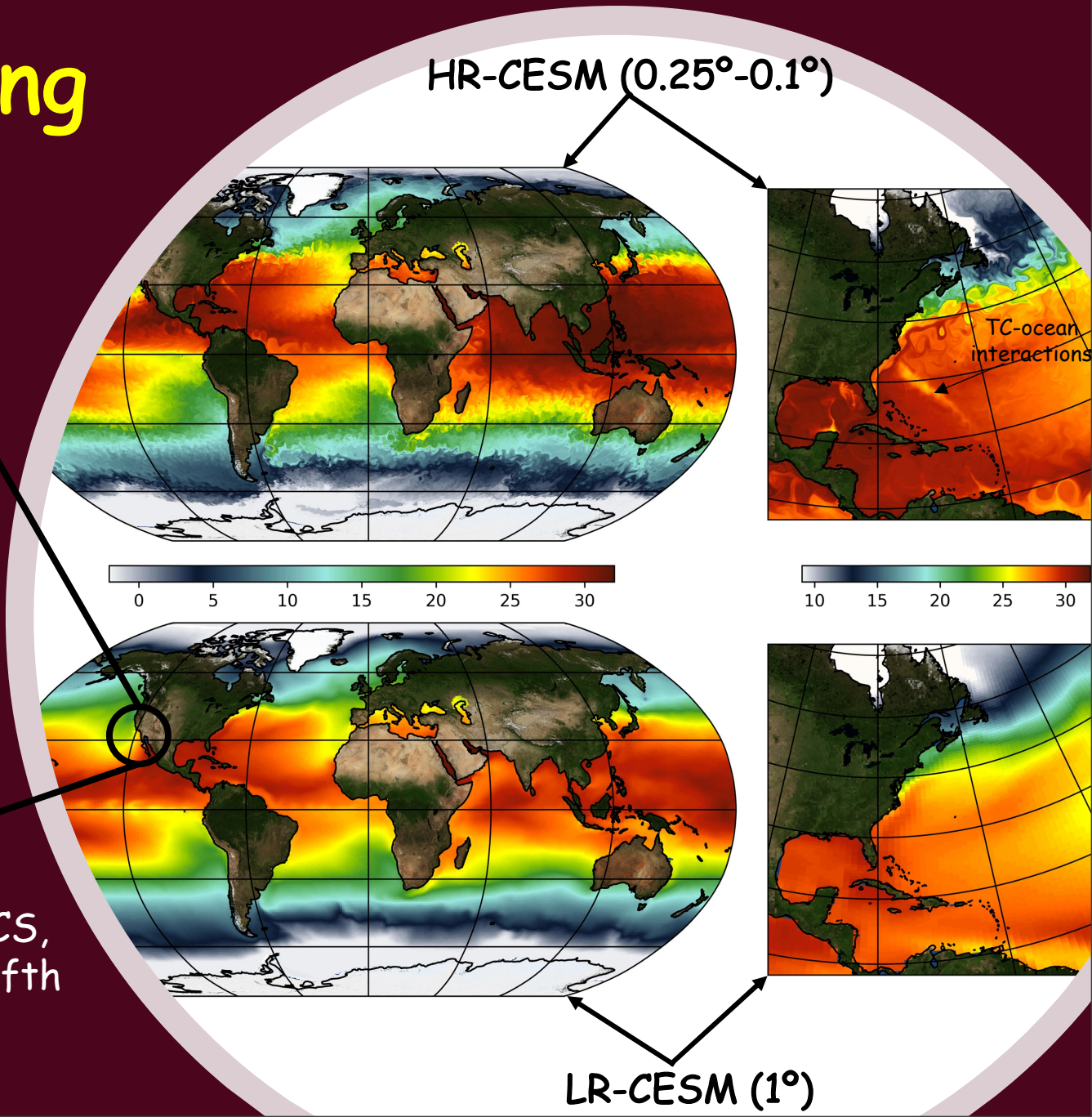


Courtesy of Xiaohui Ma

Coastal Ocean Upwelling

Upwelling along California Current System (CCS)



