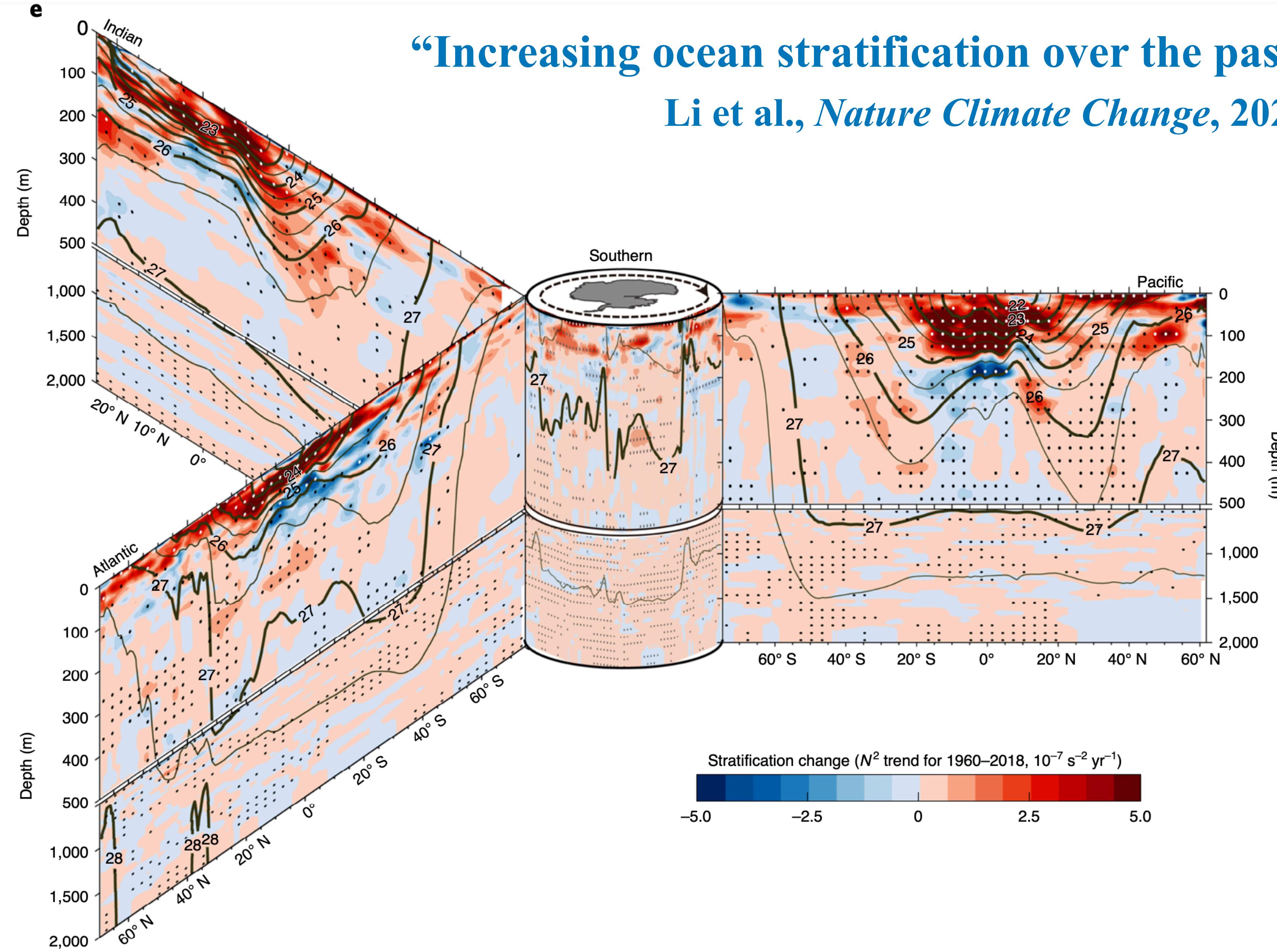


# Changing ocean stratification is changing barotropic-to-baroclinic tidal conversion: Evidence from altimetry and 3-D modeling

Richard Ray<sup>1</sup>, Michael Schindelegger<sup>2</sup>, Lana Opel<sup>2</sup>

- 1) *NASA Goddard Space Flight Center*
- 2) *University of Bonn*



# CONJECTURE

**Increasing stratification → More energetic internal tides**

**Stronger internal tides → Weaker barotropic tides**

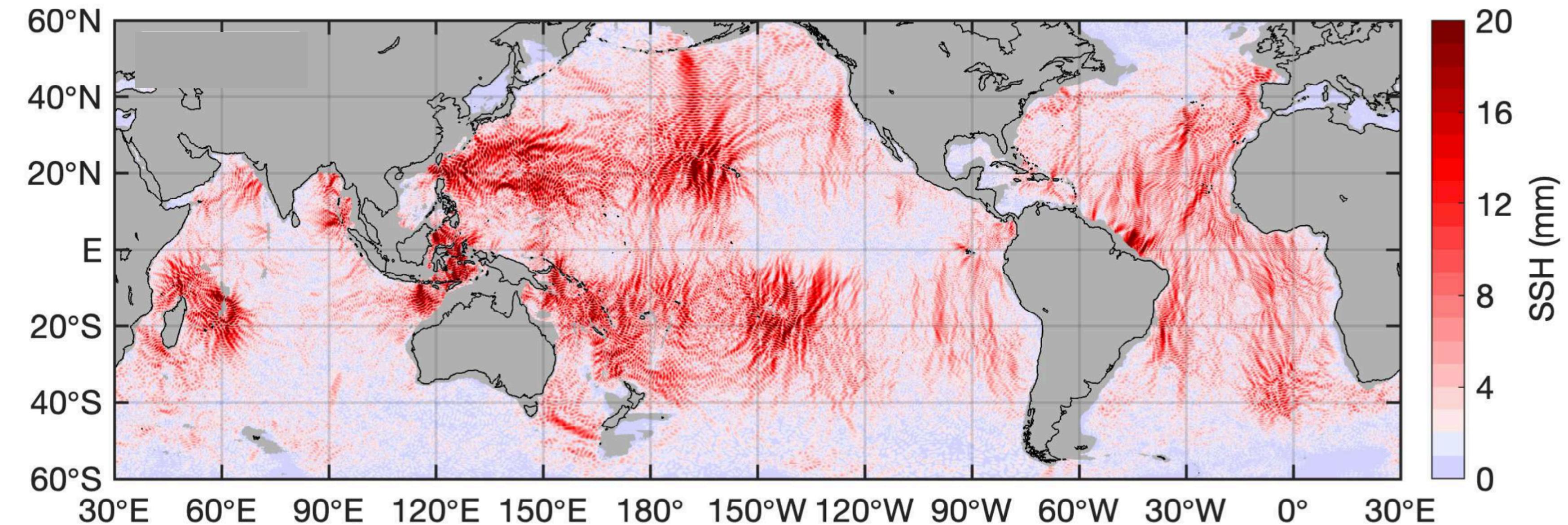
# OUTLINE

- 1. Changing internal tides — altimeter evidence (2 results)**
- 2. Changing barotropic tides — model & altimeter evidence**
- 3. Systematic errors in barotropic trends from altimetry**
  - DAC
  - Orbits, tidal geocenter motion
  - “Mesoscale correction”, CoM correction, et al.

