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Bridging Low-Resolution CMIP and Storm-Resolving Scales: High-Resolution CESM Climate Simulation Ensembles

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High-Resolution CESM (CESM-HR)

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What is CESM-HR?

Based on CESM1.3 (Meehl et al. 2019), which derives from high-resolution CESM1.1 (Small et al. 2014)

- CAM3.5: SE-DYCORE with 0.25º horizontal and resolution and 30 vertical levels (3 hPa top)
- CLM4.0: 0.25º horizontal and resolution with MOSART1.0
- POP2: 0.1º horizontal and resolution and 62 vertical levels with no mesoscale, submesoscale, and overflow parameterizations
- CICE4.0: 0.1º horizontal and resolution
- Coupler: CESM2 Common Infrastructure for Modeling the Earth (CIME)
- CESM-HR code is ported and optimized for multiple HPC systems, including Frontera at TACC and Derecho at NCAR
- On 223 CPU nodes of Derecho, CESM-HR achieves ~5 simulated yrs per day with HF IOs
- CESM-HR/CESM-LR cost ratio ~ 100

What are CESM-HR simulation ensembles?

- CMIP6 HighResMIP Ensemble (Roberts et al, 2020a&b):
  - 1950-2014 AMIP
  - 1950 CTRL and 1950-2100 historical-future (RCP8.5) simulations
  - 2015-2050 AMIP
- CMIP DECK (Chang et al. 2020, 2023, 2025):
  - 1850 PI-CTRL (650 yrs)
  - 10-mem 1920-2005 historical simulations
  - 10-mem 2006-2100 future simulations with RCP8.5
  - 10-mem 2006-2100 future simulations with RCP6.0
  - 1-mem 2006-2100 future simulation with RCP4.5
  - 1-mem 2006-2100 future simulation with RCP2.6
  - 80-yrs 1% CO2 and 150-yrs 4xCO2
  - 4-mem 1950-2015 AMIP
- High-Res Decadal Prediction (HRDP) (Yeager et al. 2023):
  - 5-cycle of 1958-2018 OMIP (with 5th cycle extended to 2023)
  - 10-mem 5-year initialized (May and Nov) predictions from 1980 to 2023
- Corresponding CESM-LR simulations
- ~6000 yrs of cumulative simulation and ~7 PB data volume
- Data accessibility: https://project.cgd.ucar.edu/projects/MESACLIP/

Global Mean Surface Temperature

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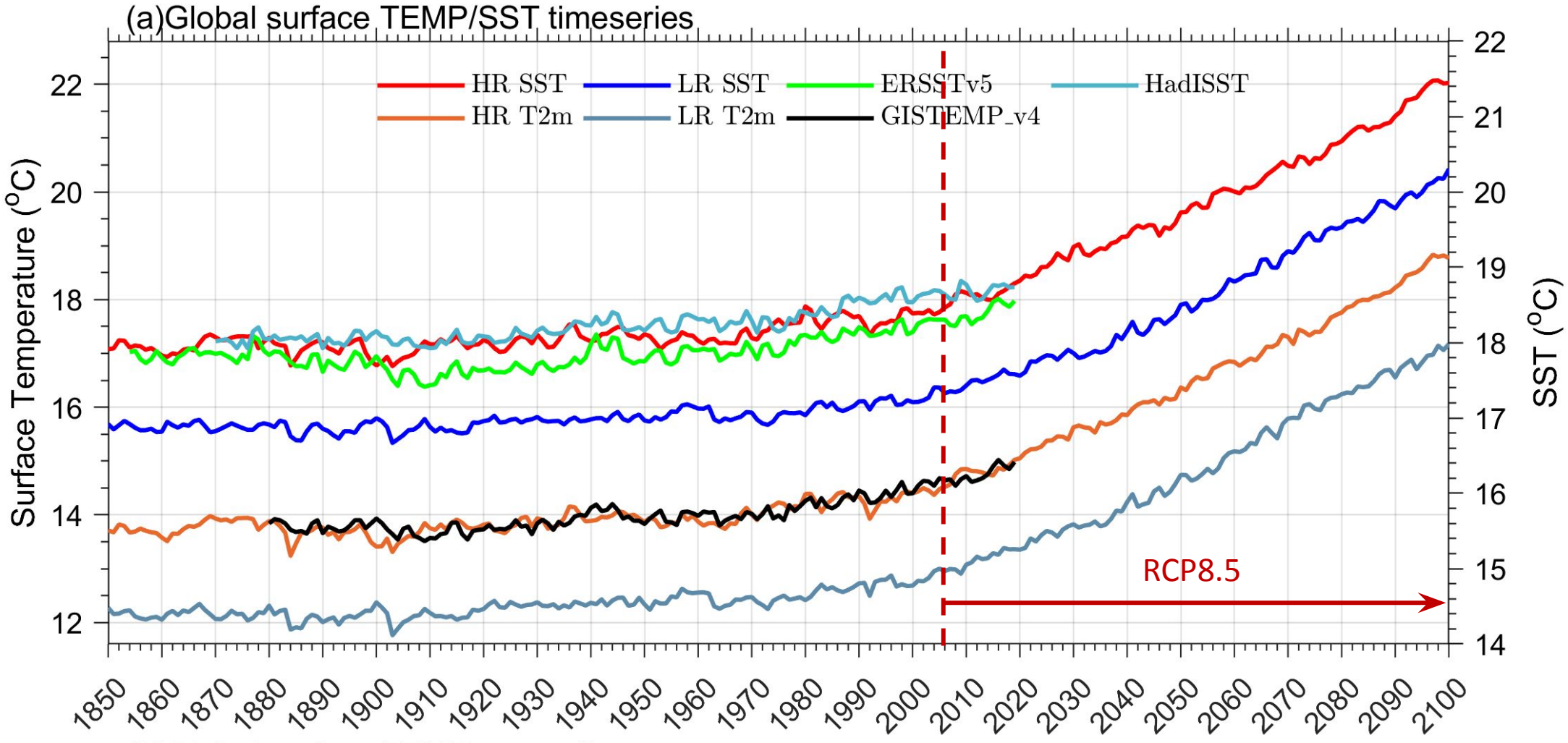