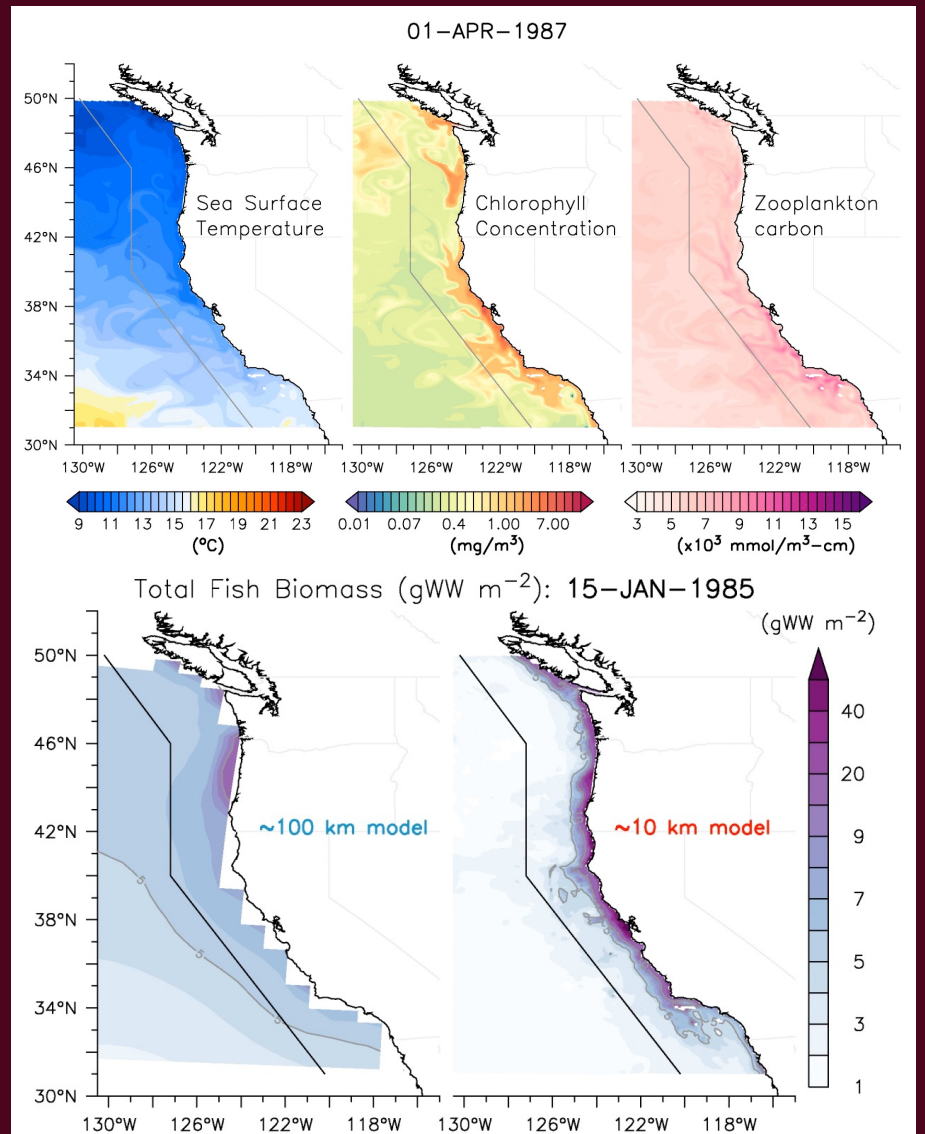


Ocean eastern boundary upwelling systems, like the CCS, are ocean's **most** productive biomes, supporting one-fifth of the world's wild marine fish harvest.

NSF Convergence Accelerator Track E:

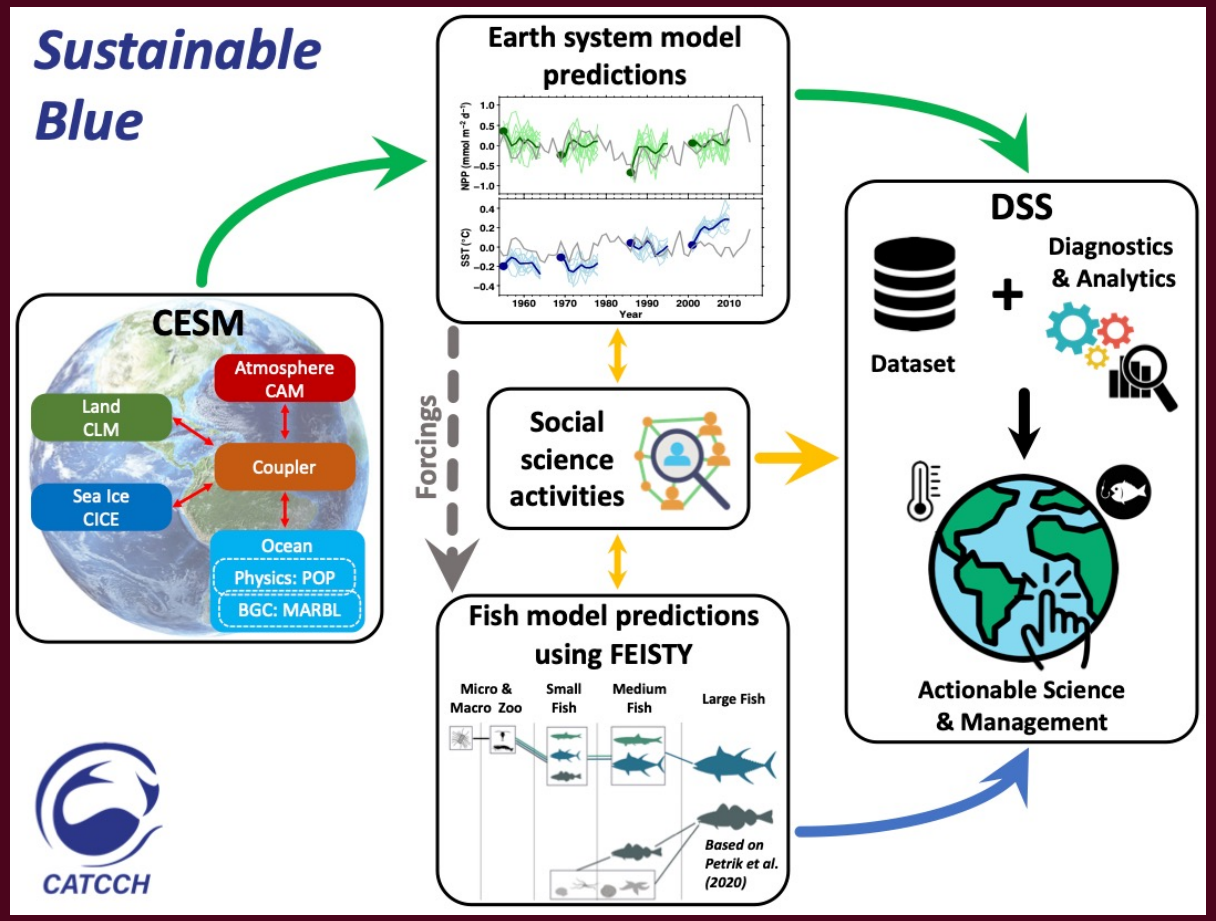
Climate Change Adaptation Tools for California Current FisHeries (CATCCH)

