Tracking Heat Pathways in a Warming Ocean

ECCO summer school 2025, Pacific Grove, California

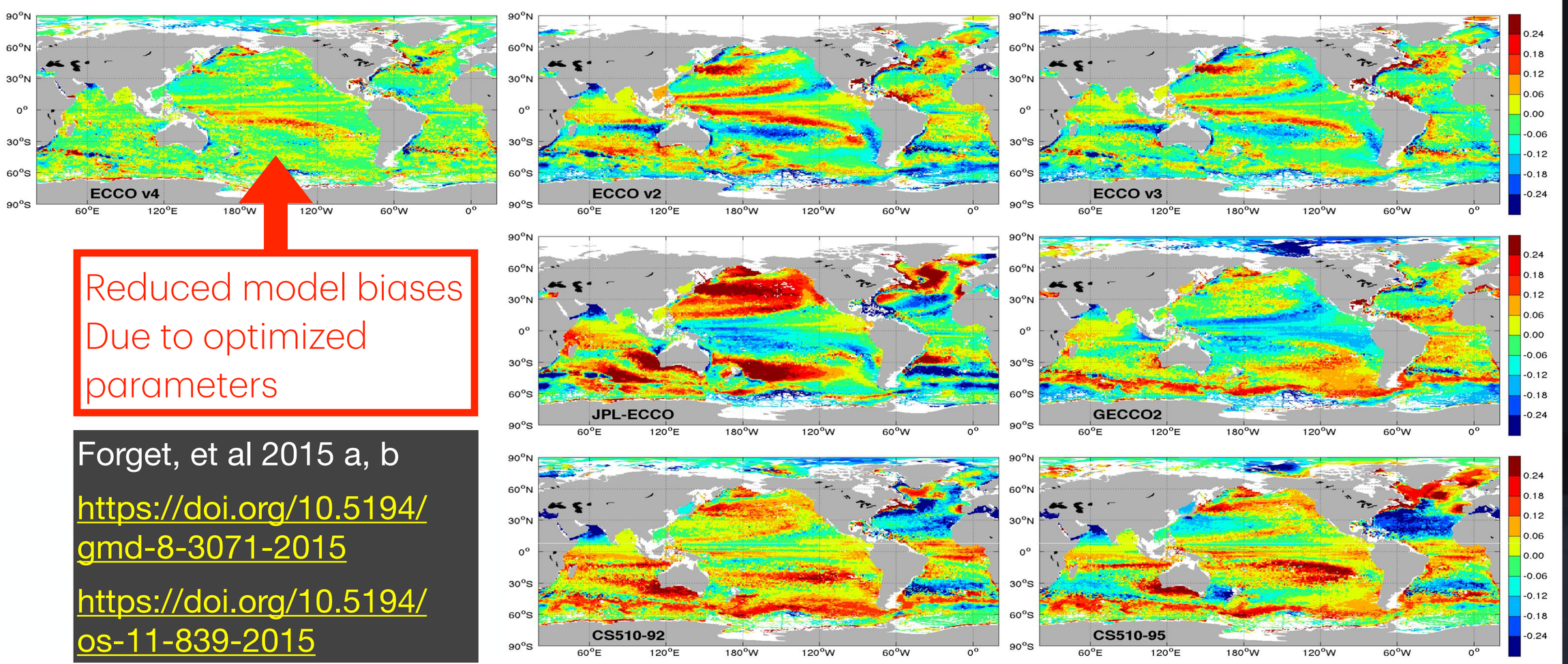
Gaël FORGET, 2025/05/28

Table of Content

- Research funded by NASA-PO, SF-CBIOMES, NOAA-CVP, NASA-ECCO, ARIA-FTP

Data-driven transport estimates (ECCO4)

Key to closely fitting data (e.g. salinity at 300m depth)



Reduced model biases
Due to optimized parameters

Forget, et al 2015 a, b

https://doi.org/10.5194/gmd-8-3071-2015

https://doi.org/10.5194/os-11-839-2015

Data-driven transport estimates (ECCO4)

Key to reduce model drifts (e.g. oxygen climatology, after 500y)

