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High-Resolution Modeling Improves Regional Sea Level Trends in CESM

Interpreting the altimeter record with MESACLIP and implications for the future

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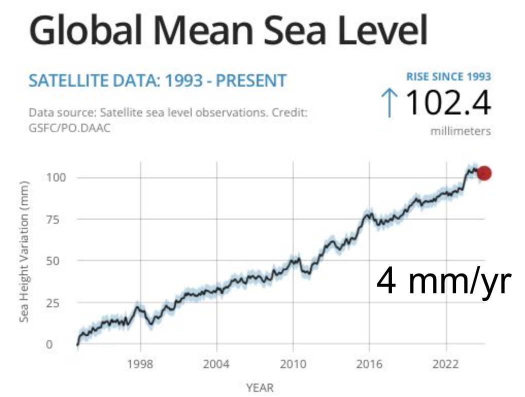
CESM Workshop 2025

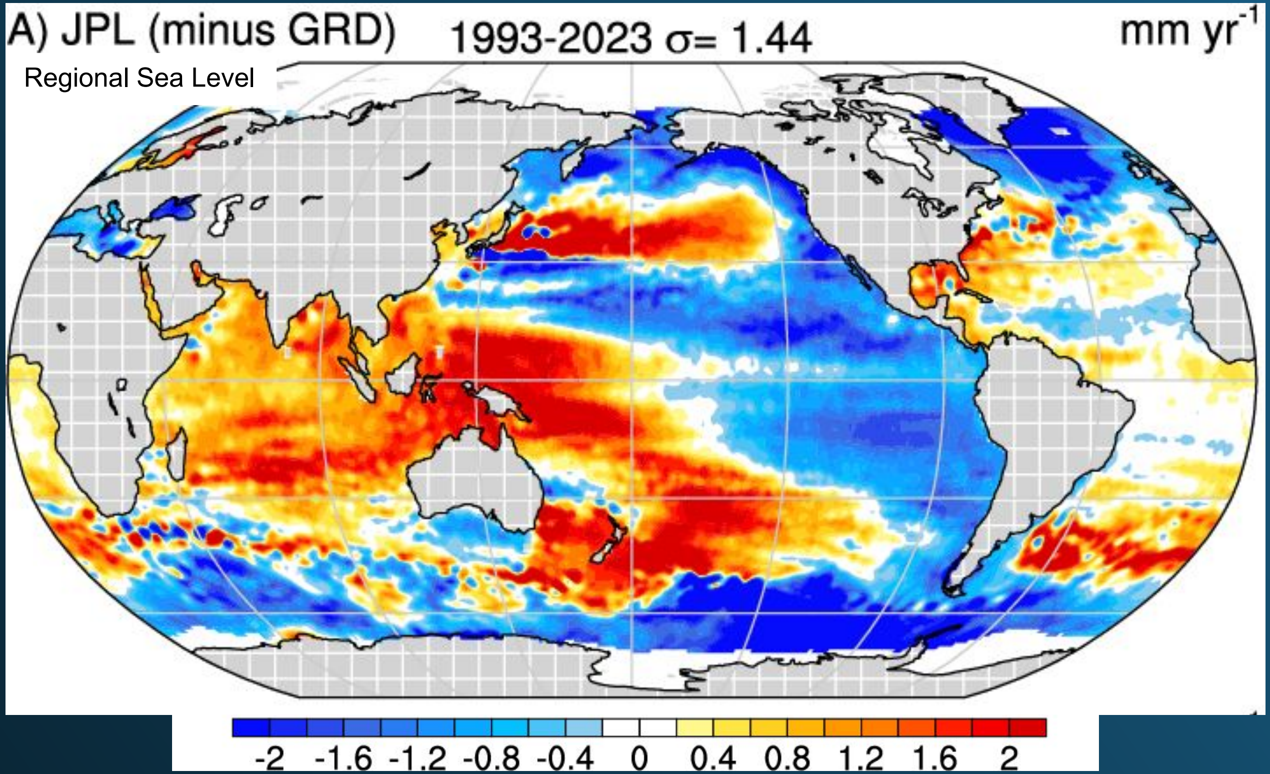
Background: Sea Level Observations



Global mean sea level rise is well understood
- driven by both ocean warming and mass gains
- changes are ~monotonic, weakly quadratic.

Regional sea level rise, is poorly understood
- can double the global rate of rise in some regions while eliminating it entirely in others.
- highly episodic and influenced by internal variability
- altimetry = huge investment, multiple missions, $$$

Key Questions (requiring models)
What drives this pattern? Is it forced?
How will it change in the future?



Background: Results from Large Ensembles

Fasullo and Nerem, 2018: we argued that climate model large ensembles suggest that the forced pattern is beginning to emerge, particularly in the Atlantic and Southern Oceans. [correlations with FR unlikely random]

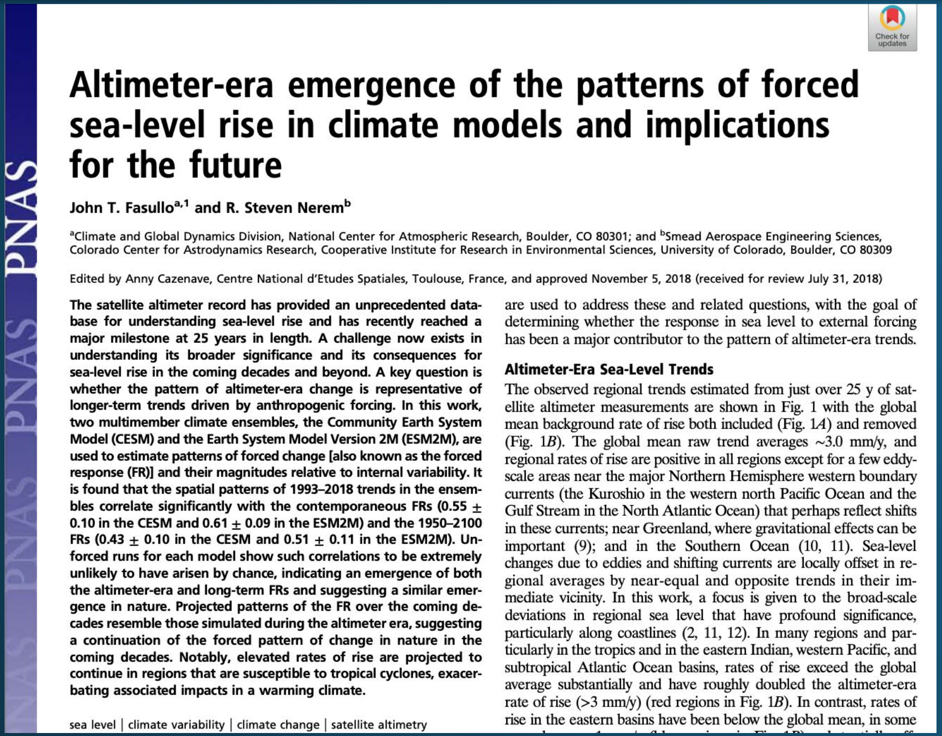
The pattern largely persists into the future.

This analysis used the CESM1-LE and GFDL-ESM2M-LE

Key Questions

Are the models used fit-for-purpose?

Are the results robust to model resolution?