Chang et al. (2020)

Eastern Boundary Upwelling (EBU)

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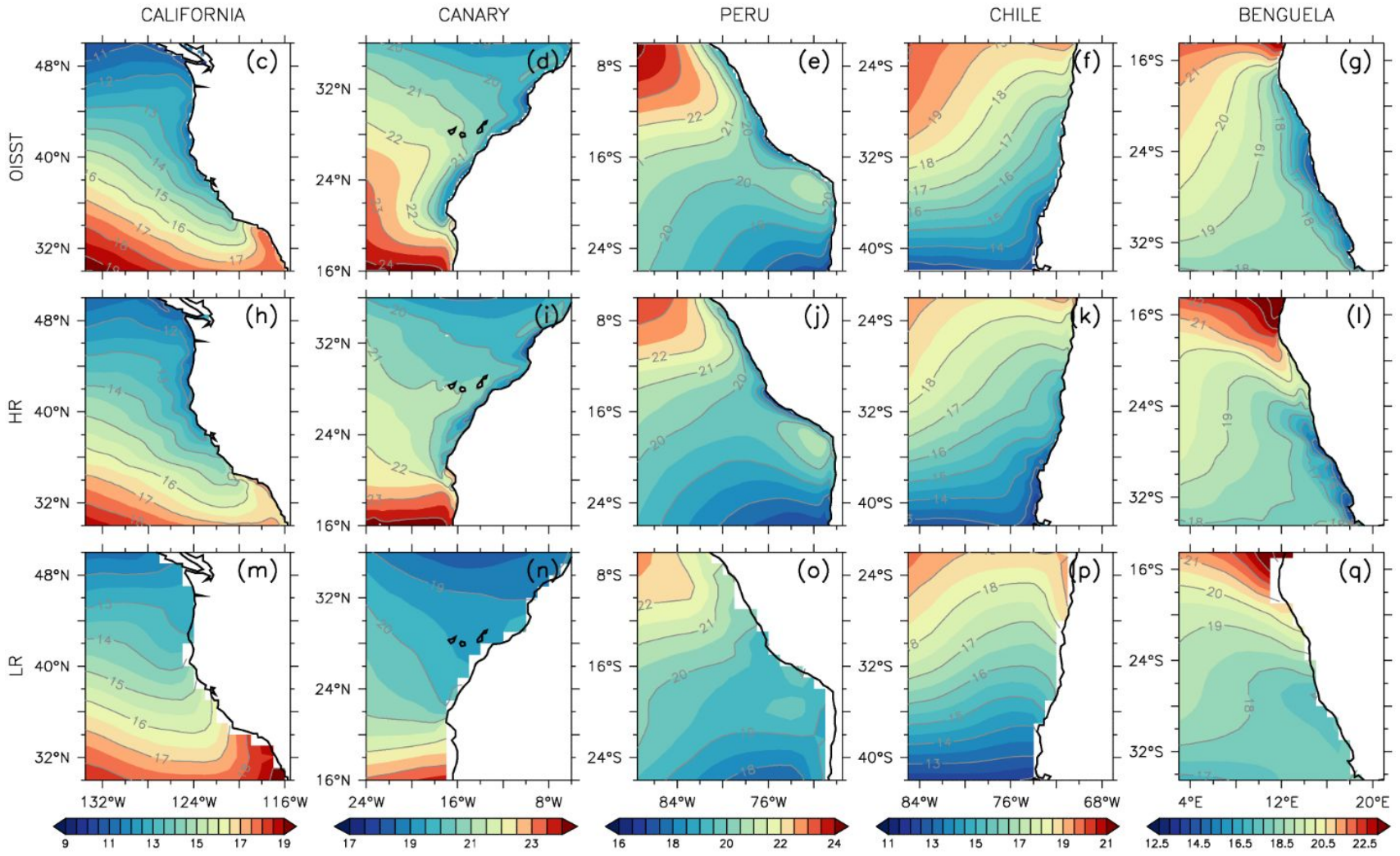
Observation →

CESM-HR →

CESM-LR →



CESM-HR provides more reliable projections of future ecosystem changes in EBUS → important for future fisheries planning

Chang et al. (2023)