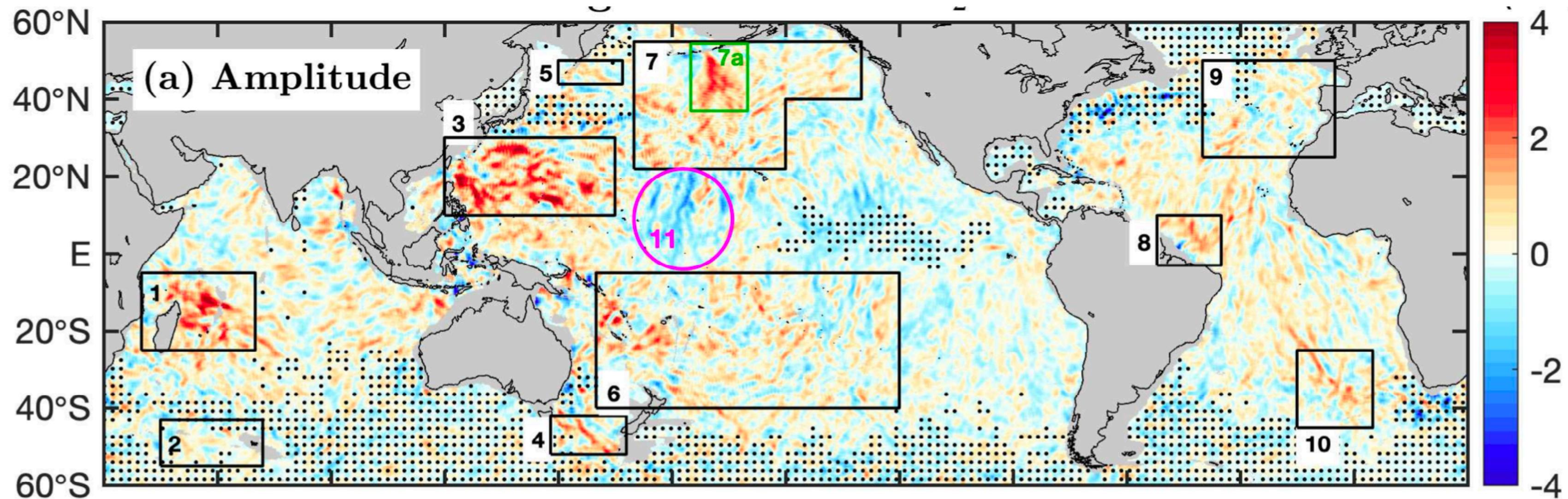
**Baroclinic**

Z. Zhao (2023), Satellite Evidence for Strengthened M2 Internal Tides in the Past 30 Years

M2  
internal tide  
amplitudes

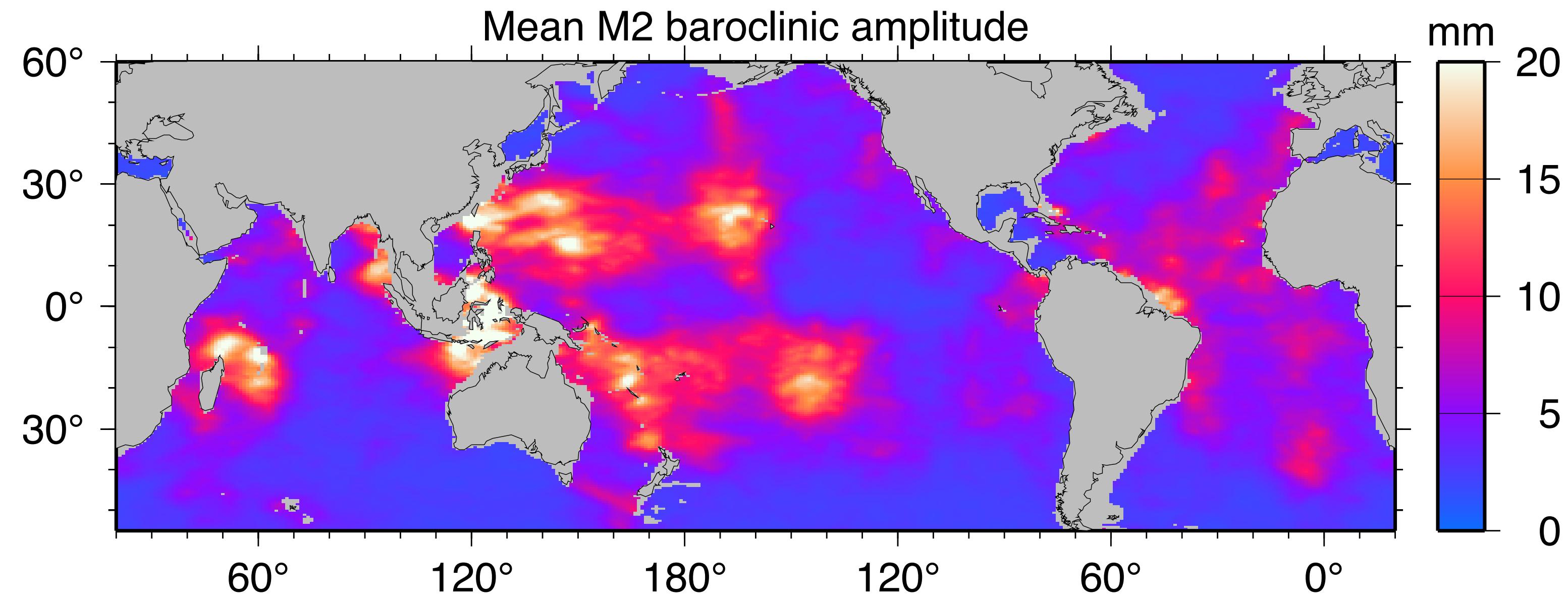


M2  
amplitude  
change  
(over 20 years)

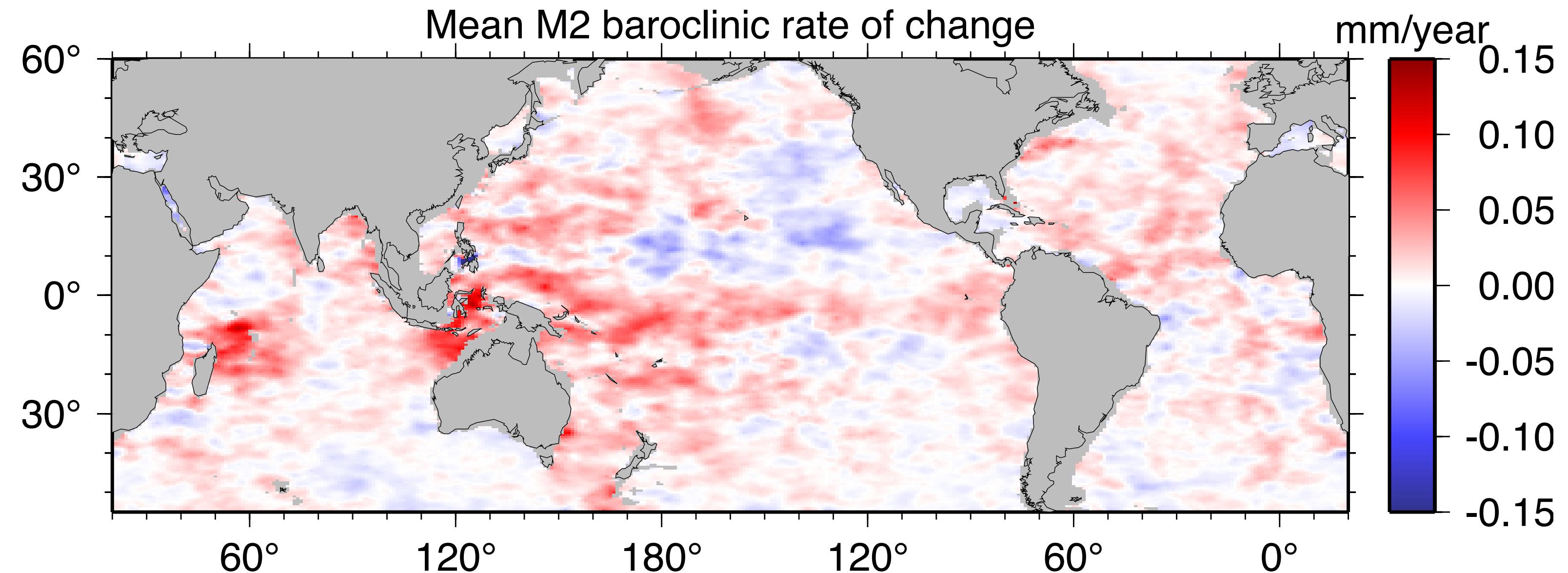


## Another (blurry) view: Based on strictly T/P-Jason-S6 on primary orbit

M2  
internal tide  
amplitudes

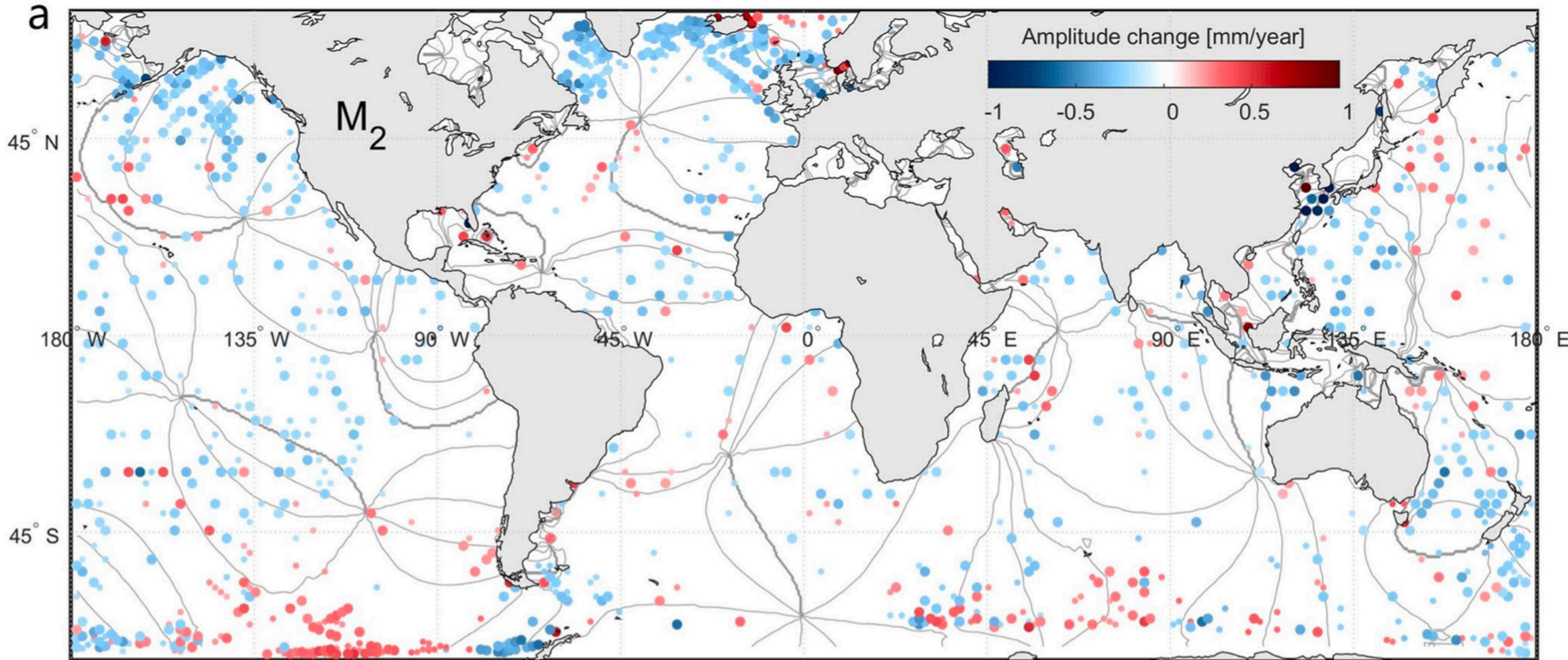


M2  
amplitude  
change  
(over 20 years)



**Barotropic**

Bij de Vaate, Slobbe, Verlaan, “Secular trends in global tides derived from satellite radar altimetry,” *JGR Oceans*, 2022.



Change in M2 amplitude, 1993–2020.

Analyzed cross-overs: cannot distinguish barotropic from baroclinic change.  
Stimulated further work; Inge deserves acknowledgement for sticking her neck out first!