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Altimeter-era emergence of the patterns of forced sea-level rise in climate models and implications for the future

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Edited by Anny Cazenave, Centre National d'Etudes Spatiales, Toulouse, France, and approved November 5, 2018 (received for review July 31, 2018)

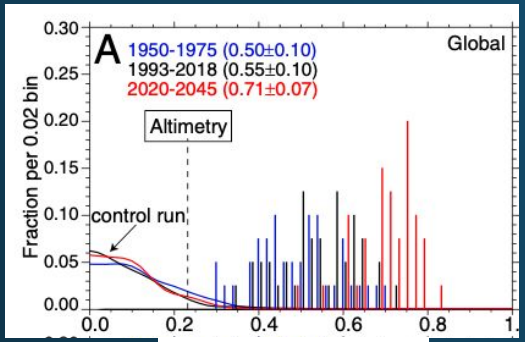
The satellite altimeter record has provided an unprecedented database for understanding sea-level rise and has recently reached a major milestone at 25 years in length. A challenge now exists in understanding its broader significance and its consequences for sea-level rise in the coming decades and beyond. A key question is whether the pattern of altimeter-era change is representative of longer-term trends driven by anthropogenic forcing. In this work, two multimember climate ensembles, the Community Earth System Model (CESM) and the Earth System Model Version 2M (ESM2M), are used to estimate patterns of forced change [also known as the forced response (FR)] and their magnitudes relative to internal variability. It is found that the spatial patterns of 1993–2018 trends in the ensembles correlate significantly with the contemporaneous FRs (0.55 ± 0.10 in the CESM and 0.61 ± 0.09 in the ESM2M) and the 1950–2100 FRs (0.43 ± 0.10 in the CESM and 0.51 ± 0.11 in the ESM2M). Unforced runs for each model show such correlations to be extremely unlikely to have arisen by chance, indicating an emergence of both the altimeter-era and long-term FRs and suggesting a similar emergence in nature. Projected patterns of the FR over the coming decades resemble those simulated during the altimeter era, suggesting a continuation of the forced pattern of change in nature in the coming decades. Notably, elevated rates of rise are projected to continue in regions that are susceptible to tropical cyclones, exacerbating associated impacts in a warming climate.

sea level | climate variability | climate change | satellite altimetry

are used to address these and related questions, with the goal of determining whether the response in sea level to external forcing has been a major contributor to the pattern of altimeter-era trends.

Altimeter-Era Sea-Level Trends

The observed regional trends estimated from just over 25 y of satellite altimeter measurements are shown in Fig. 1 with the global mean background rate of rise both included (Fig. 1*A*) and removed (Fig. 1*B*). The global mean raw trend averages ~3.0 mm/y, and regional rates of rise are positive in all regions except for a few eddy-scale areas near the major Northern Hemisphere western boundary currents (the Kuroshio in the western north Pacific Ocean and the Gulf Stream in the North Atlantic Ocean) that perhaps reflect shifts in these currents; near Greenland, where gravitational effects can be important (9); and in the Southern Ocean (10, 11). Sea-level changes due to eddies and shifting currents are locally offset in regional averages by near-equal and opposite trends in their immediate vicinity. In this work, a focus is given to the broad-scale deviations in regional sea level that have profound significance, particularly along coastlines (2, 11, 12). In many regions and particularly in the tropics and in the eastern Indian, western Pacific, and subtropical Atlantic Ocean basins, rates of rise exceed the global average substantially and have roughly doubled the altimeter-era rate of rise (>3 mm/y) (red regions in Fig. 1*B*). In contrast, rates of rise in the eastern basins have been below the global mean, in some

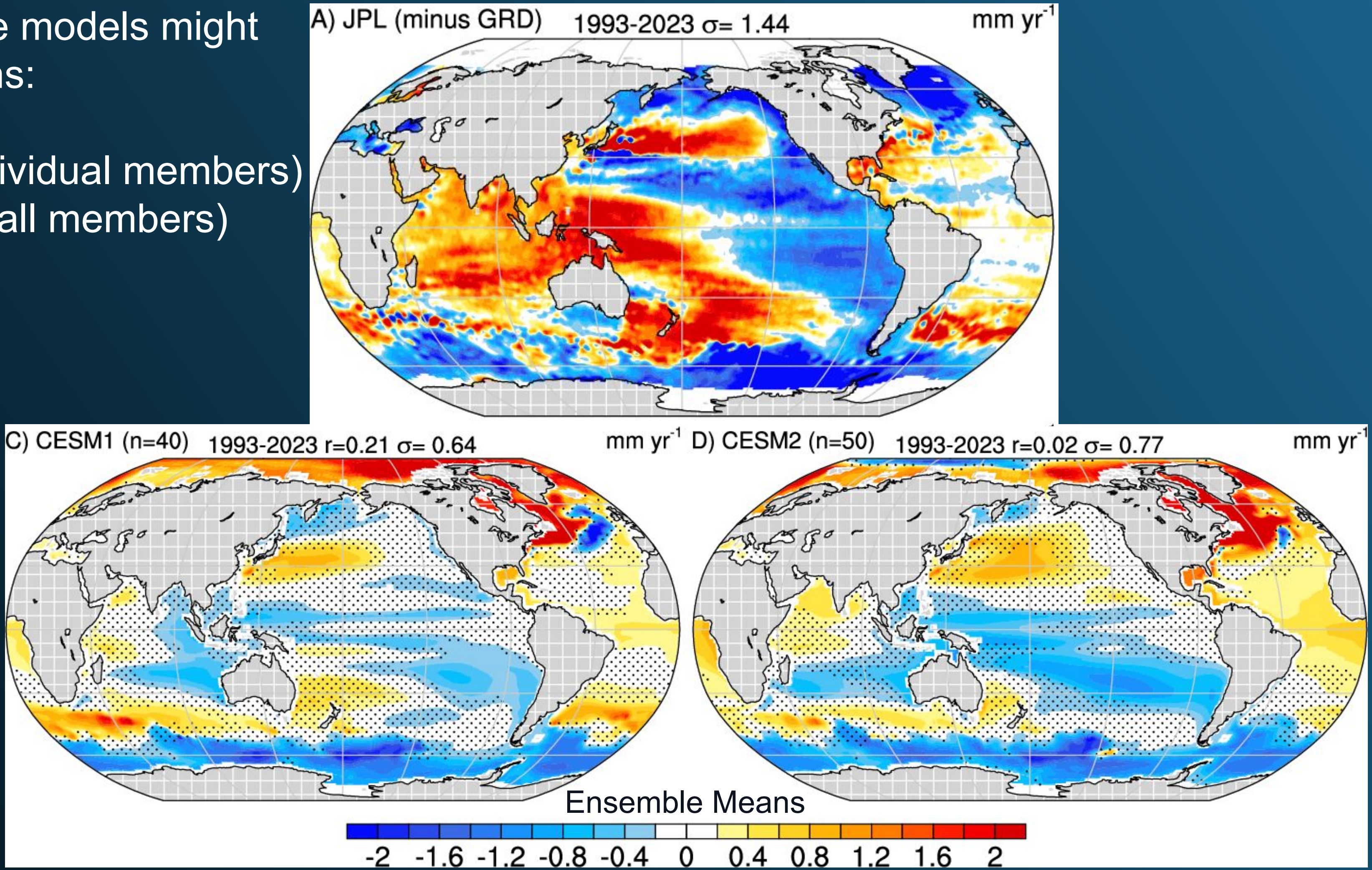


Pattern correlations

Background: Models Fit-for-Purpose?