Climate Sensitivity of CESM-HR/LR

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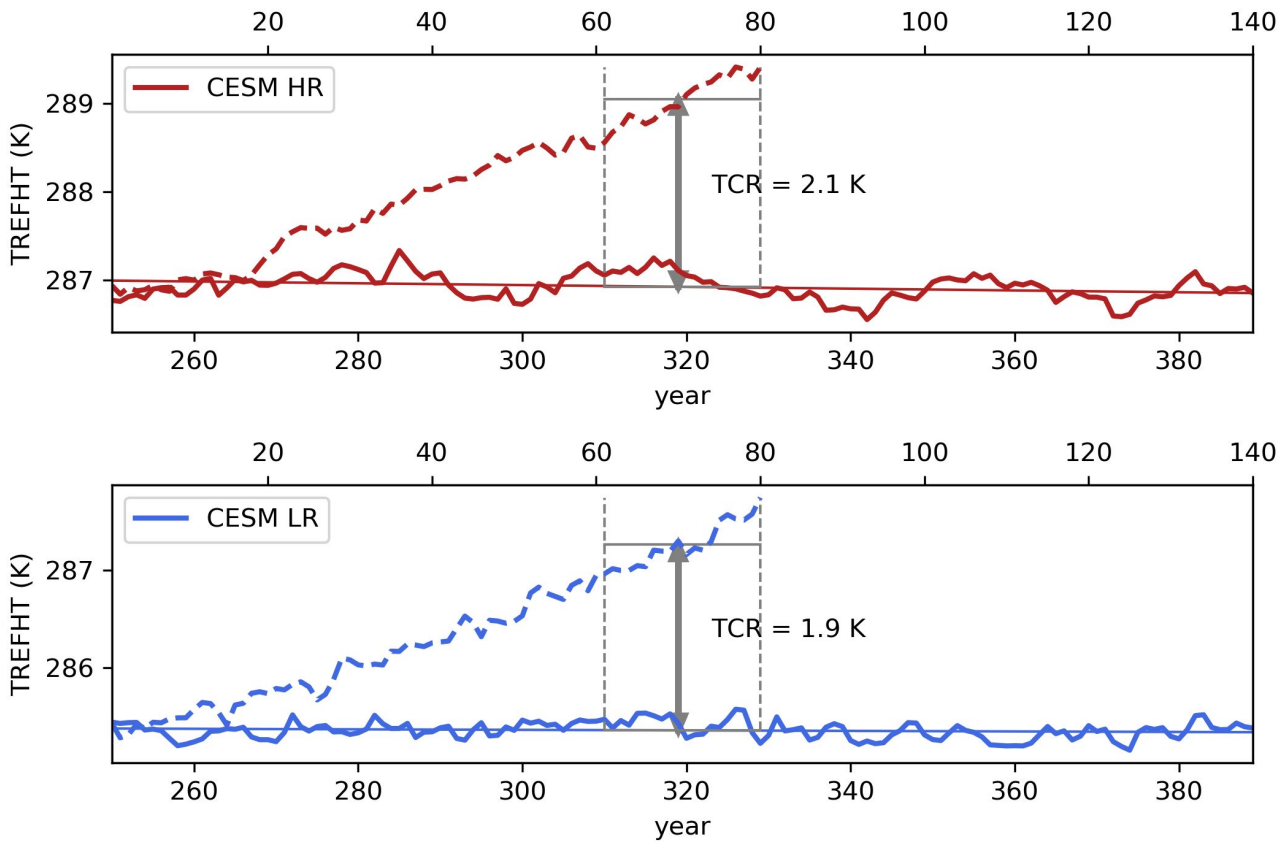
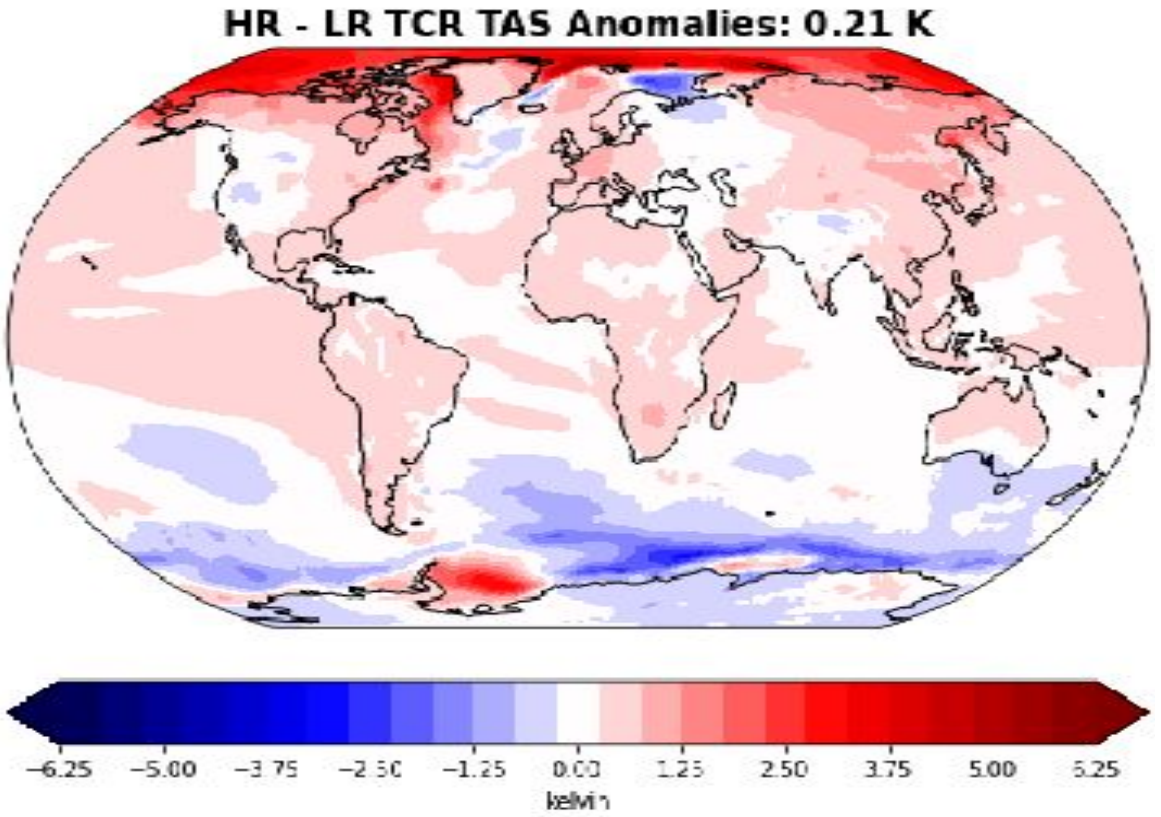
Transient Climate Response (TCR)



Courtesy of Castruccio



Courtesy of Cameron Rencurrel

Arctic amplification is stronger in CESM-HR due to enhanced ocean heat transport through the Bering Strait (Xu et al. 2024)