CESM-HR with Ocean Biogeochemistry plus Fisheries

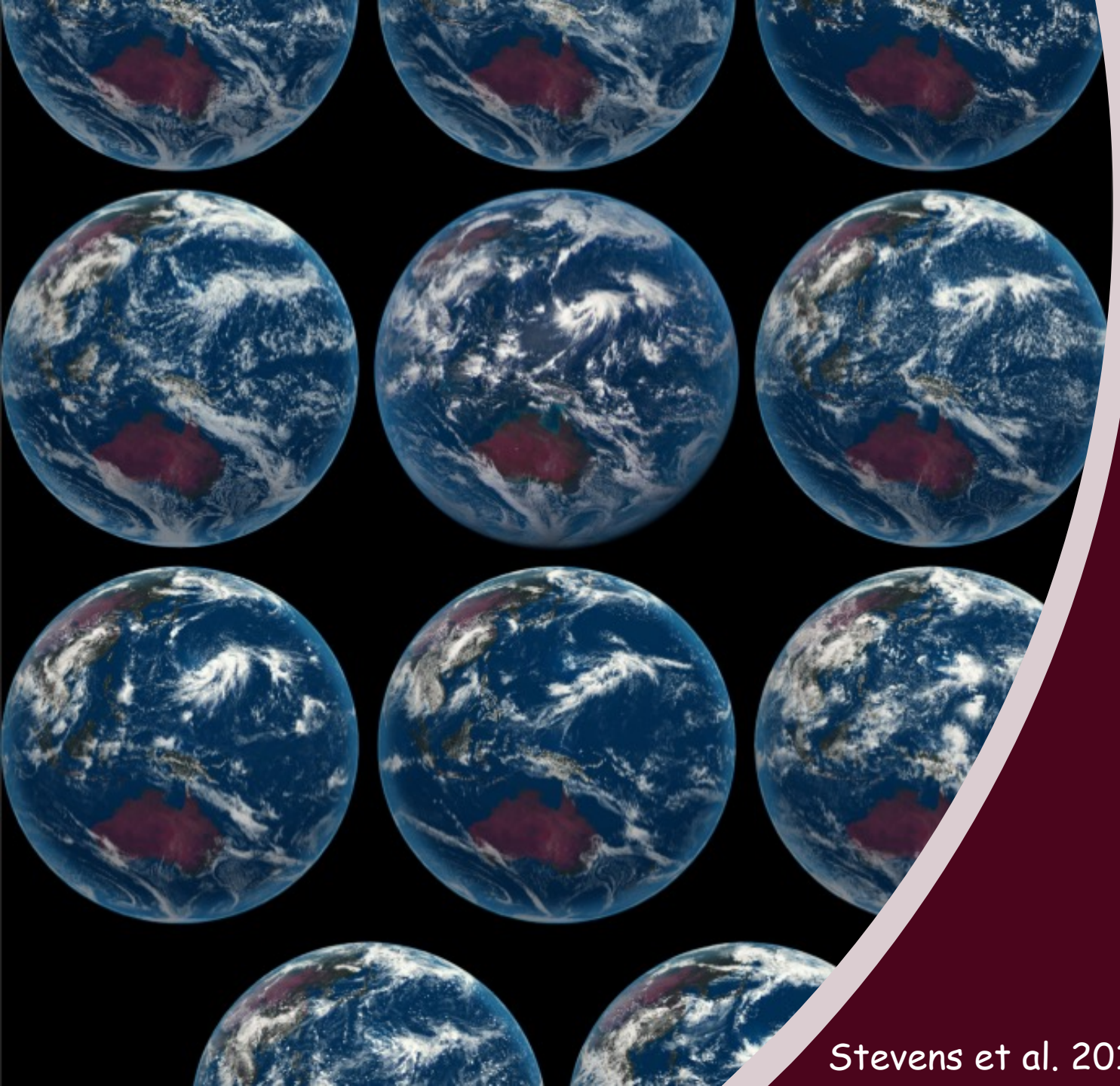


(courtesy of Jaison Kurian)

Decision Support System for Sustainable Future Fisheries



(courtesy of Fred Castruccio)