In 2018, we had some concerns that the models might not be fit-for-purpose. Simulated patterns:

1. were weaker than altimetry (also individual members)
2. didn't agree with altimetry (r<0.4 for all members)



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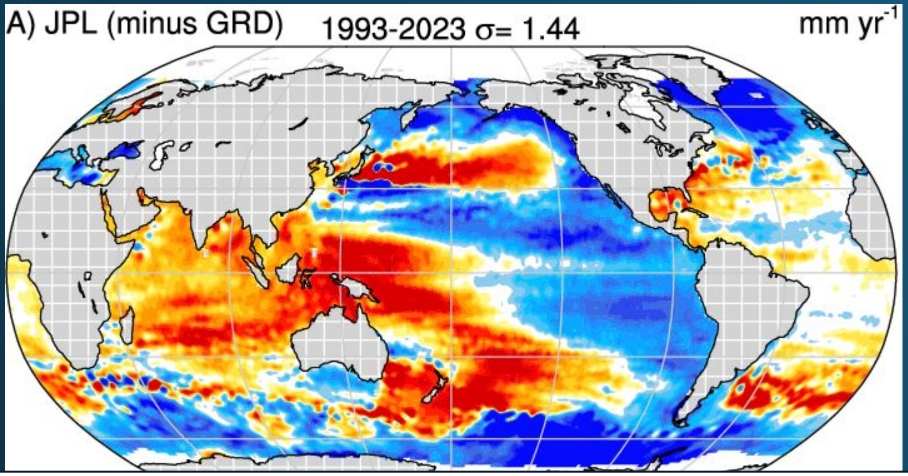
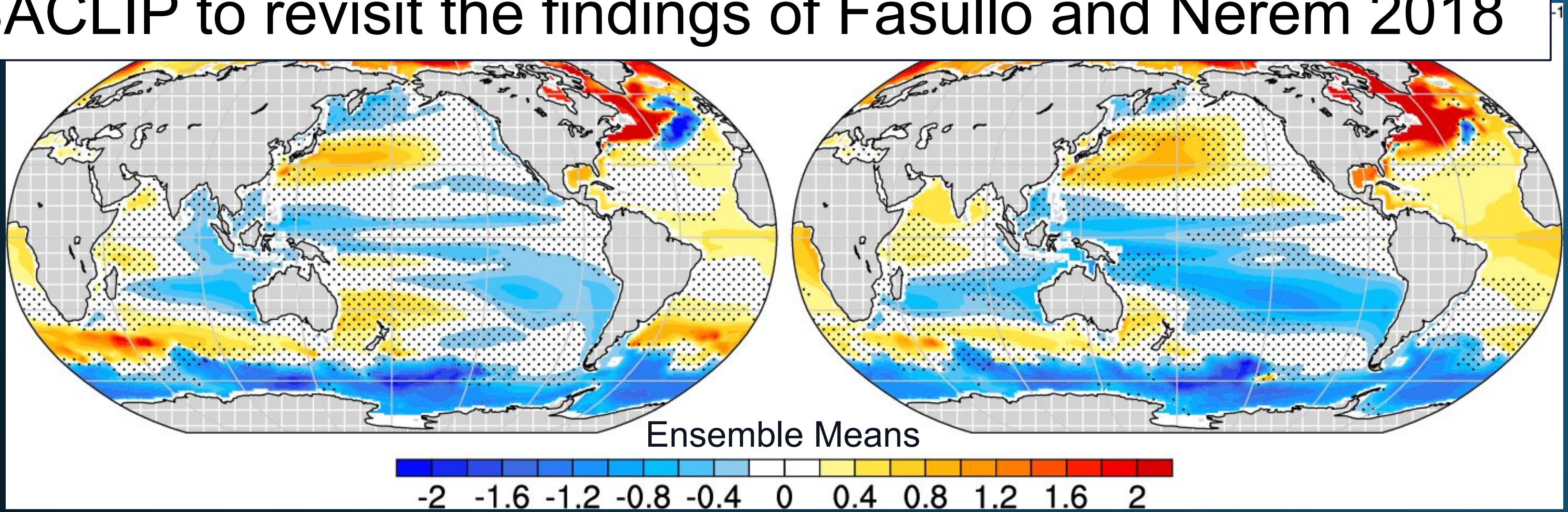


Our goal here is to use MESACLIP to revisit the findings of Fasullo and Nerem 2018



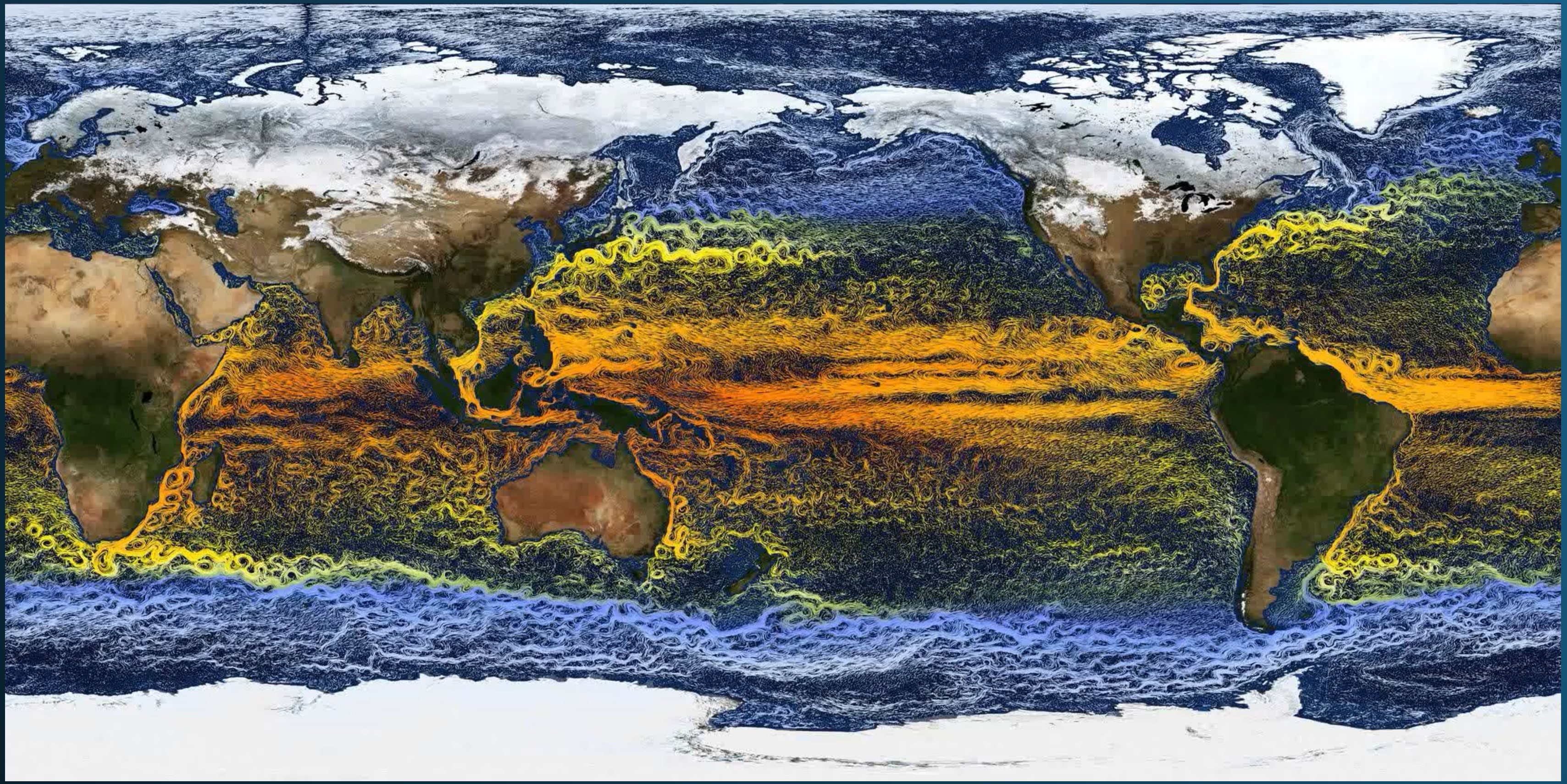
Models and Methods

MESACLIP
10-members: 1920-2100
0.25 degree atmosphere/land
0.10 degree ocean/sea ice
Companion nominal 1º version

Altimeter Data
JPL altimeter grids: Willis et al. 2024 doc.