1980-2022 Climate Trends

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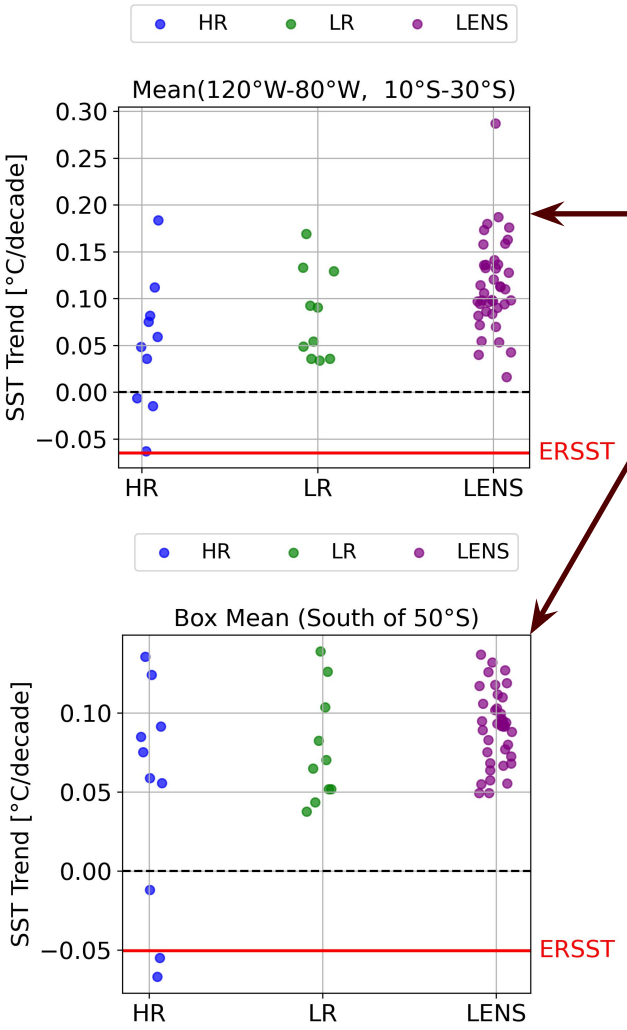
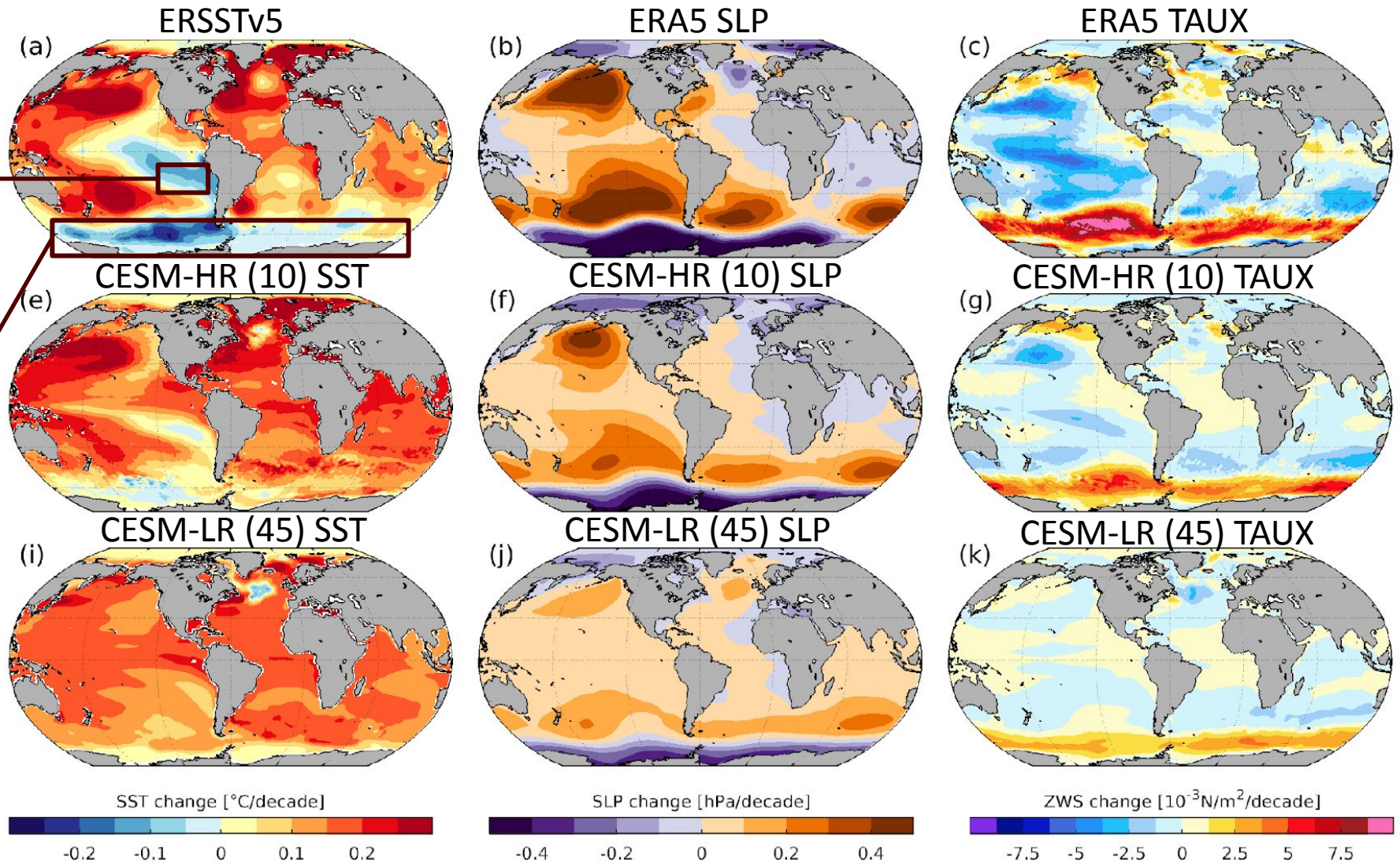