# A changing barotropic tide?

## Modeling Approach

**MITgcm – global ocean**

**Horizontal  $(1/12)^\circ$ , Vertical 59 layers**

**Tidal forcing: M2, S2, K1, O1**

**Includes self-attraction/loading**

**Annual time slices, 1993–2019**

**Stratification defined by GLORYS12 reanalysis**

**+**

**Independent barotropic run with sea level rise**

## Altimetry Analysis

**Topex, Jason-1, -2, -3, Sentinel-6**

**(too coarse for shallow seas)**

**RADS – with all default corrections**

**FES2014 default tide**

**+ non-tidal Aviso SSH removal**

**+ Zaron internal tides**

**Binned tidal analysis, solving for:**

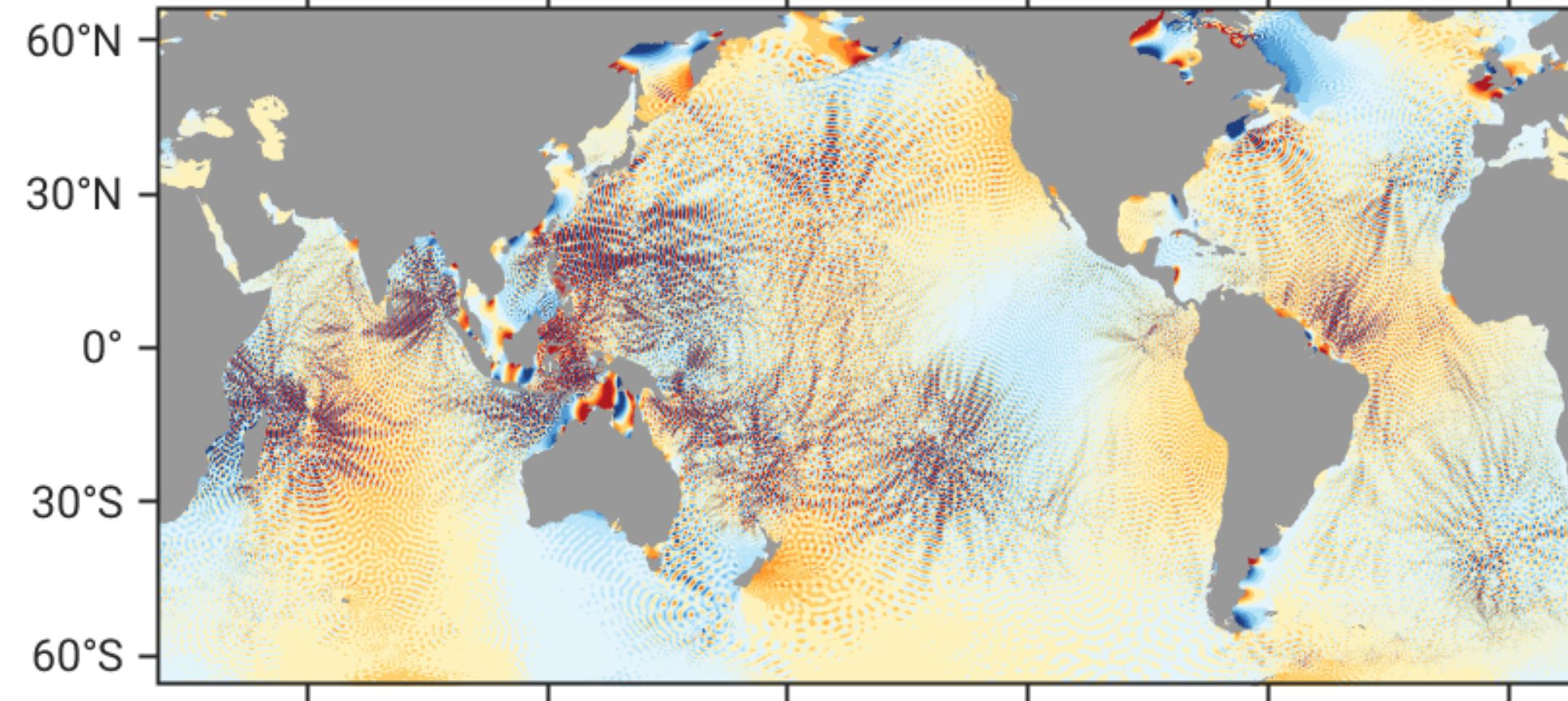