To compare models against altimetry, GRD effects are accounted for [gravity, rotation, deform.]. We account for gravitational fingerprints and VLM from GIA and present-day Δ loading.

All fields regridded to 1º, area-weighted pattern correlations and RMS pattern magnitudes are used.



Results: Simulated Patterns

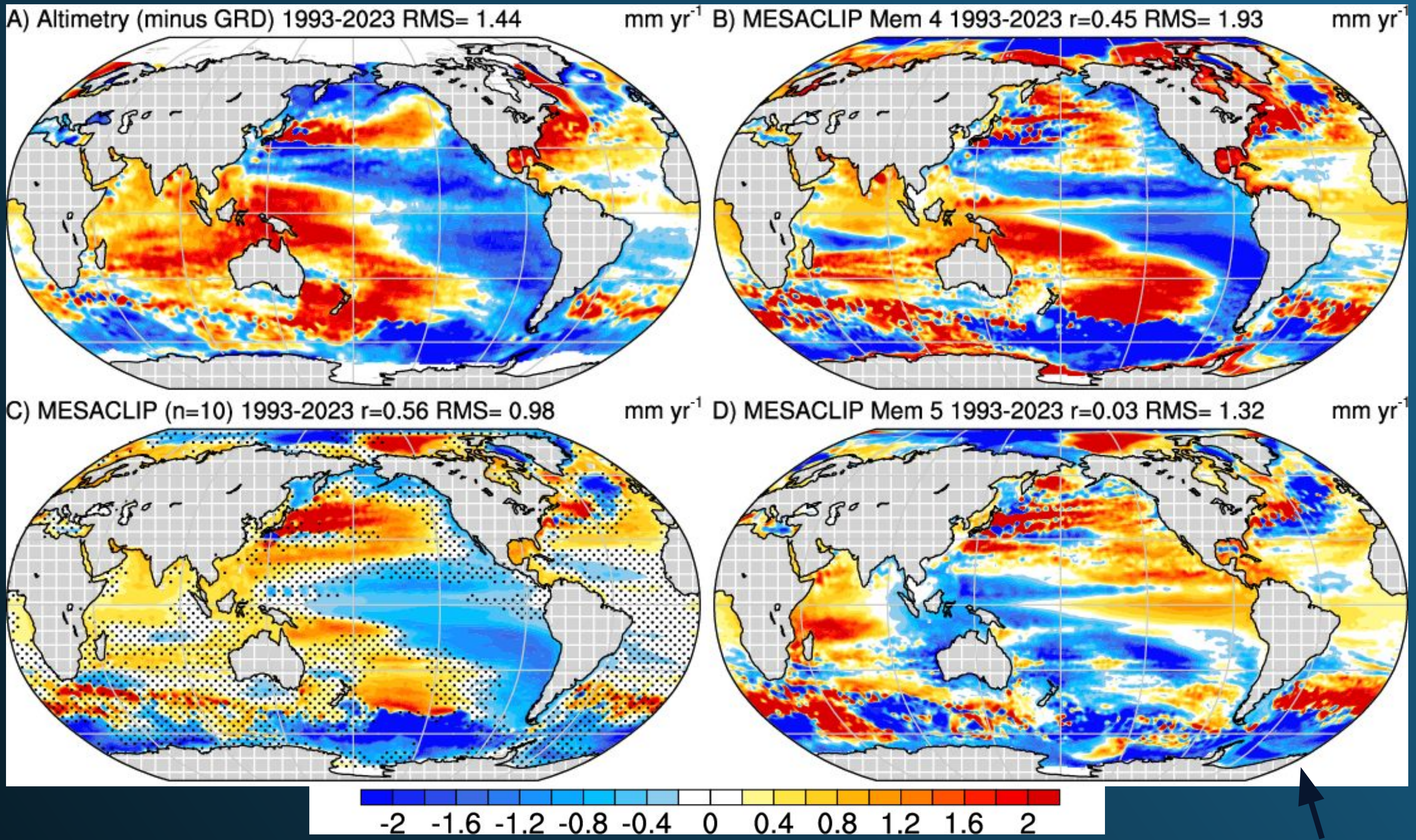
Key Points

1. Some MESACLIP members closely match altimetry in both pattern and magnitude (B).

2. MESACLIP ensemble mean (C) correlates well with altimetry – stronger than any other model or member – exhibits forced La Niña.