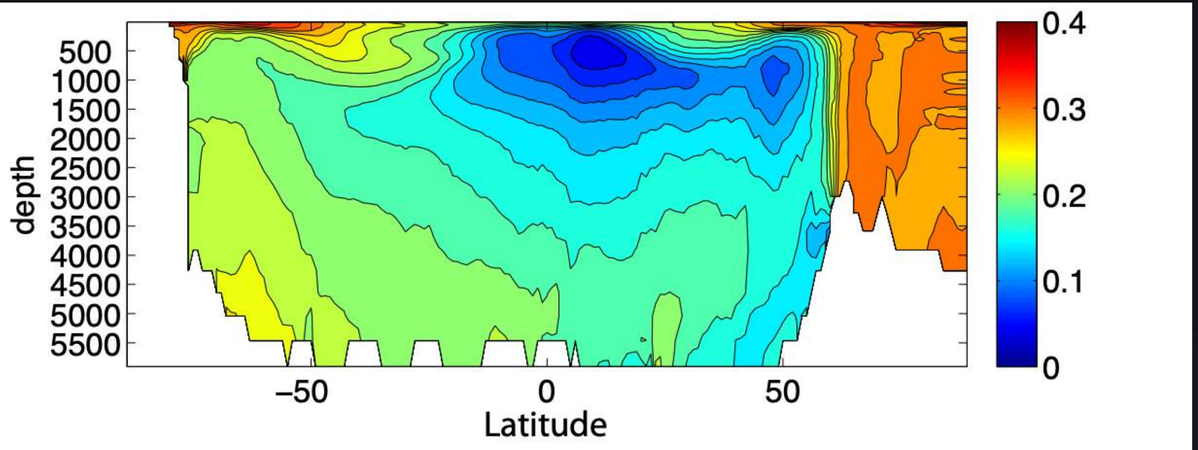
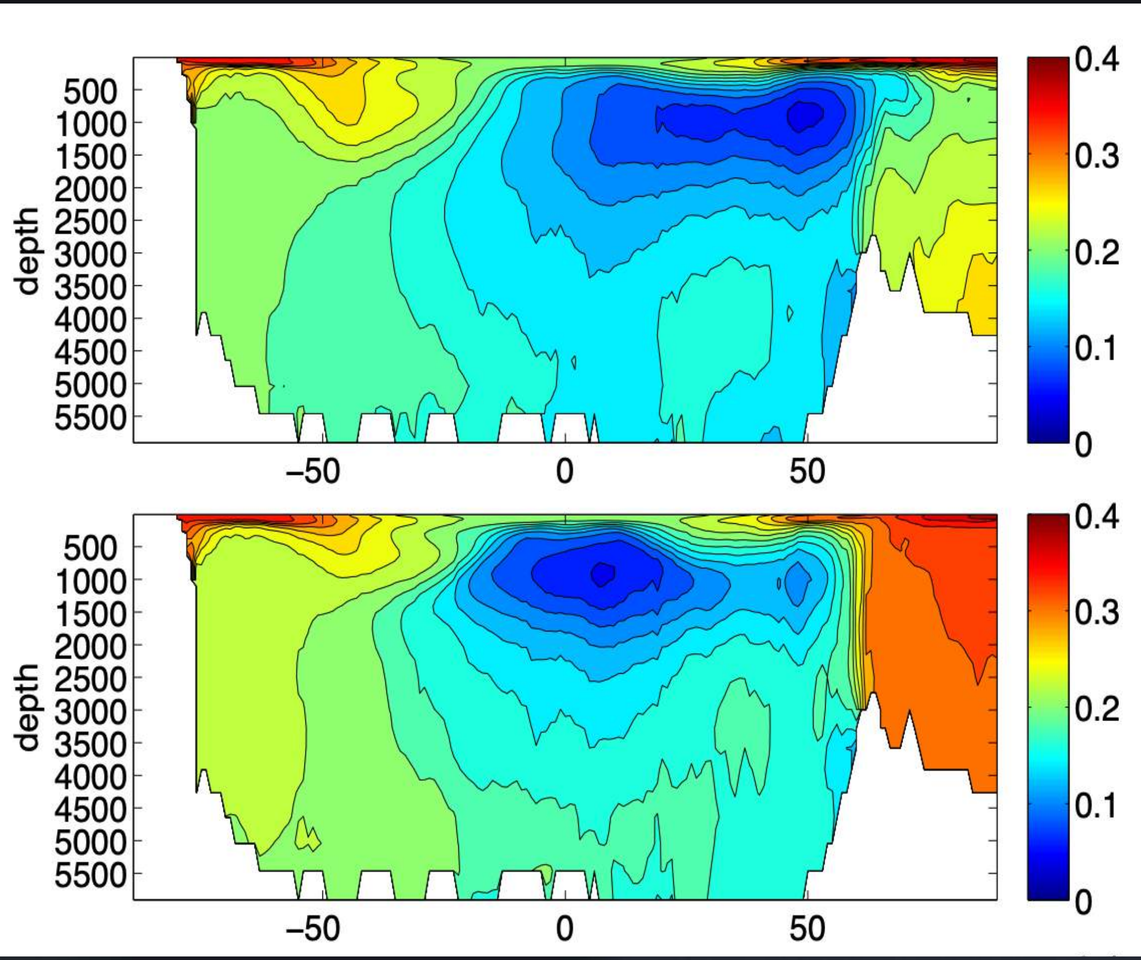