**M2, S2, K1, O1 mean corrections**

**M2 nodal sideline correction**

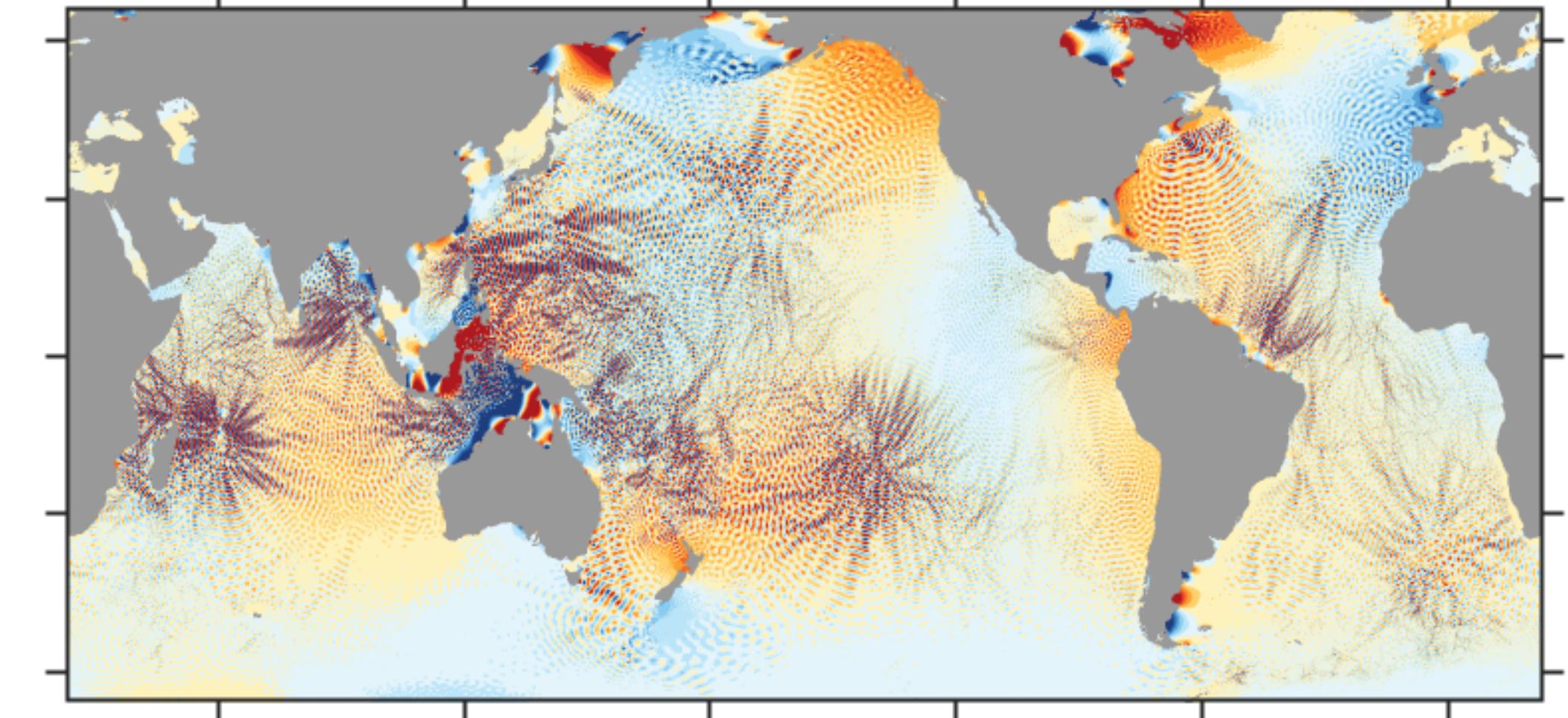
**M2, S2, K1, O1 linear trends**

# Resulting M2 Trends from MITgcm

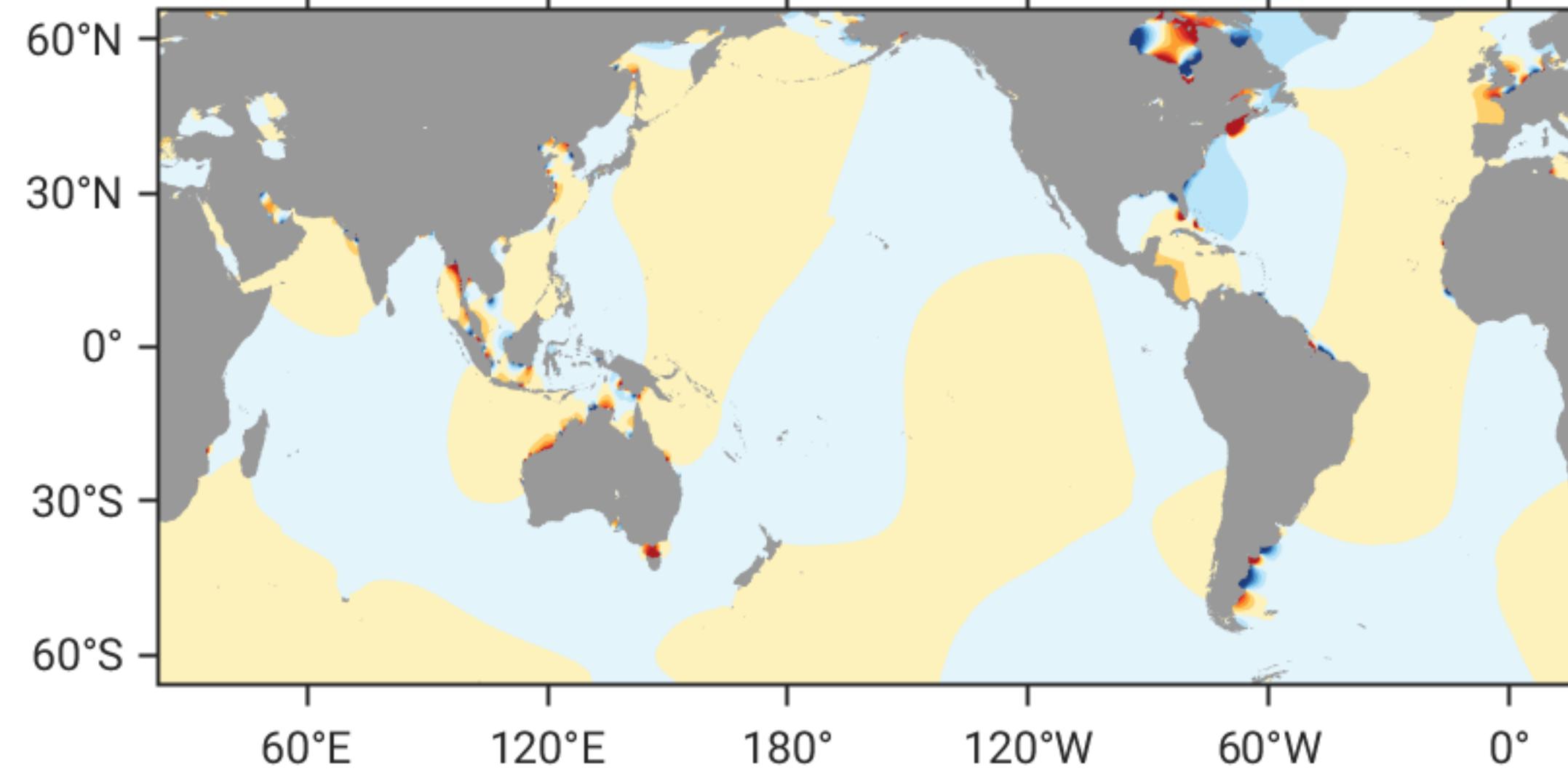
M2 in-phase trend, stratification



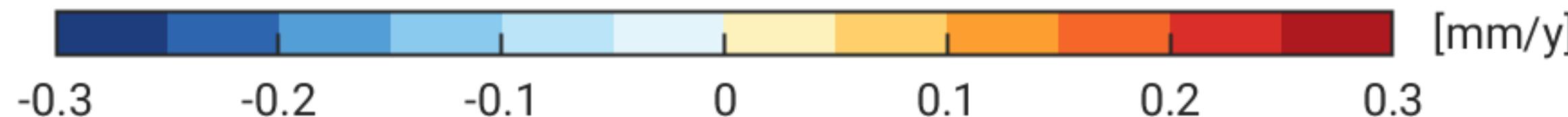
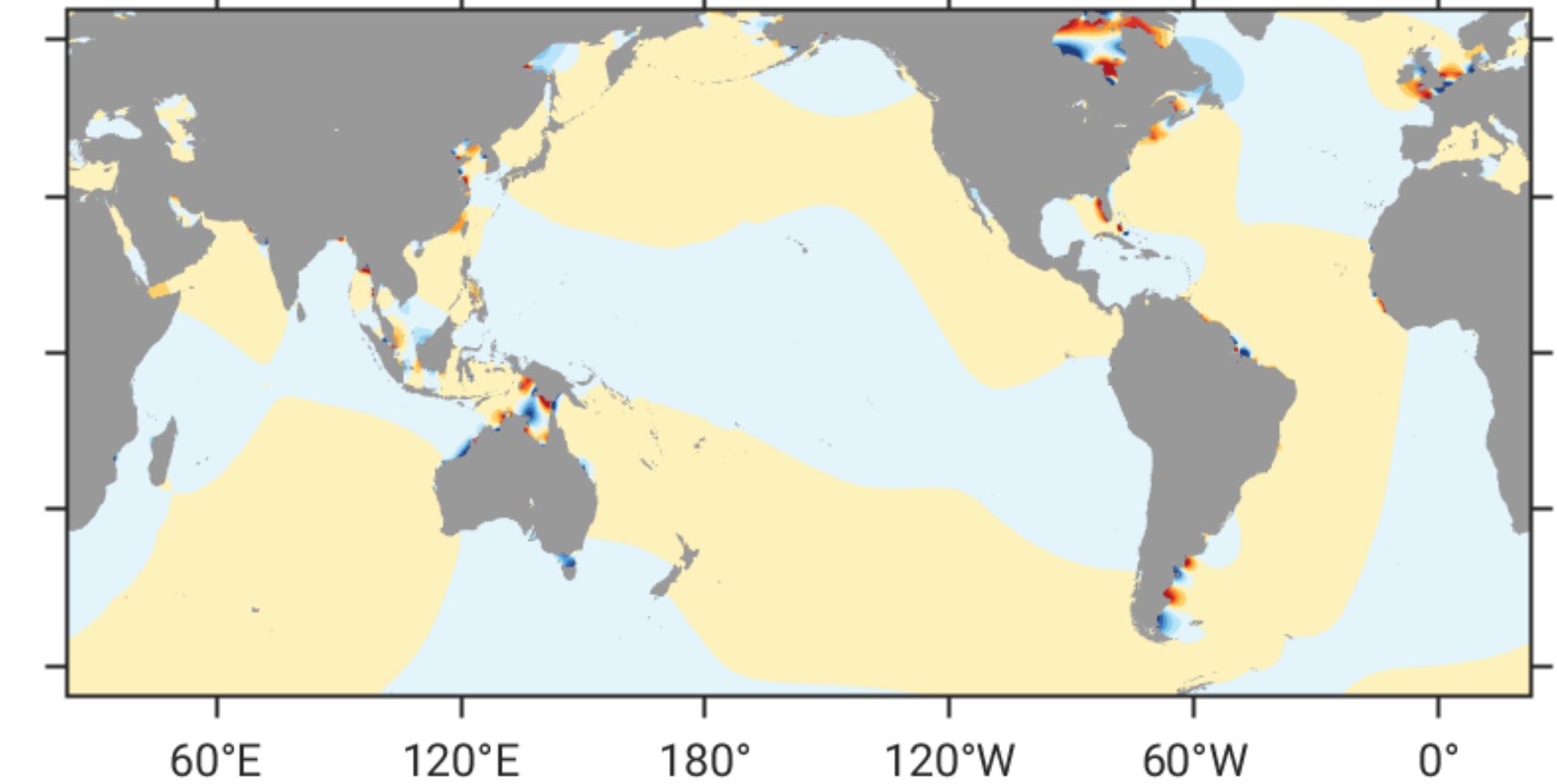
M2 quadrature trend, stratification



M2 in-phase trend, sea-level rise

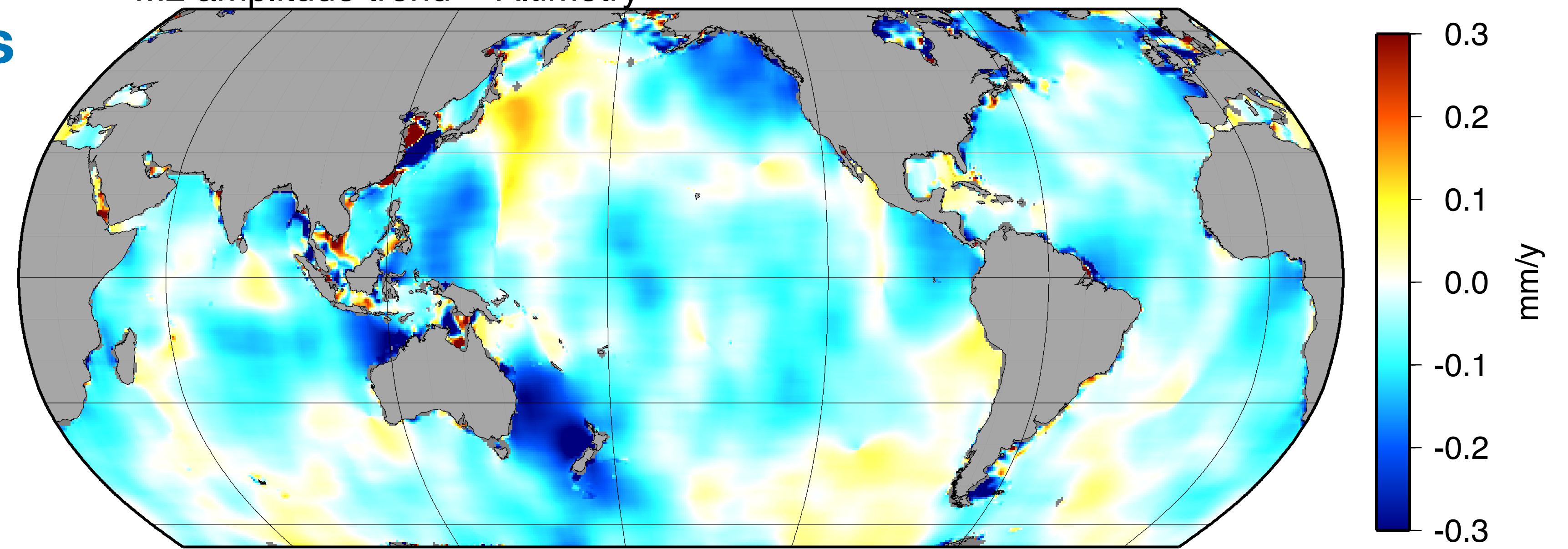


M2 quadrature trend, sea-level rise

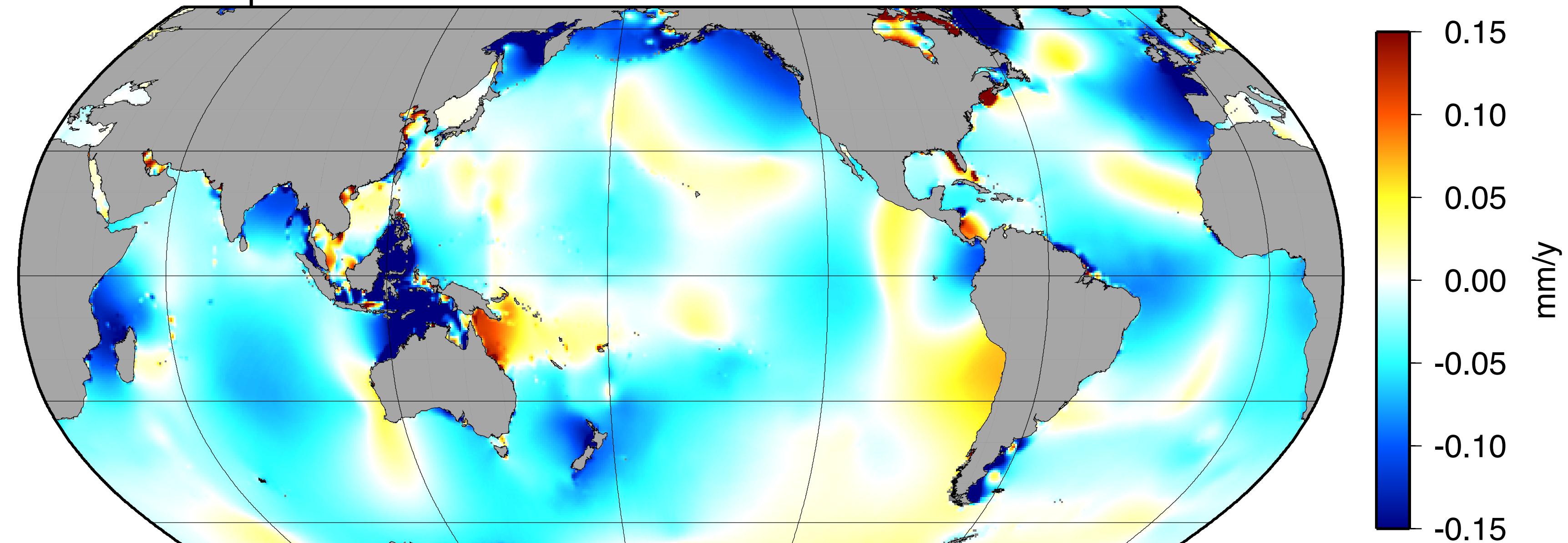


# M2 Barotropic Trends 1993–2019

M2 amplitude trend -- Altimetry



M2 amplitude trend -- Model



Note scale bar difference!