3. MESACLIP pattern strength is also consistent with observations (B).

4. Emergent regions now include broad portions of the Pacific and Indian Oceans (C) [but not tropical Atlantic].



Not all members correlate well
Internal variability remains important

Results: Simulated Patterns : Taylor Plot Summaries

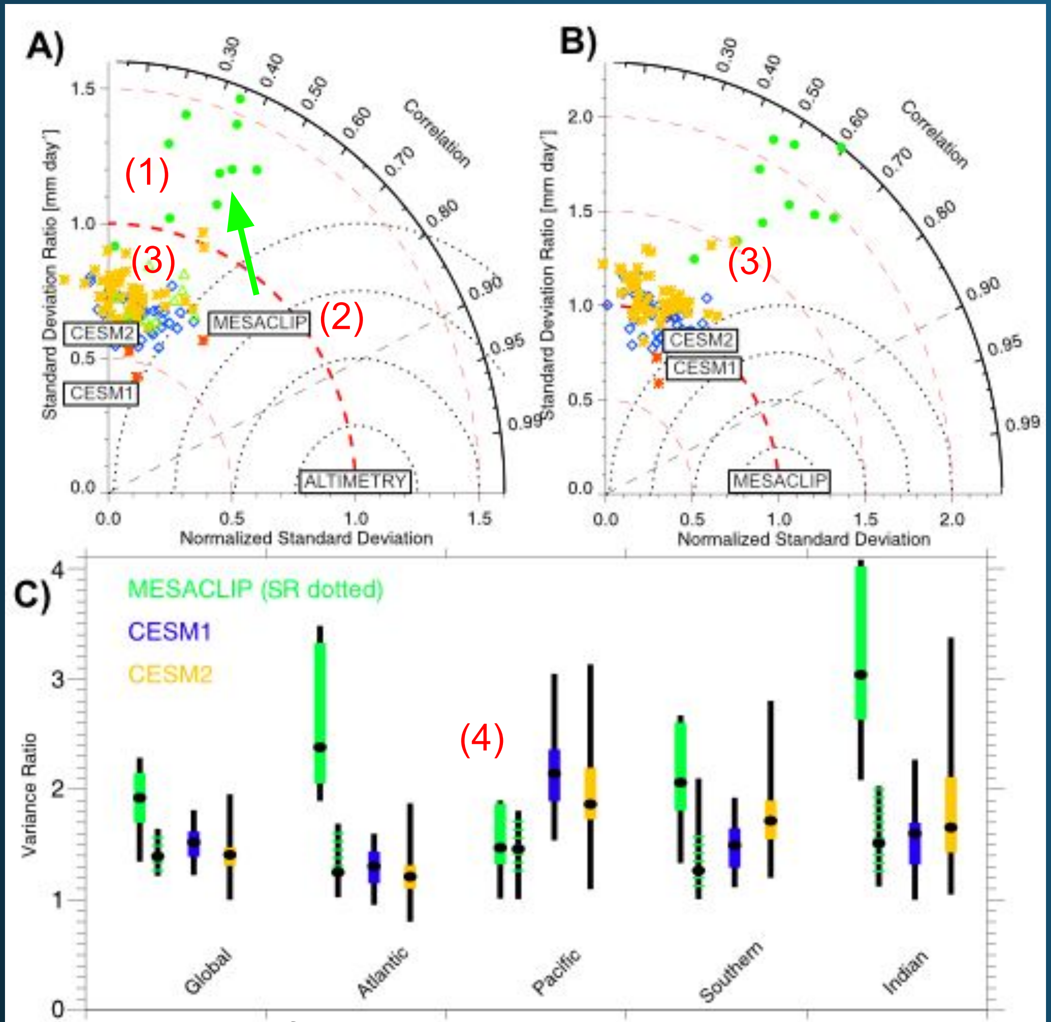
Key Points

1. Individual MESACLIP members exhibit systematically stronger patterns, SD ratios encompass observation.

2. MESACLIP ensemble mean correlates well with altimetry – stronger than any CMIP5/6 model.

3. MESACLIP HR members exhibit systematic differences from CESM1.3 1º and CESM1/2 LE members.

4. Ratio of MESACLIP pattern strength in EM vs members is greater in all basins except Pacific Ocean.

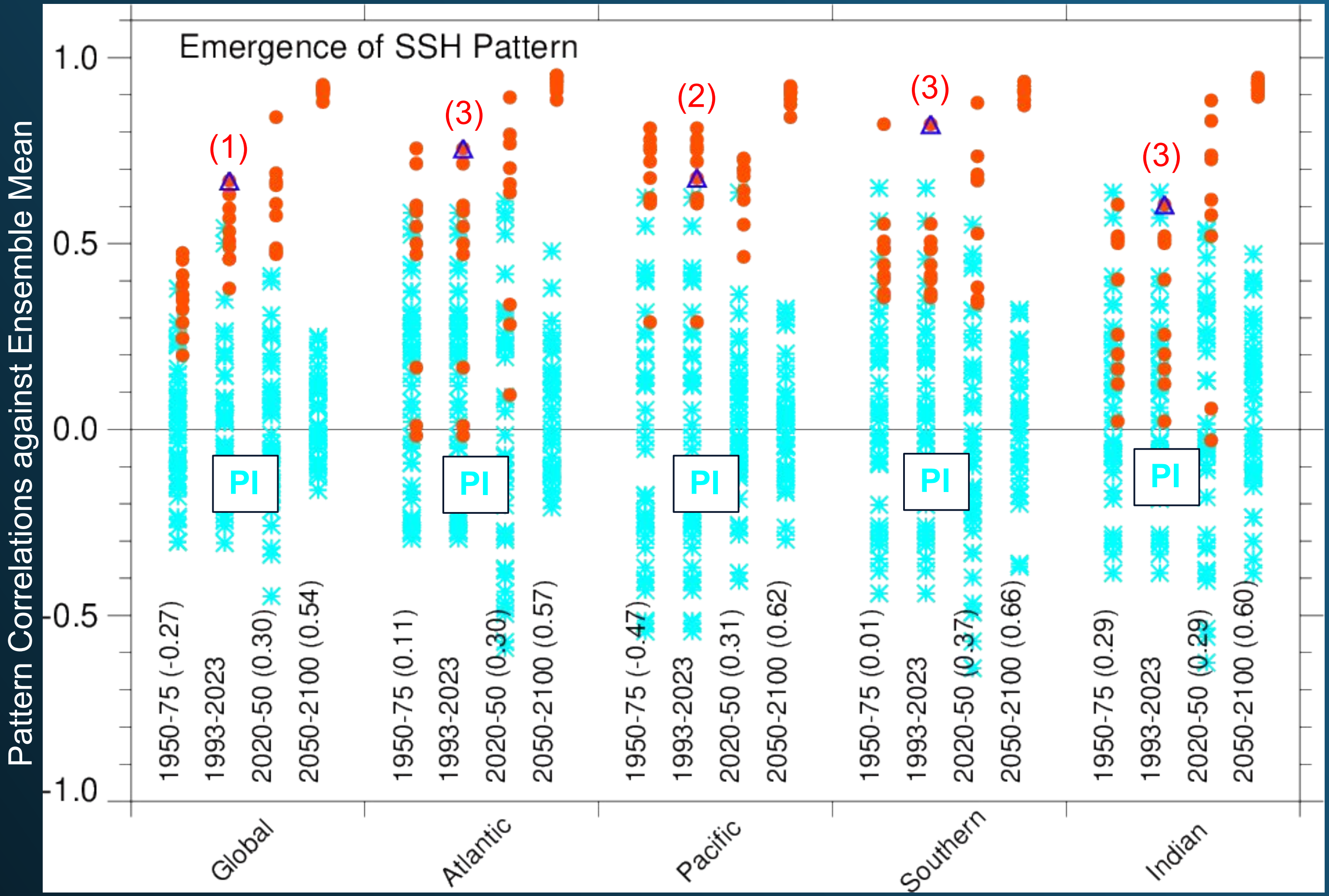


Ratio of member variance to EM variance

Results: Emergence

Key Points

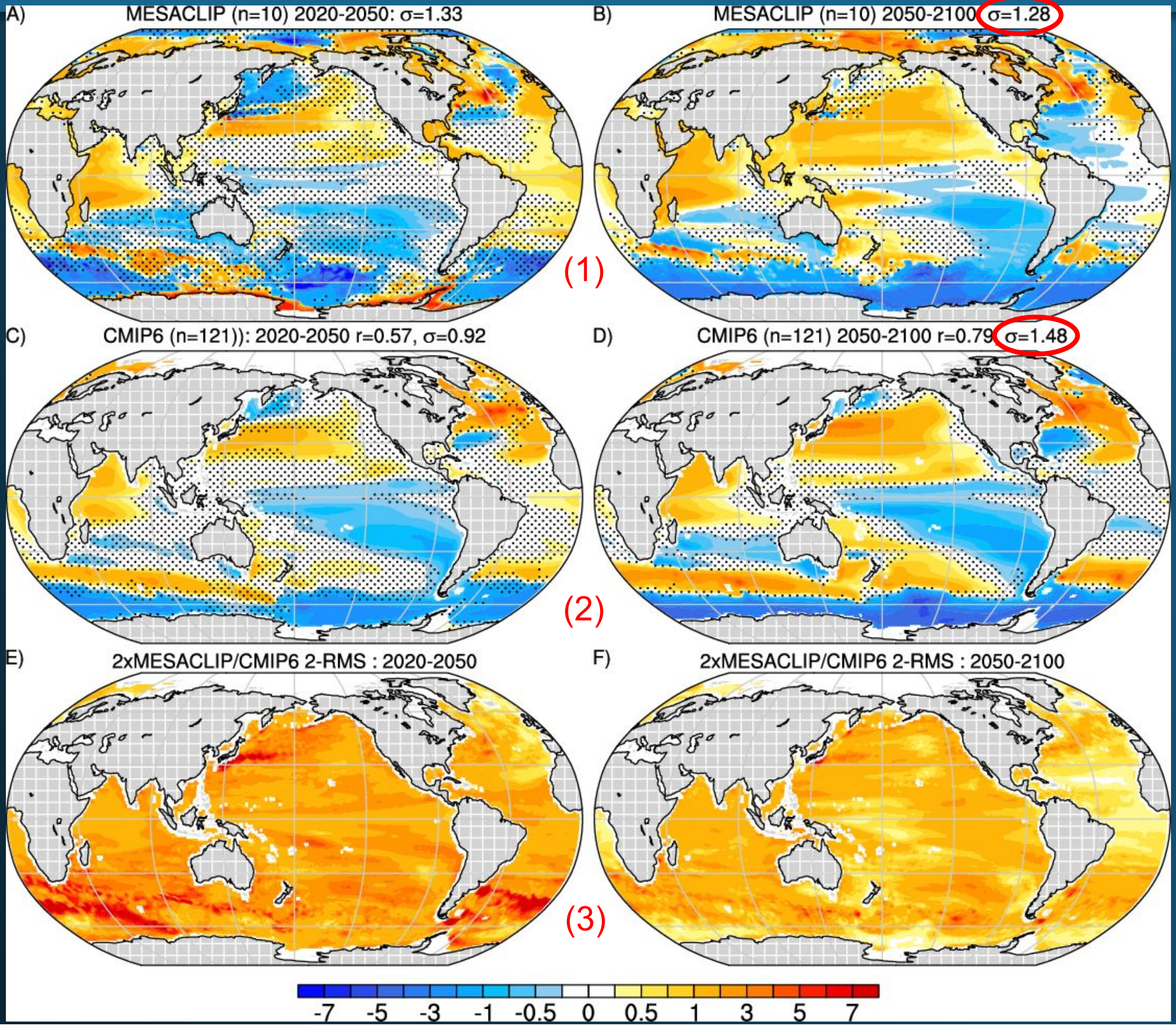
1. Global emergence of 1993-2023 trends is evident at $p<0.1$ with all but 3 (of 40) pre-industrial segments correlating weaker than weakest MESACLIP member
2. Emergence is strongest in the Pacific
3. Member 4 has strongest global correlation due mainly to basins aside from the Pacific where most members exhibit greater consistency with altimetry.