Courtesy of Xue Liu



Courtesy of Qiuying Zhang

Improved Decadal Predictions

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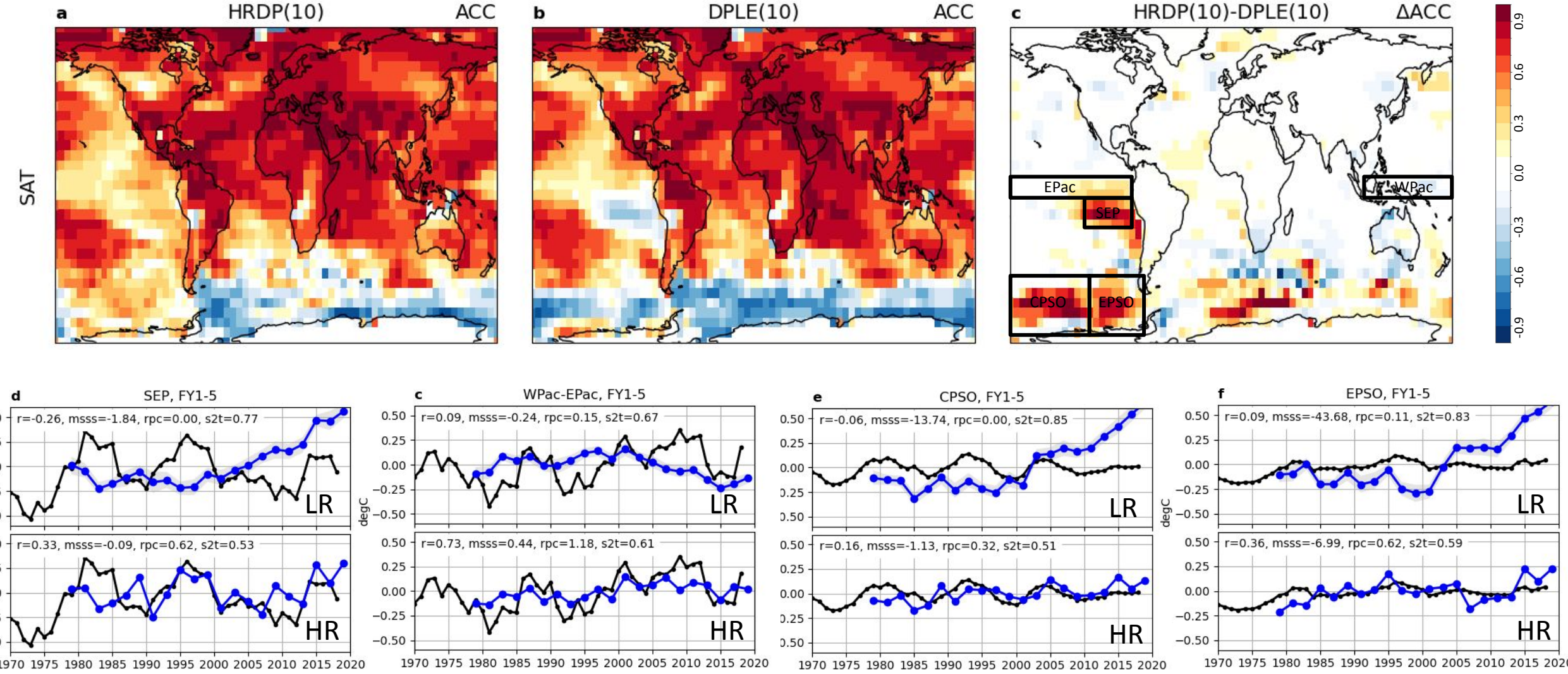

Yeager et al. (2023)

Improved Extreme Precipitation

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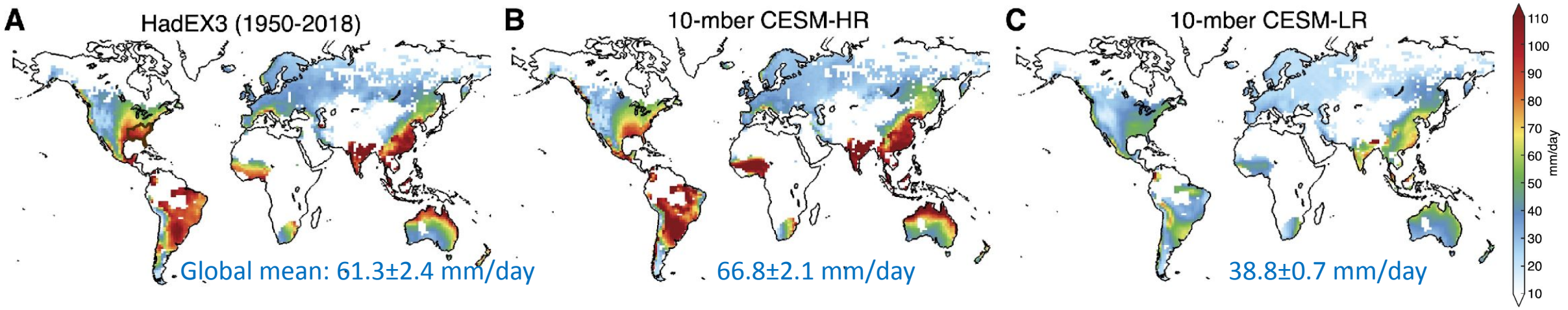
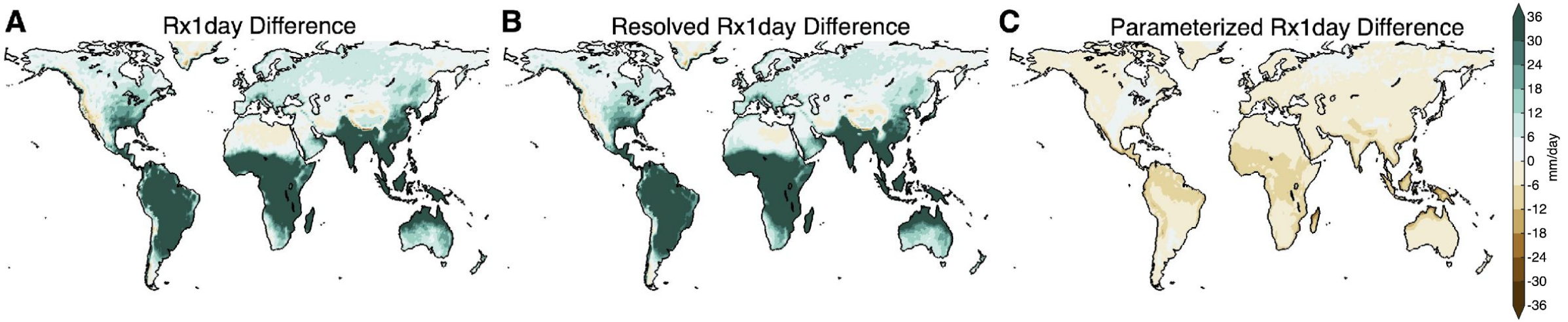
Annual Maximum Daily Precipitation (Rx1day)



Rx1day Difference Between CESM-HR and CESM-LR



Chang et al (2025, in rev.)