## Possible systematic errors in altimeter results

- DAC de-aliasing correction
- Orbits / Tidal geocenter models
- Others (e.g., “Mesoscale” correction)

# Dynamic Atmosphere Correction (DAC) – for dealiasing

Carrère et al. (2003, 2016)

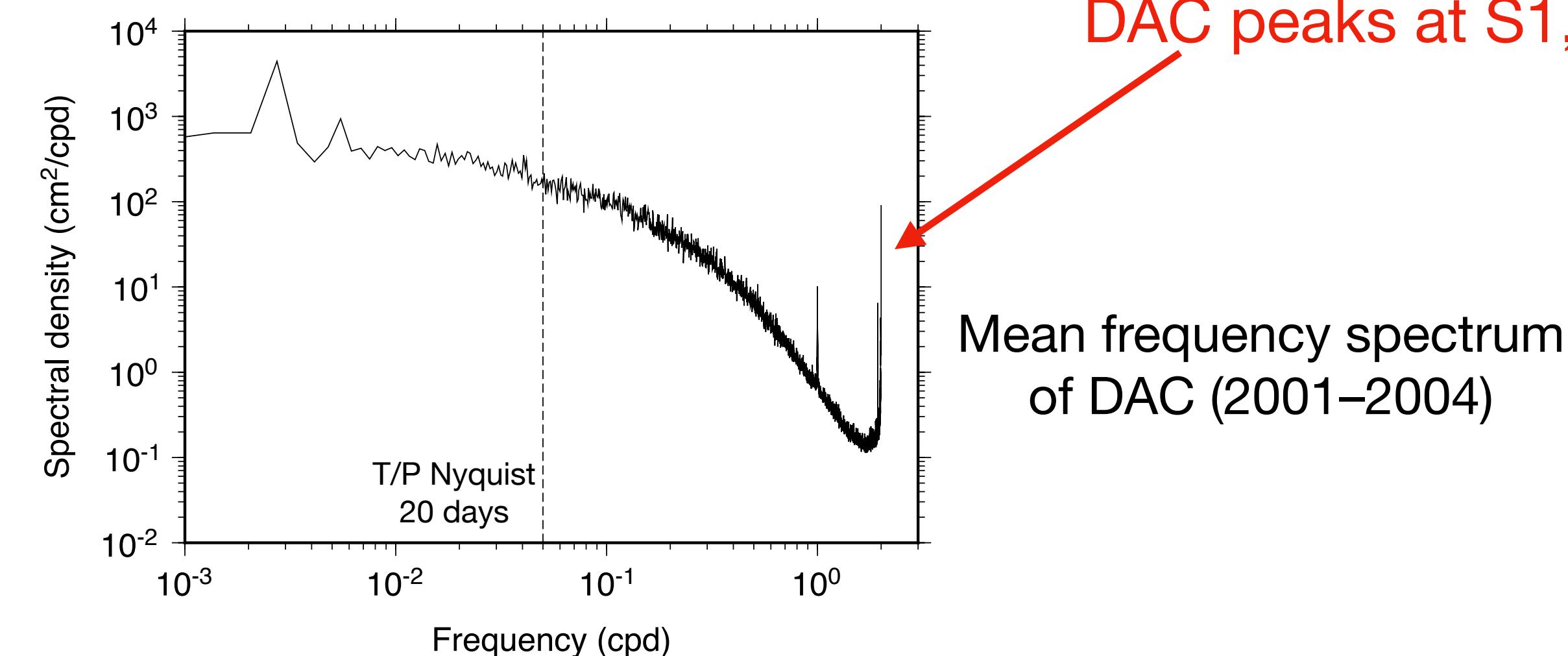
Periods < 20 day: wind/pressure-driven barotropic model  
Periods > 20 day: Inverted barometer

## IN PRINCIPLE:

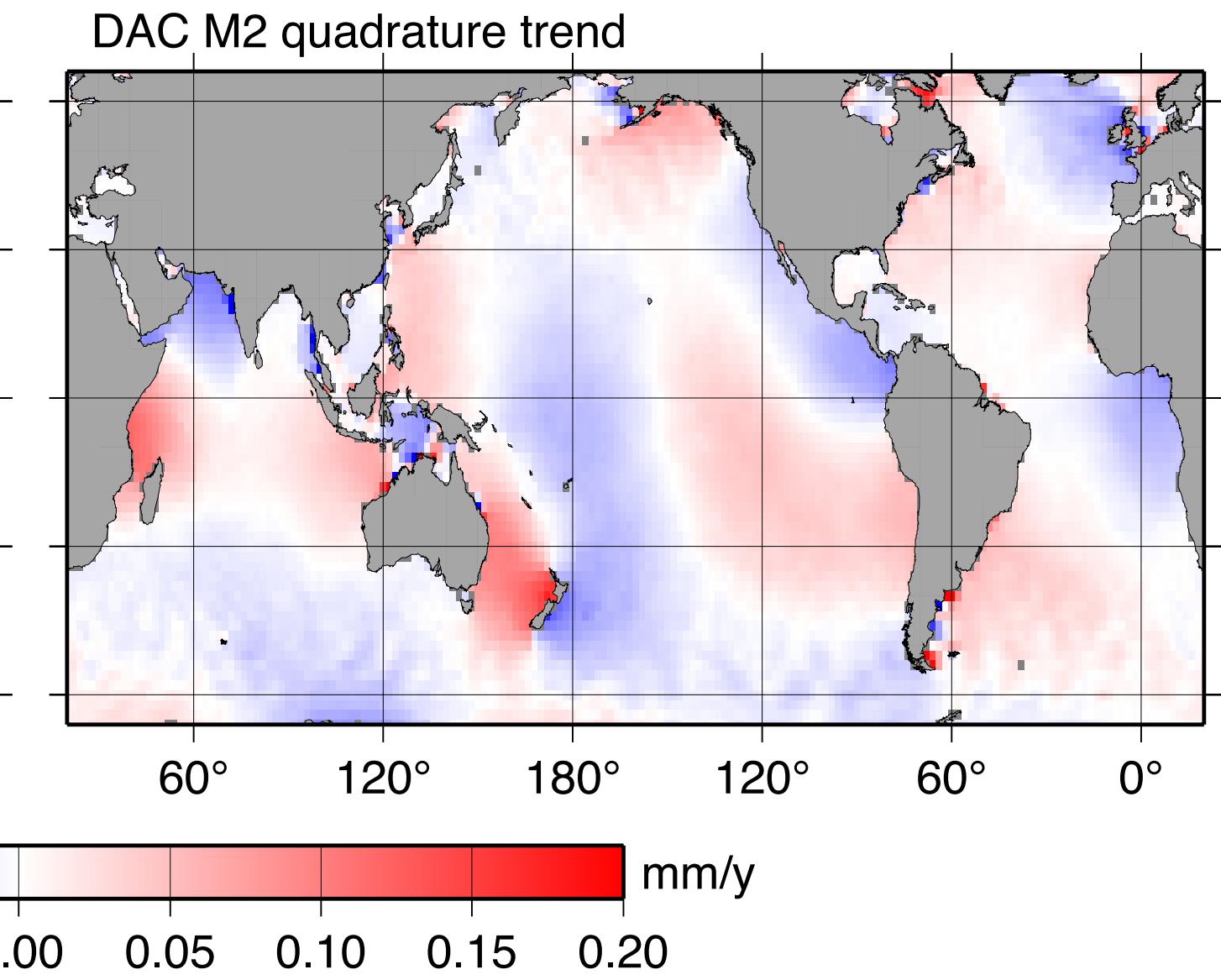
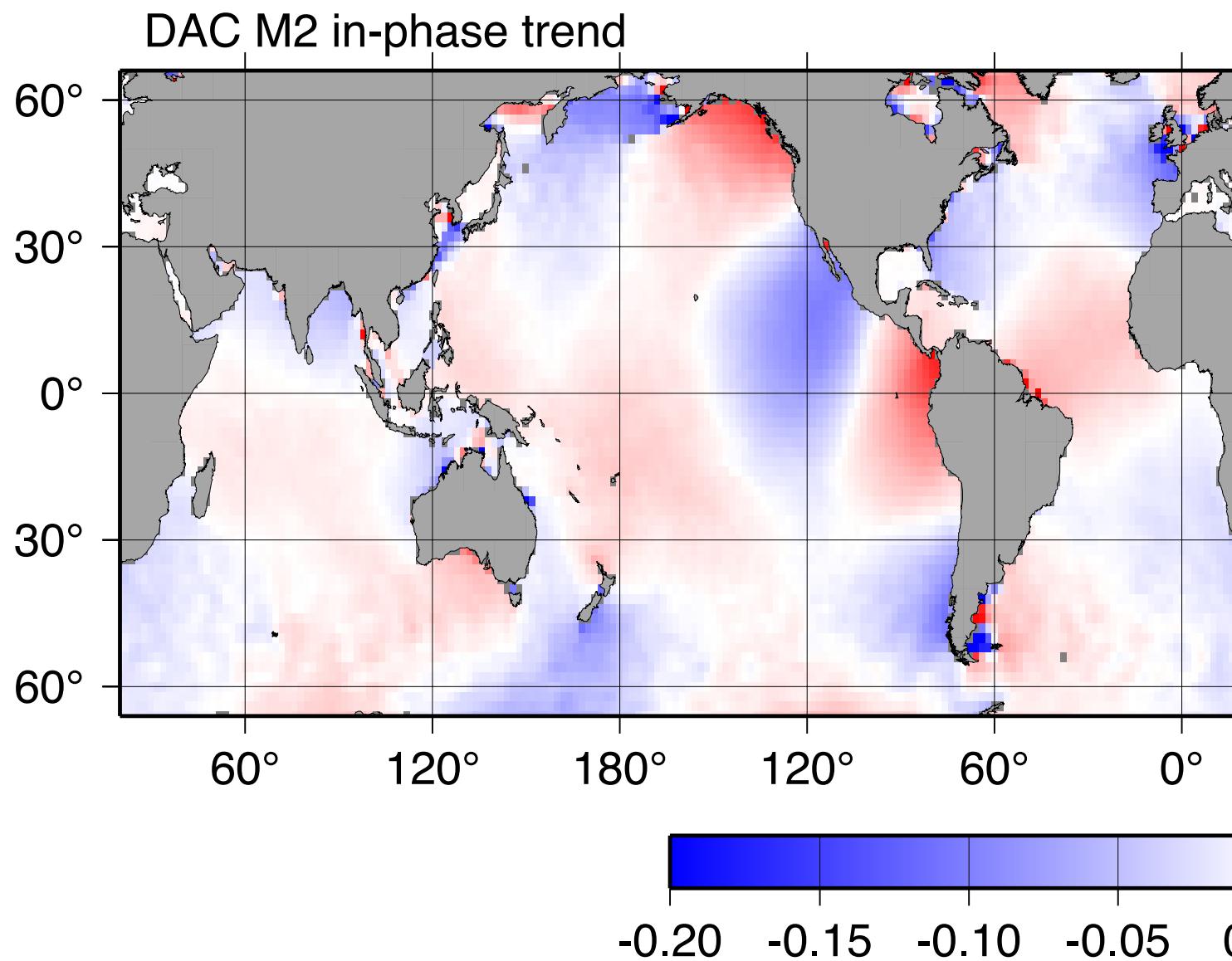
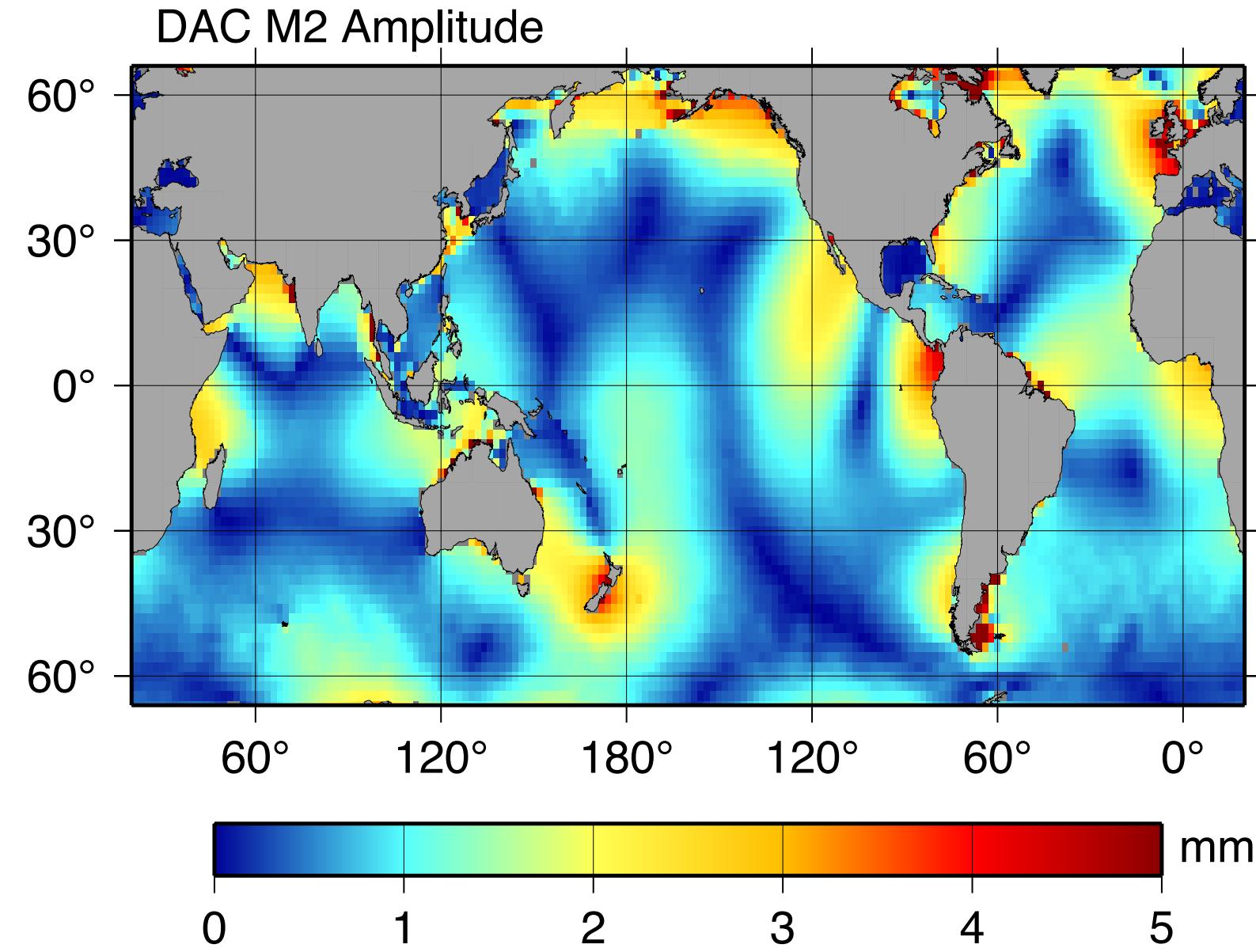
Air tides are removed from forcing to prevent radiational tides from being double-counted.  
(Ocean tide corrections account for full tides, gravity+radiational.)