Results: Projected Trends

Key Points

1. The altimeter-era forced La Niña-like pattern weakens in the future. Hemispheric asymmetry strengthens: NH>SH.
2. CMIP6 MMM pattern becomes more similar to MESACLIP over time (r=0.79 for 2050-2100) and is stronger than MESACLIP for 2050-2100.
3. MESACLIP ensemble spread (σ) is greater than CMIP6 – suggests a broader range of possible outcomes.



Conclusions

1. MESACLIP produces sea level trends that are more consistent with altimetry in pattern (La Niña) and strength (stronger) than CESM1/2 LE and CMIP6 models.

2. MESACLIP's altimeter-era forced response is strongly La Niña-like. (relevant to pattern effect discussion).

3. MESACLIP confirms the emergence of the global trend pattern, despite simulating significant additional variance in both the FR and internal variability.

Conclusions

1. MESACLIP produces sea level trends that are more consistent with altimetry in pattern (La Niña) and strength (stronger) than CESM1/2 LE and CMIP6 models.

2. MESACLIP's altimeter-era forced response is strongly La Niña-like. (relevant to pattern effect discussion).

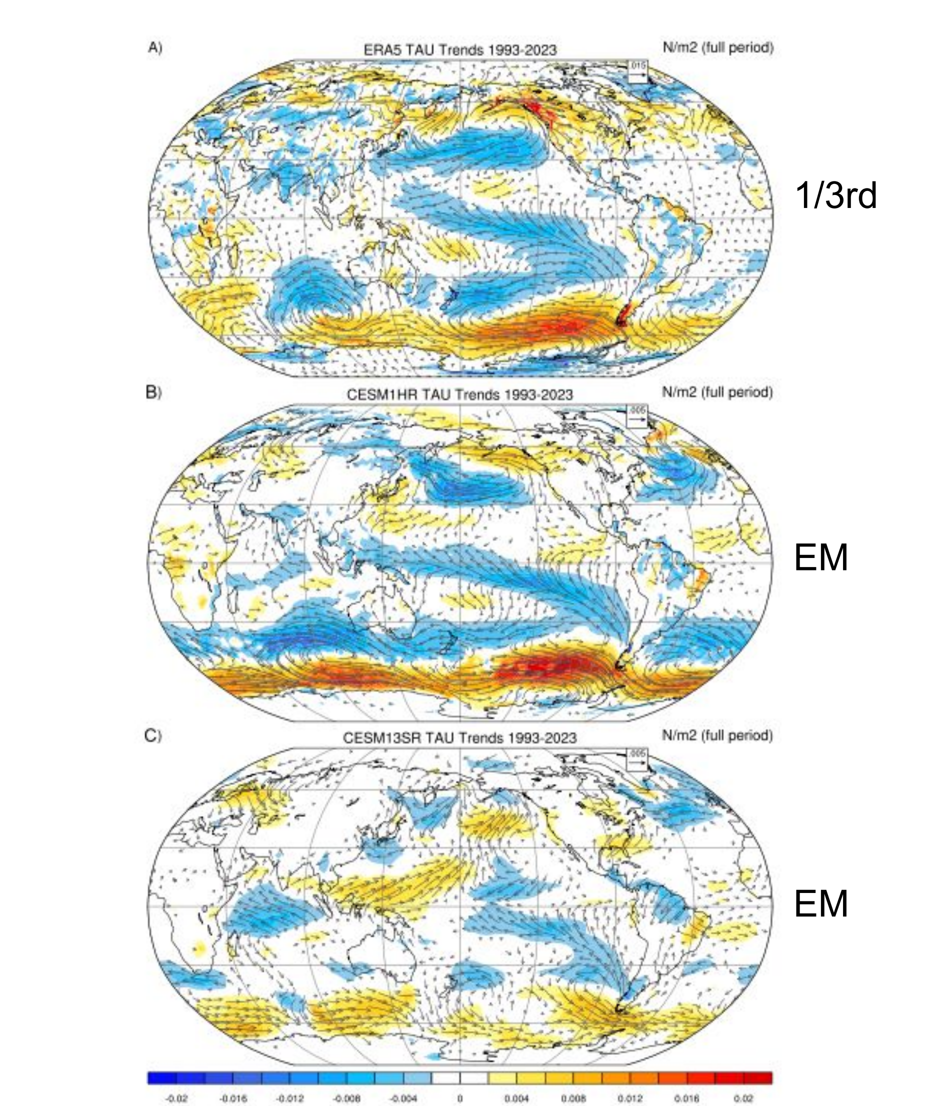
3. MESACLIP confirms the emergence of the global trend pattern, despite simulating significant additional variance in both the FR and internal variability.

4. The spatial structure of emergence is shifted into the Indo-Pacific domain.

5. Trend patterns in MESACLIP and CMIP6 become more similar in the mid/late 21st C though MESACLIP has a broader ensemble spread.