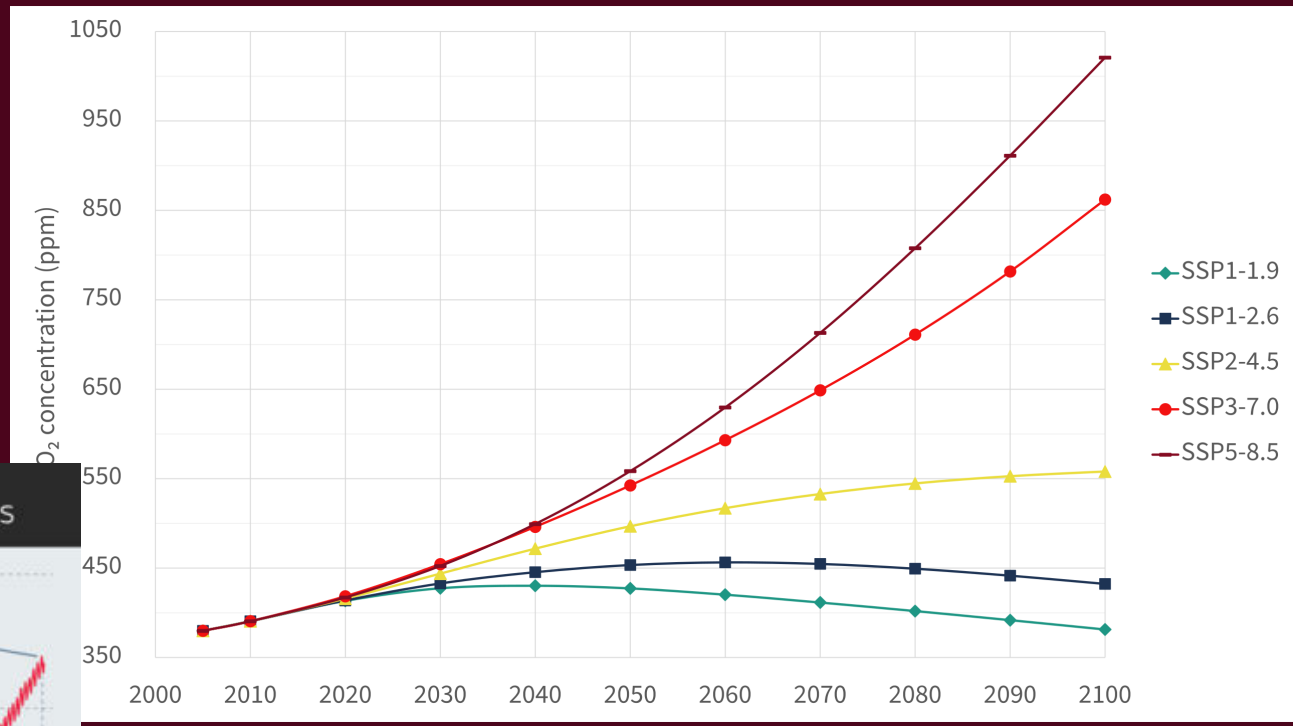


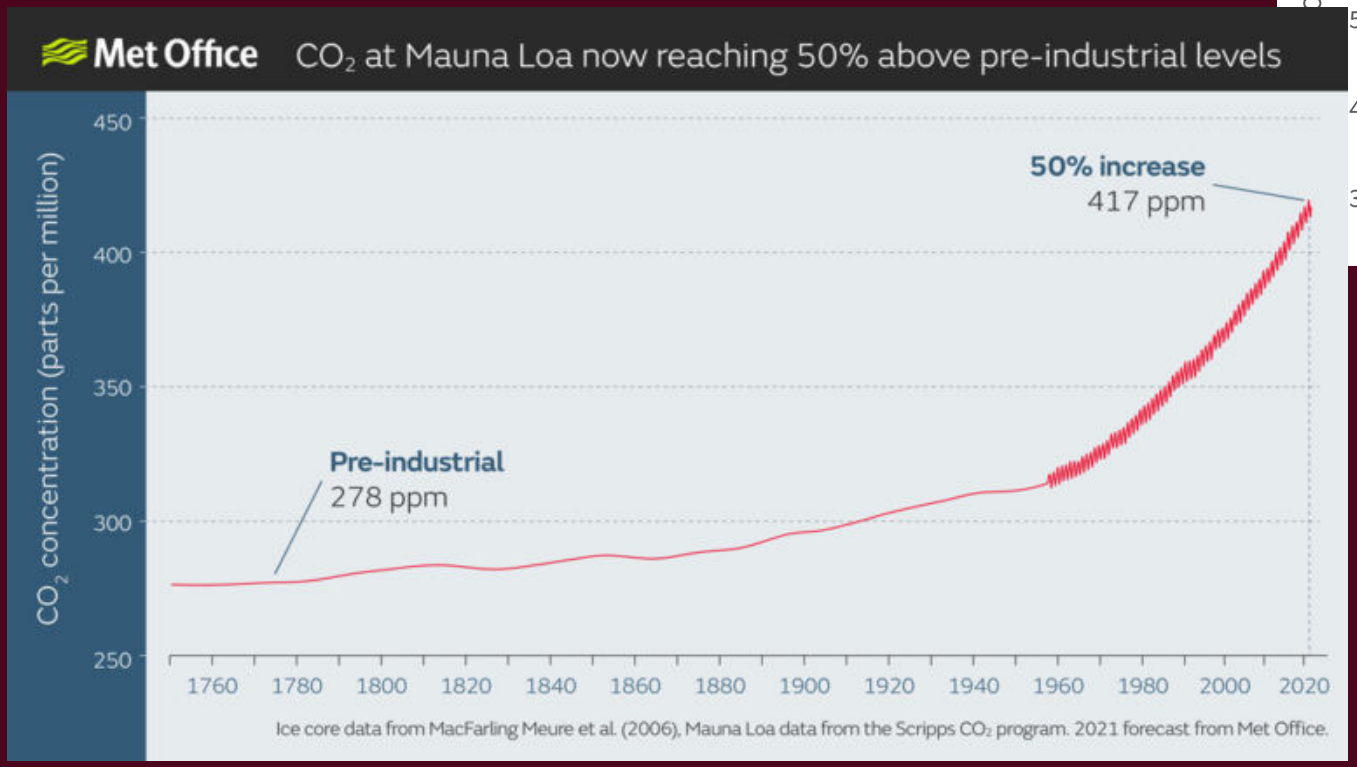
Stevens et al. 2019

Storm-resolving Global Climate Models – A New Challenge

- Explicitly representing convection requires non-hydrostatic dynamics
- Horizontal resolutions < 4 km and vertical levels > 80
- ~200 times more costly than current high-resolution climate models (~**0.25° & 30 vertical levels)**
- **500 CPU-based nodes → ~1 simulation week per day**
- **GPU-based HPCs are expected to deliver a better performance (~3 simulation months per day)**
- **Not to expect ~1000-yr climate simulations in the near future**