MCSs and Extreme Precipitation

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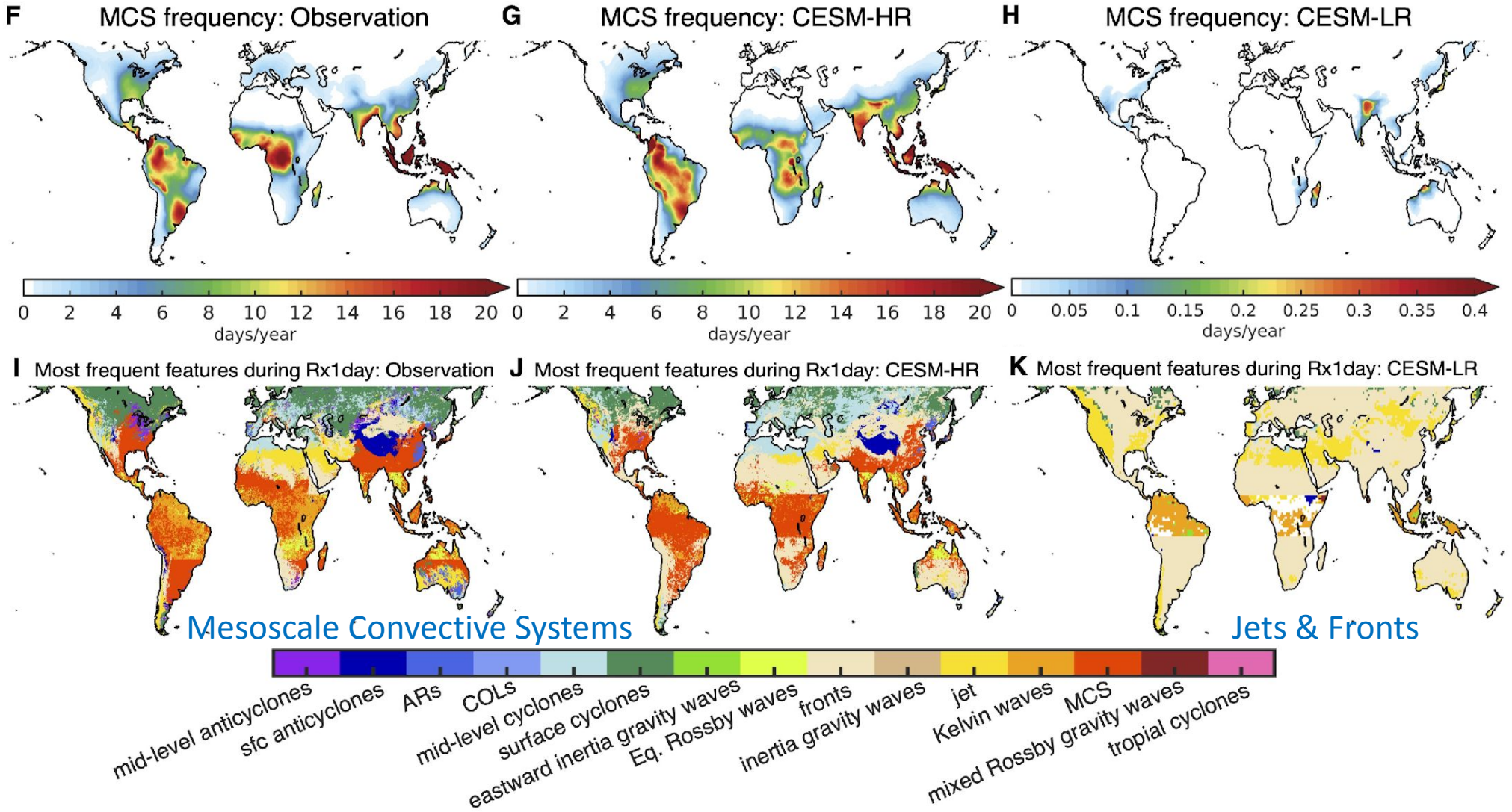
MCSs tracked by Multi-Obj. Anal. of Atmos.Phen. (MOAAP) (Prein et al. 2023)

Phenomena most frequently occur on Rx1day



Chang et al (2025, in rev.)

Future Changes in Rx1day and MCSs

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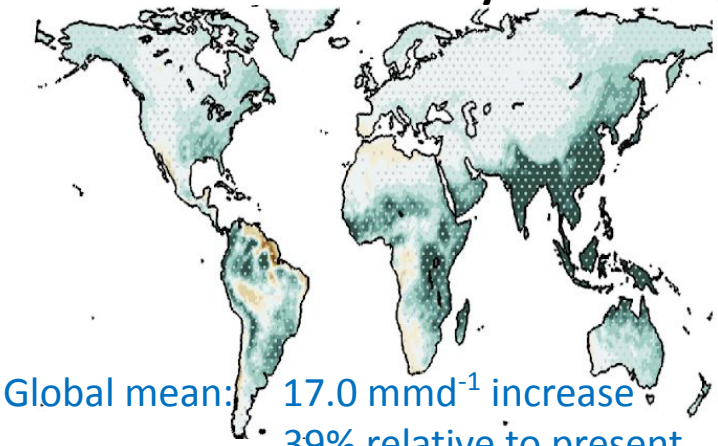
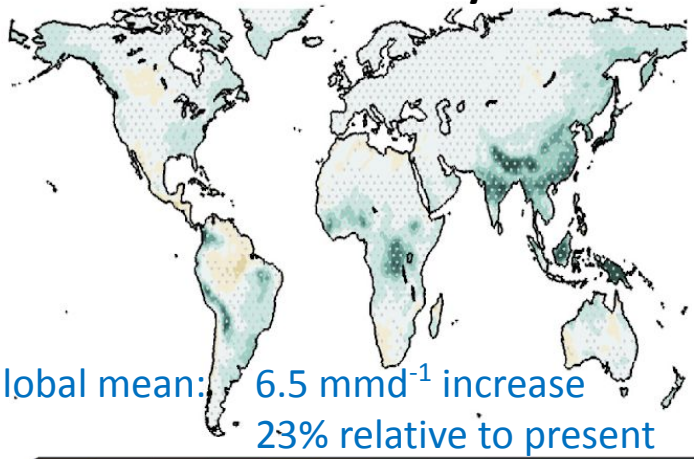
Future – Present Rx1day: CESM-HR