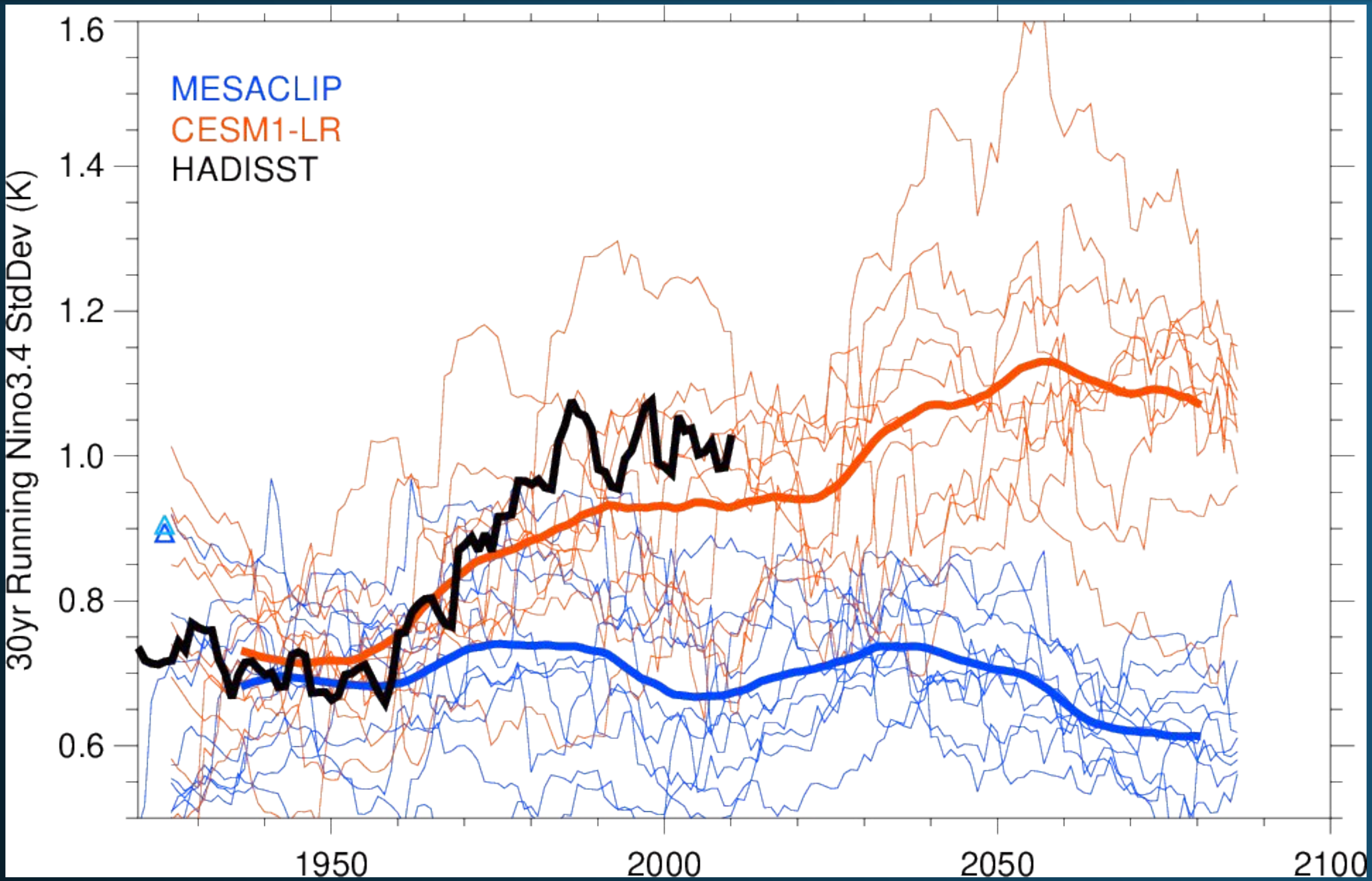
Extra Slides: Physical Drivers of the Pattern

MESACLIP better reproduces observed wind stress trend patterns and magnitudes – and these are key drivers of the regional sea level rise pattern.



Extra Slides: Is ENSO too weak in MESACLIP?

ENSO may be too weak in MESACLIP, with 30-yr running σ similar to observed from 1920-1950 but with no members capturing present-day observed variability.



Altimeter-Era Regional Sea Level Trends

Observed (top left) and simulated ensemble-mean trends in regional sea level (global-mean, GRD removed).

Pattern **correlation** between observed and ensemble mean sea level increases in MESACLIP runs (0.59) vs LR (0.21, 0.02).

Pattern **strength** also increases with high resolution (though not appropriate to directly compare these ensemble means to observations – a single realization).

MESACLIP changes the spatial distribution of regions with detectable change (un-stippled), from the Atlantic in LR and into Indo-Pacific in MESACLIP. Southern ocean response strengthens.

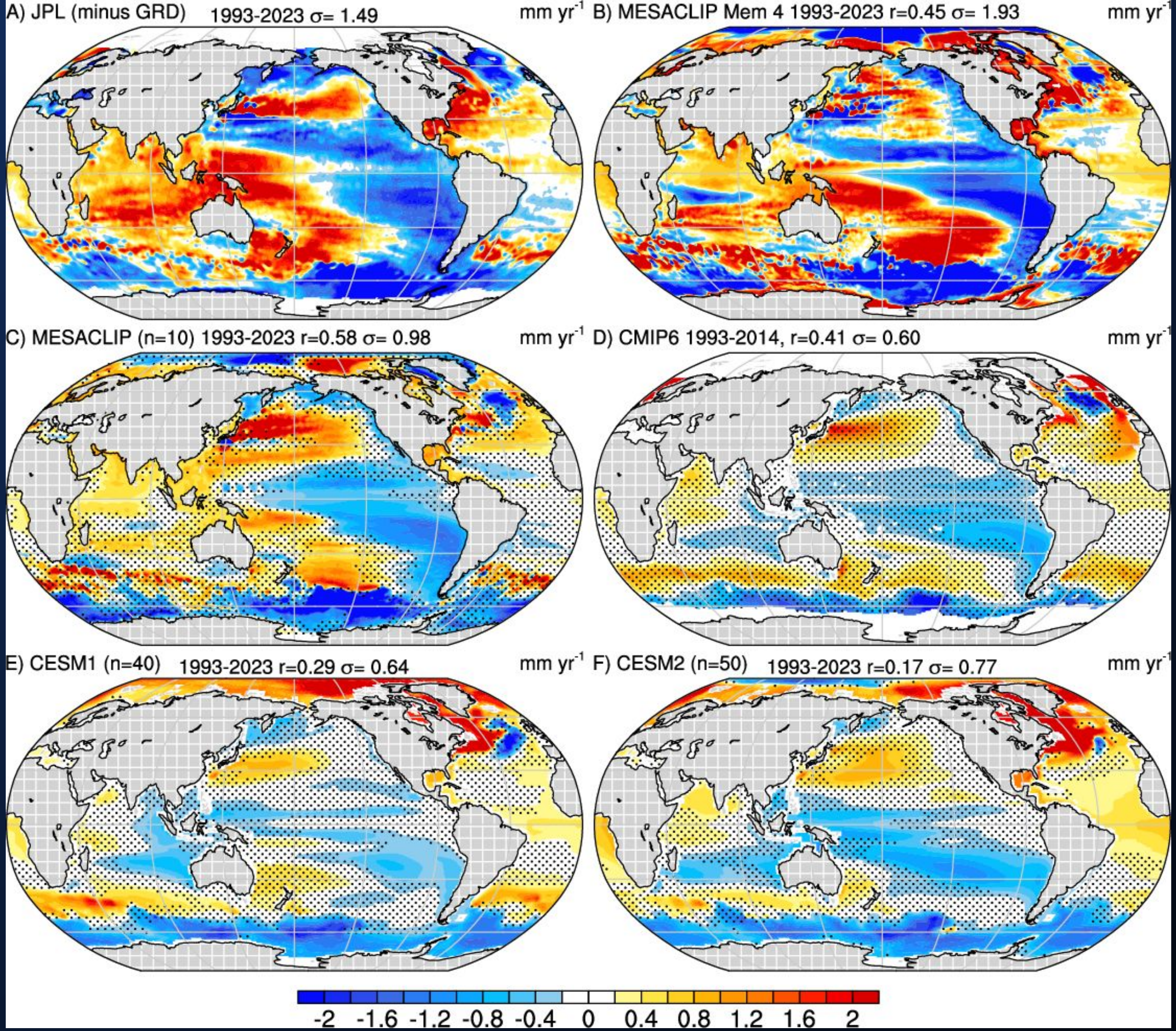


Figure 1: Regional sea level trends as a) observed from GRD-adjusted JPL altimetry data and simulated in MESACLIP, including its highest correlating member (b) and the ensemble mean (c). Also shown are the ensemble means for d) CMIP6, and the e) CESM1-LE and f) CESM2-LE. Stippling in c, e, and f denote trends failing to exceed the two std err range based on 10 members. The global mean is removed from all fields.

Ensemble Mean 21st C Regional Sea Level Trends

Projected trends for 2020-2050 (A) and 2050-2100 (B) in MESACLIP exhibit a number of features observed in altimetry including:

- Depressed rates of rise in the Southern Ocean and eastern S Indian and S Pacific basins,
- Elevated rates of rise in much of the Indian Ocean and N Pacific Ocean, also Kuroshio and Gulf Stream and their extensions.