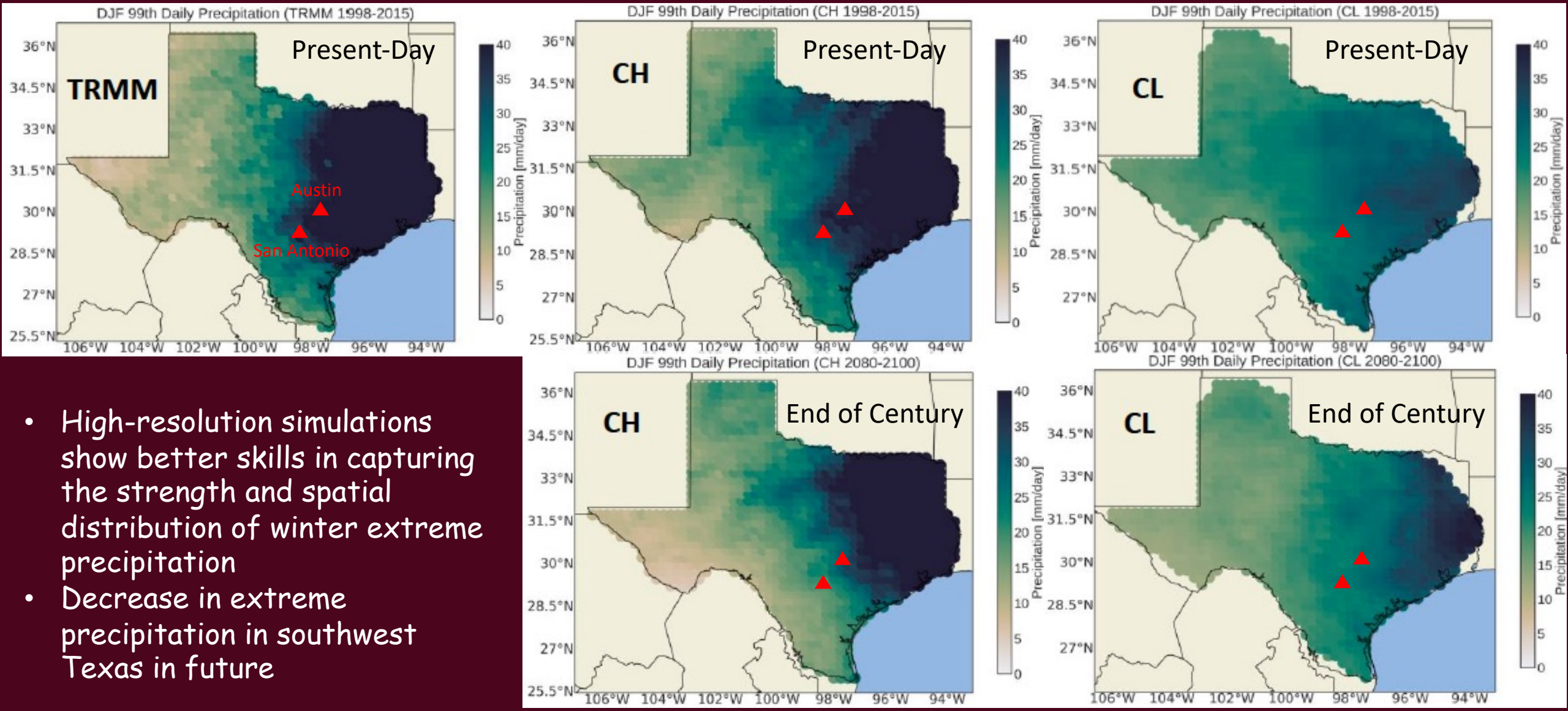
Different CO2 Emission Scenarios in CMIP





Winter (DJF) Extreme Precipitation in Texas

Observation | HR CESM | LR CESM



- High-resolution simulations show better skills in capturing the strength and spatial distribution of winter extreme precipitation
- Decrease in extreme precipitation in southwest Texas in future