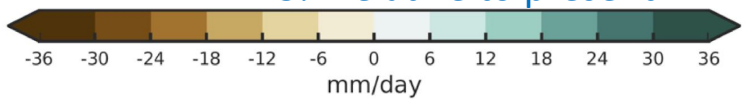


Global mean: 17.0 mmd^{-1} increase
39% relative to present

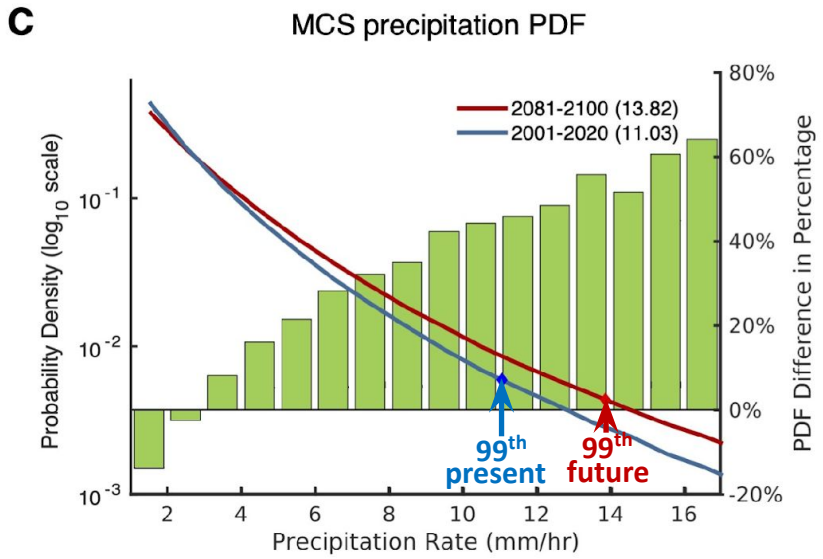
Future – Present Rx1 day: CESM-LR

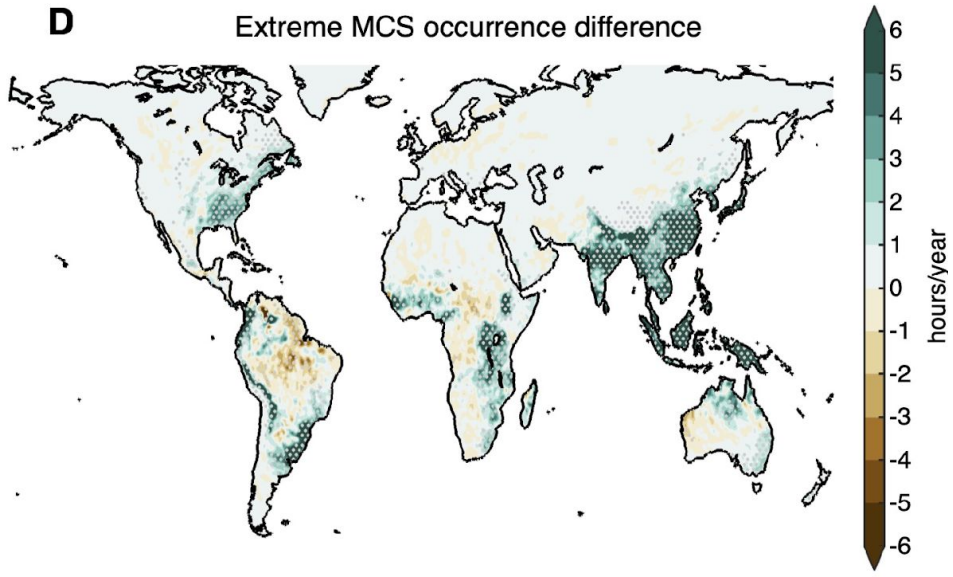


Global mean: 6.5 mmd^{-1} increase
23% relative to present



Future MCS Changes





The muted future Rx1day response in CESM-LR is due to its inability to capture intensifying MCSs under warmer climates, which CESM-HR does capture.

Chang et al (2025, in rev.)

Key Takeaways

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- **First HR (10–25 km) CMIP DECK ensembles released to the public**, including preindustrial control, historical, future climate scenarios, and decadal predictions
- **HR simulations offer substantial benefits**, such as reduced biases, improved prediction skills and signal-to-noise ratio, and more accurate representation of extreme events, particularly extreme precipitation and coastal sea-level rise, making them a more reliable tool for climate prediction and projection
- **While not resolving convection and submesoscale ocean features**, the HR model significantly improves simulation of mesoscale phenomena such as MCSs, ocean eddies, and their interaction with the atmosphere, representing a major step forward from conventional ~100 km CMIP models
- **These advances open new frontiers for research and technology**, including ML-based climate models, and novel diagnostics for understanding explicit and parameterized physics in climate modeling