[also show 2 panels for CMIP6 multi model mean for comparison – bottom panes]

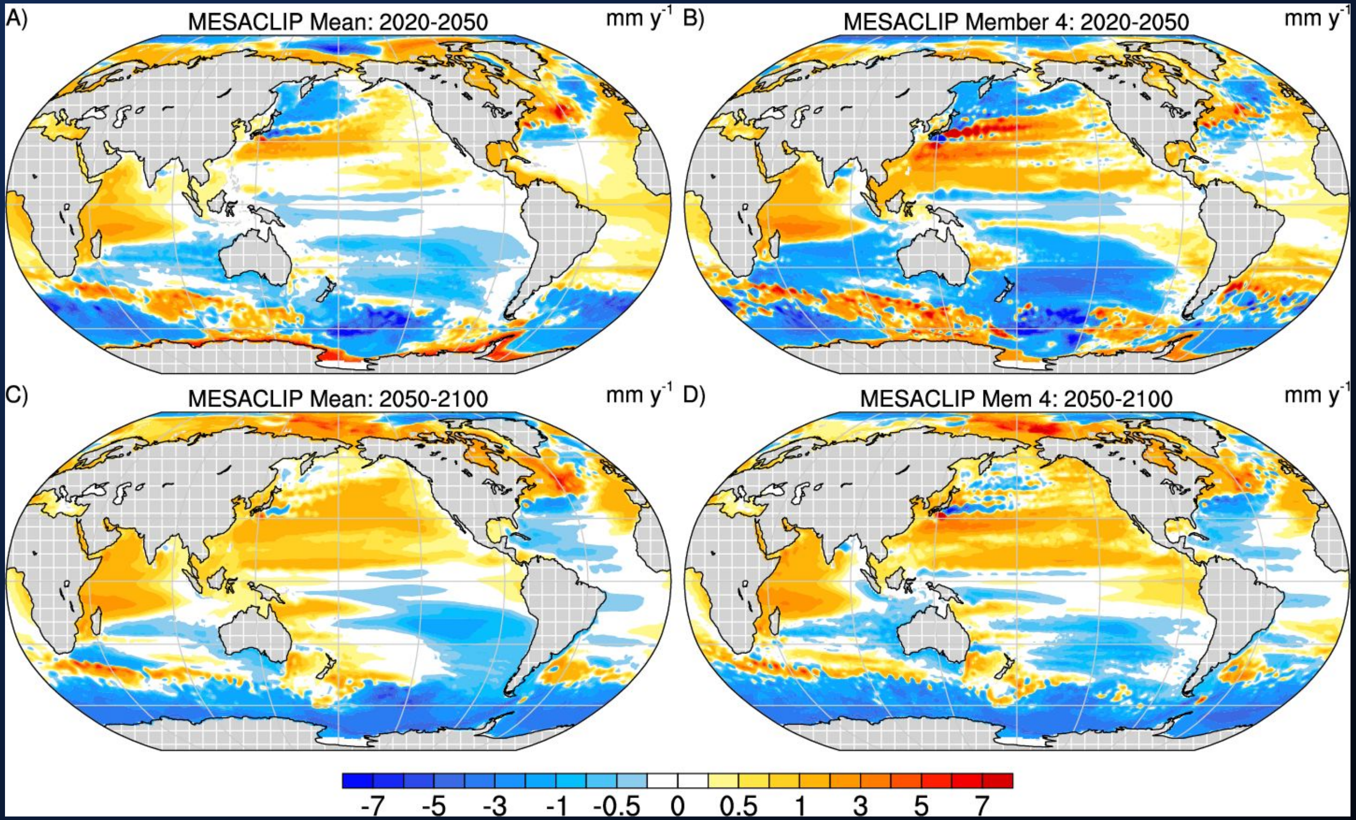
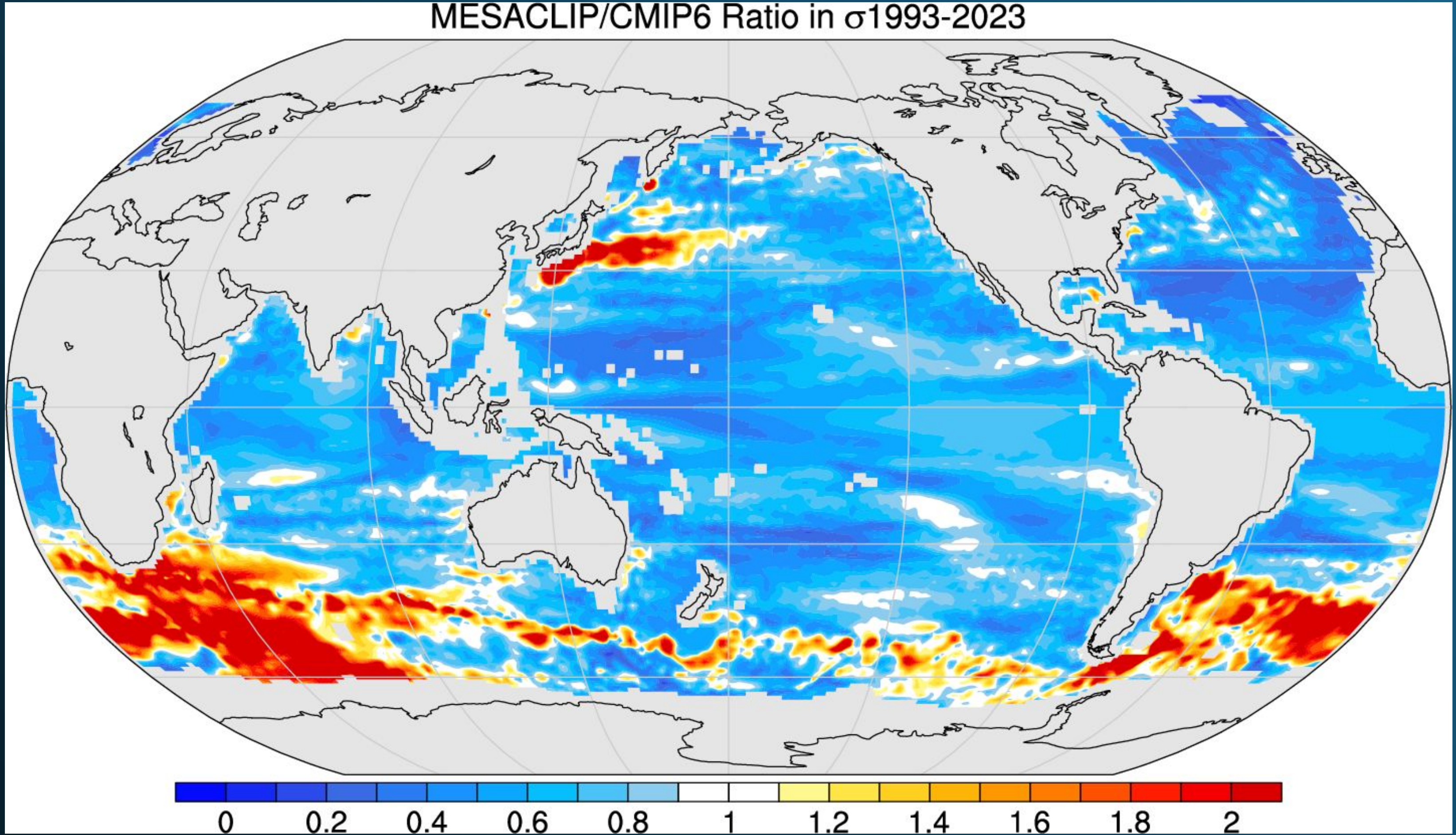


Figure 4: Ensemble mean projected changes in regional sea level for 2020-2050 (A) and 2050-2100 (B) from MESACLIP.

Fig S3: Contrasts in Ensemble Spread (2 sigma)

Shown by ratio of ensemble sigma



Supplementary Information

Cumulative Sea Level Rise 1993-2050 and 1993-2100 and their differences.