## IN PRACTICE:

Solar air tides not completely removed.  
Lunar air tides were overlooked.

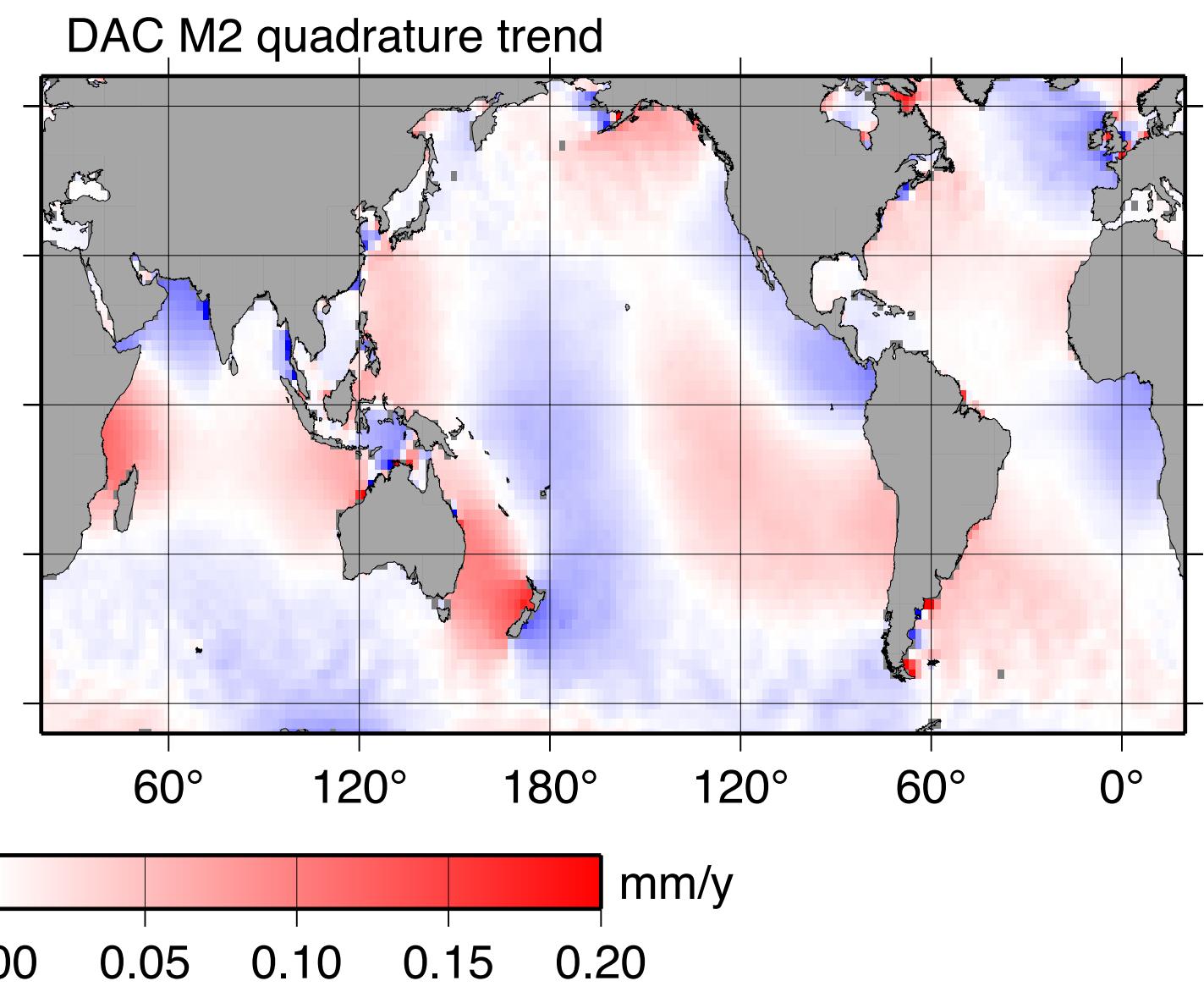
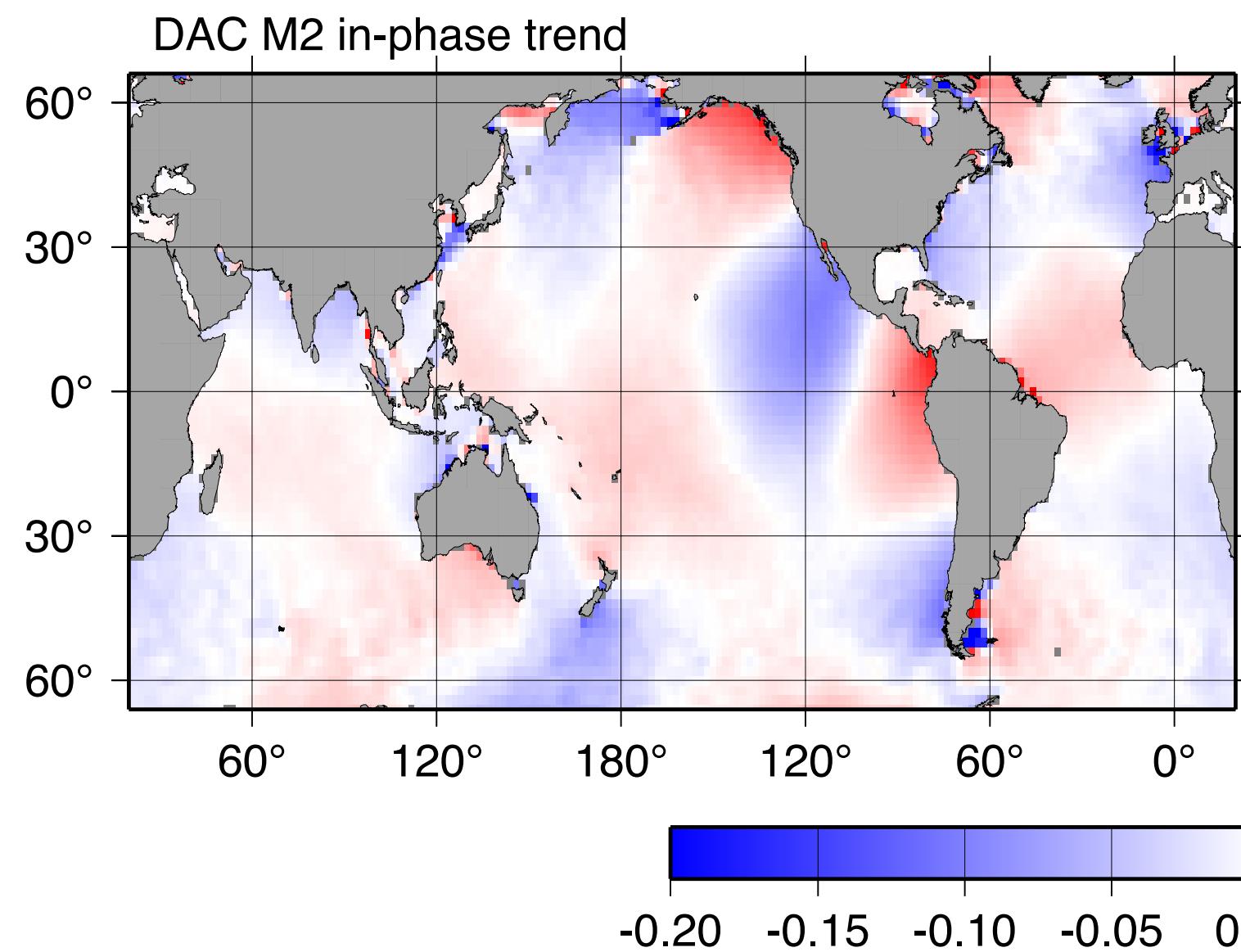
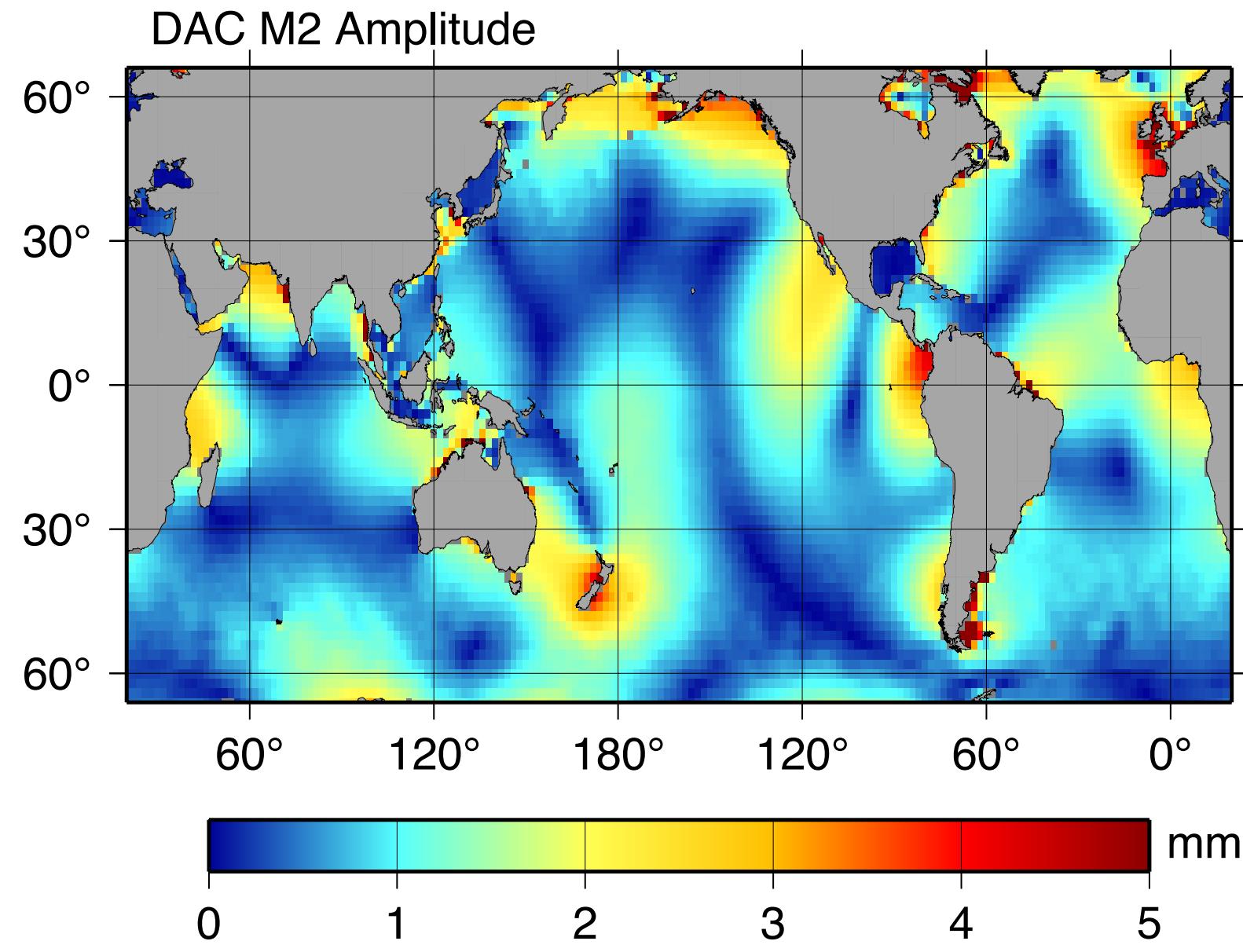