Mesoscale Variability and Coupling

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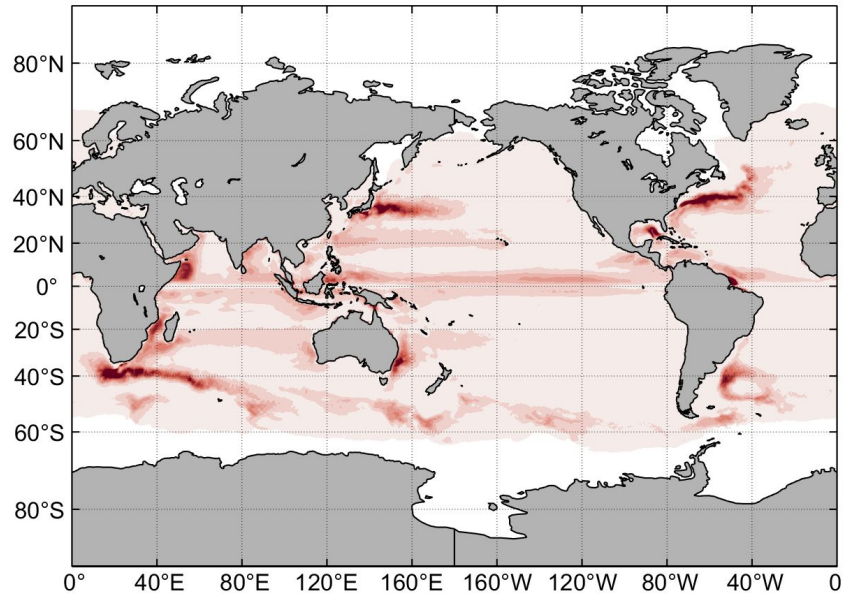
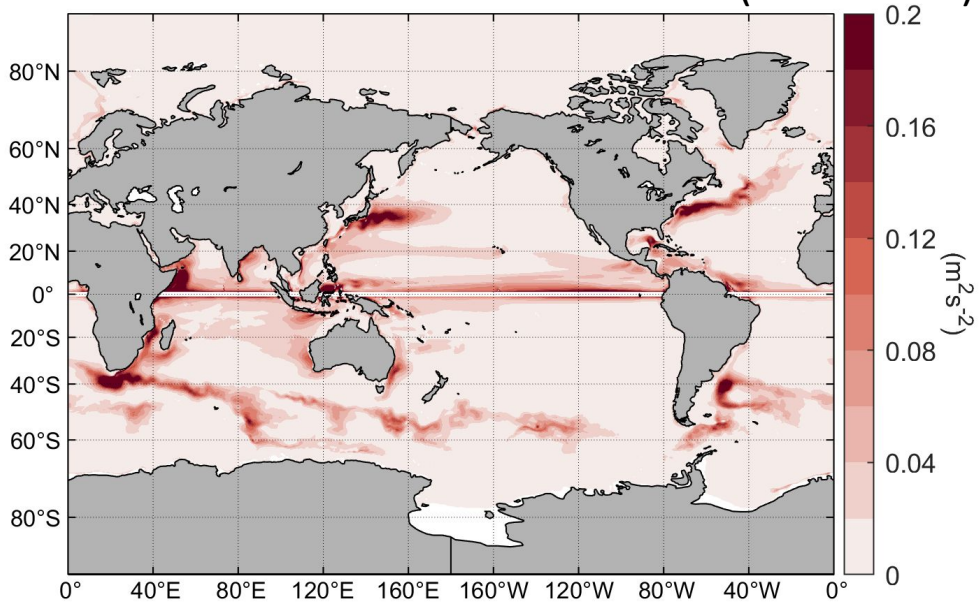
Observed EKE: DUACS (1993-2020)

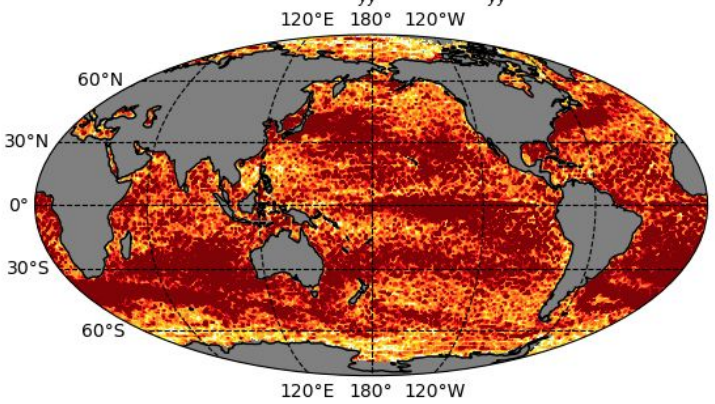


Modeled EKE: 10-mem Mean CESM-HR (1993-2020)

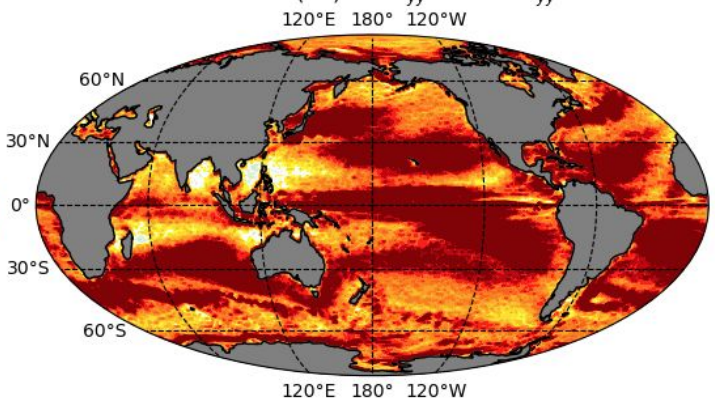


Courtesy of Gaopeng Xu

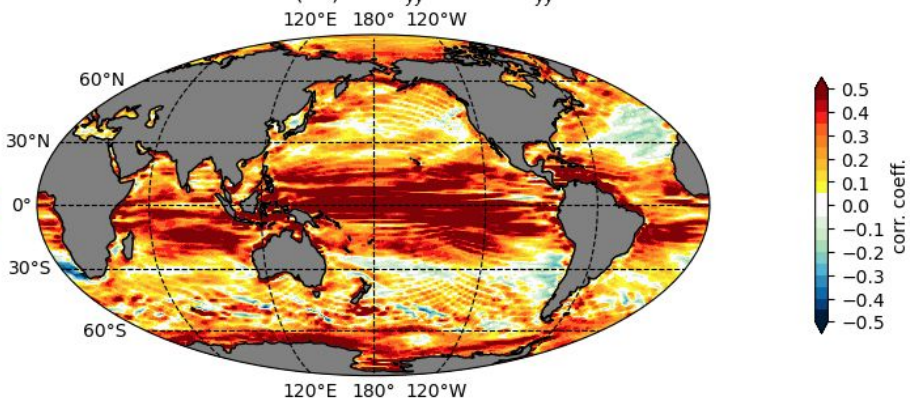
ERA5 $-SST_{yy}<->SLP_{yy}$



CESM-HR (10) $-SST_{yy}<->SLP_{yy}$



CESM-LR (10) $-SST_{yy}<->SLP_{yy}$



Courtesy of Travis Prochko