# M2 Tide Leakage into DAC



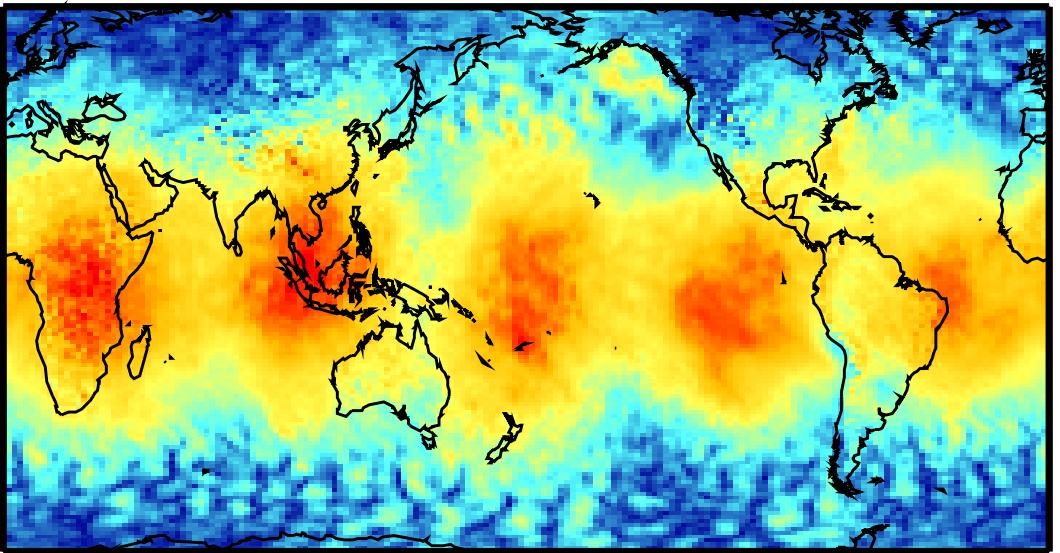
Why is there a trend???

# M2 Tide Leakage in DAC

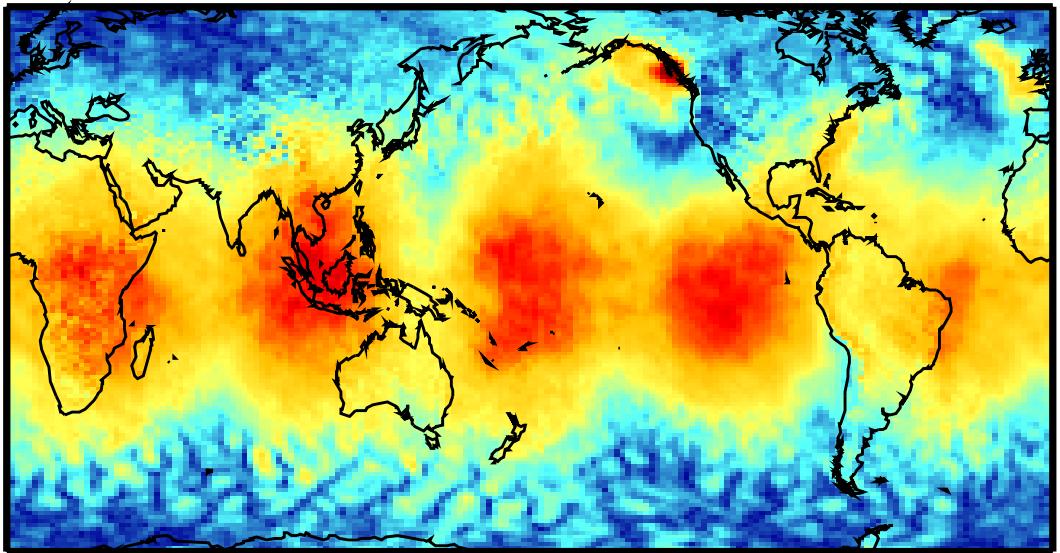


Why is there a trend?? Because of ECMWF forcing.

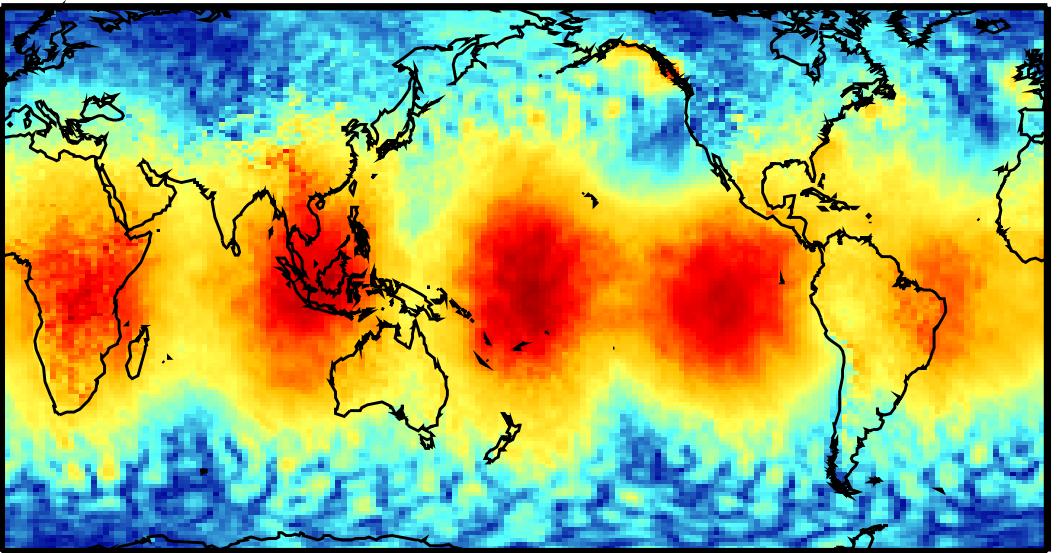
1980-1987



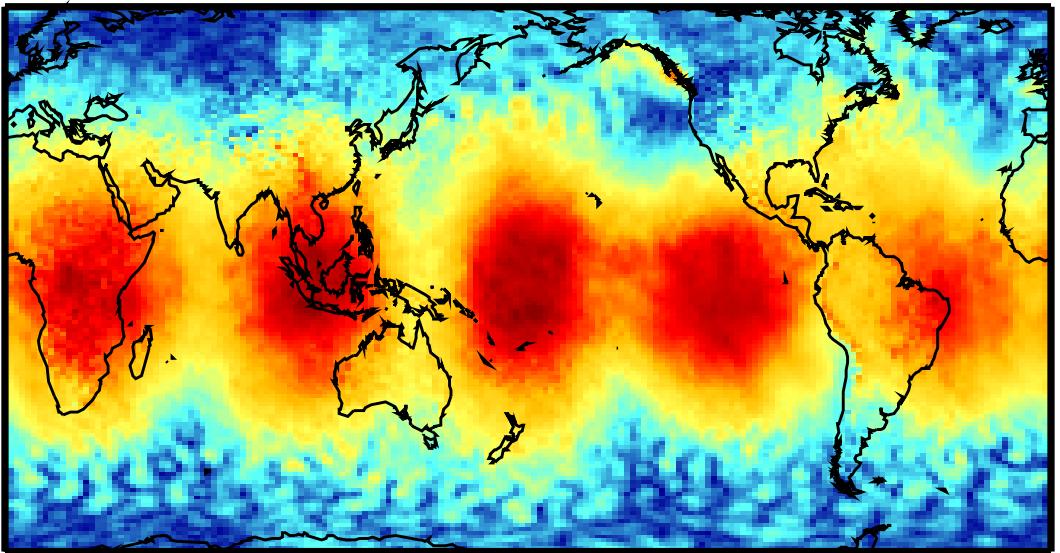
1993-2000



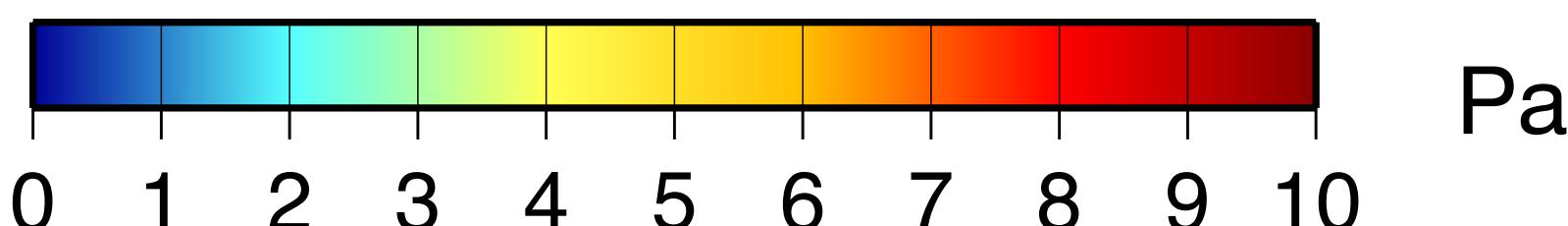
2003-2010



2013-2020



see Schindelegger & Dobslaw (JGR, 2016)  
for early 20th century: M2 vanishes!



M2 air tide

# Systematic Errors from Orbits/Geocenter

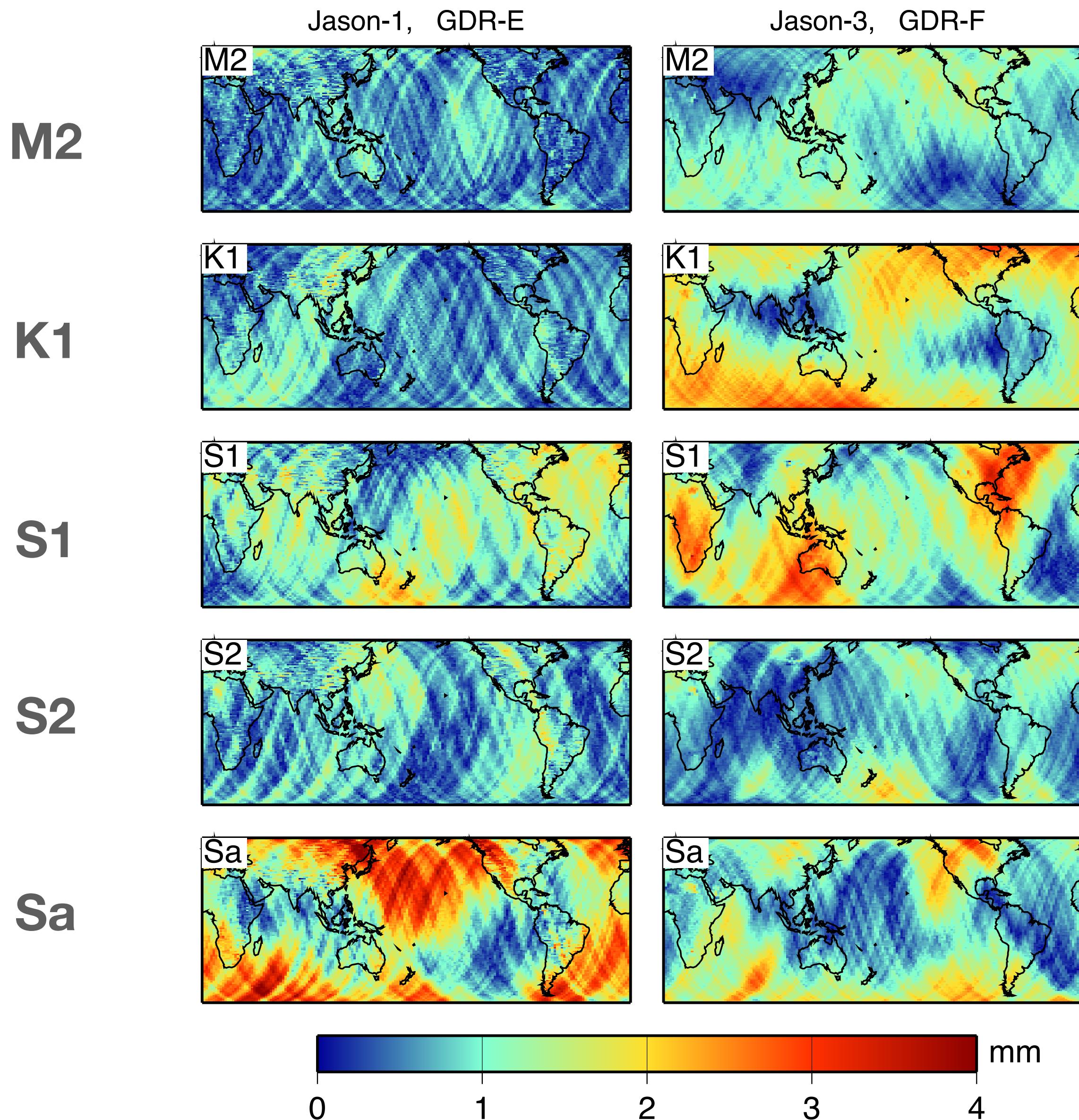
1. Tidally coherent errors in orbits
2. Inconsistent tidal geocenter models for different missions.

	Geocenter model		
Default orbits in RADS	Topex/Poseidon	GDR-C'	??
	Jason-1	GDR-E	FES2012
	Jason-2	GDR-E	FES2012
	Jason-3	GDR-F	FES2014
	Sentinel-6A	GDR-F	FES2014

How large are the tidally coherent errors in these orbits?

Inconsistencies between missions affect estimated tide trends!

# Tidal Analysis of Orbit Differences, Amplitudes



## Approach:

Form differences, RADS-GSFC orbits  
Compute tidal analysis over globe

## Conclusions:

Perhaps significant for M2  
Likely disastrous for K1  
Why large differences, GSFC – GDR-F ??  
Why large differences, GDR-E – GDR-F ??

## Implications:

Use consistent models/orbits for all missions  
But we cannot overcome inconsistent tracking

## SUMMARY

- Open-ocean M2 changes, 1993–2019 – ‘tentative’
  - Barotropic tide trends predominantly negative.
  - Baroclinic tide trends predominantly positive.
- Likely cause of both: changes in ocean stratification
- Problems in the altimeter DAC correction
  1. M2 air-tide forcing
  2. False trend in M2 air tide from ERA5
- Altimeter analysis for barotropic tides requires consistent orbits.
  - need to ensure consistent geocenter models
  - cannot overcome inconsistent tracking over time