Figure 4. Zonal mean oxygen concentration (in $\mathrm{mol\,m^{-3}}$) from Garcia et al. (2010) (bottom panel) and from the two 500-year simulations (see Fig. 3 caption for details) using the $\mathcal{K}_{\mathrm{gm}}$, $\mathcal{K}_{\sigma}$, and $\mathcal{K}_{\mathrm{d}}$ estimate (middle) or the K_{gm}, K_{σ}, and K_{d} first guess (top).

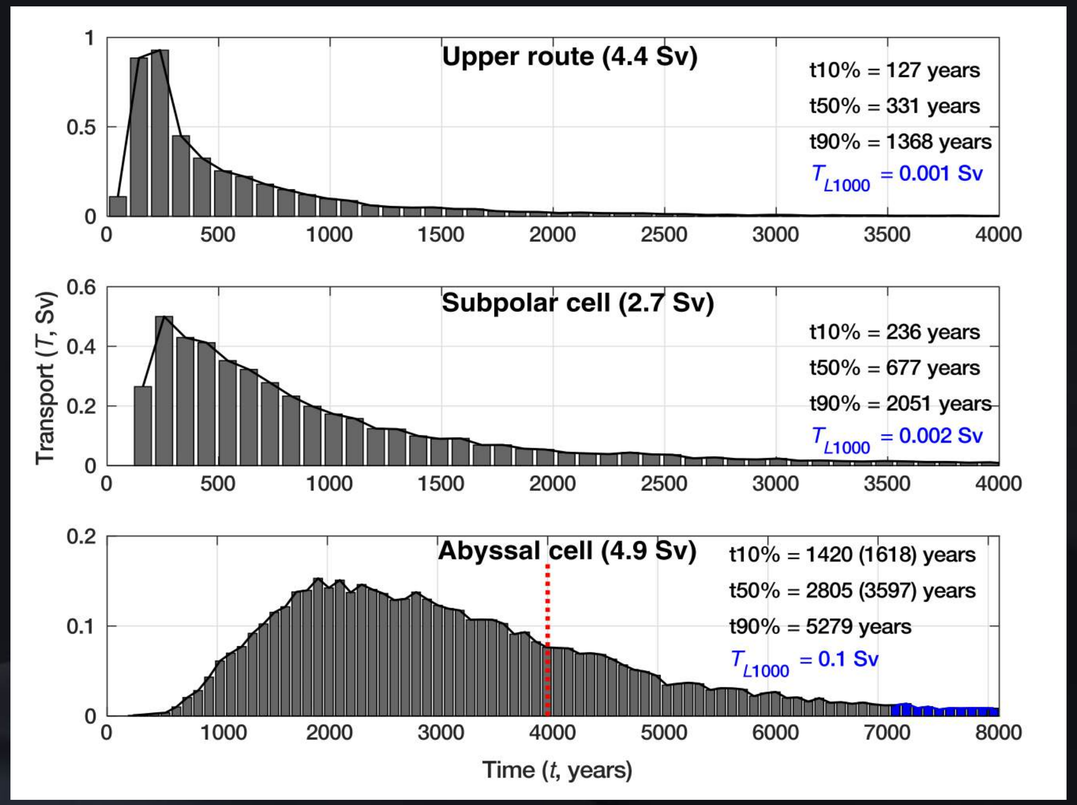
Forget, Ferreira, and Liang 2015

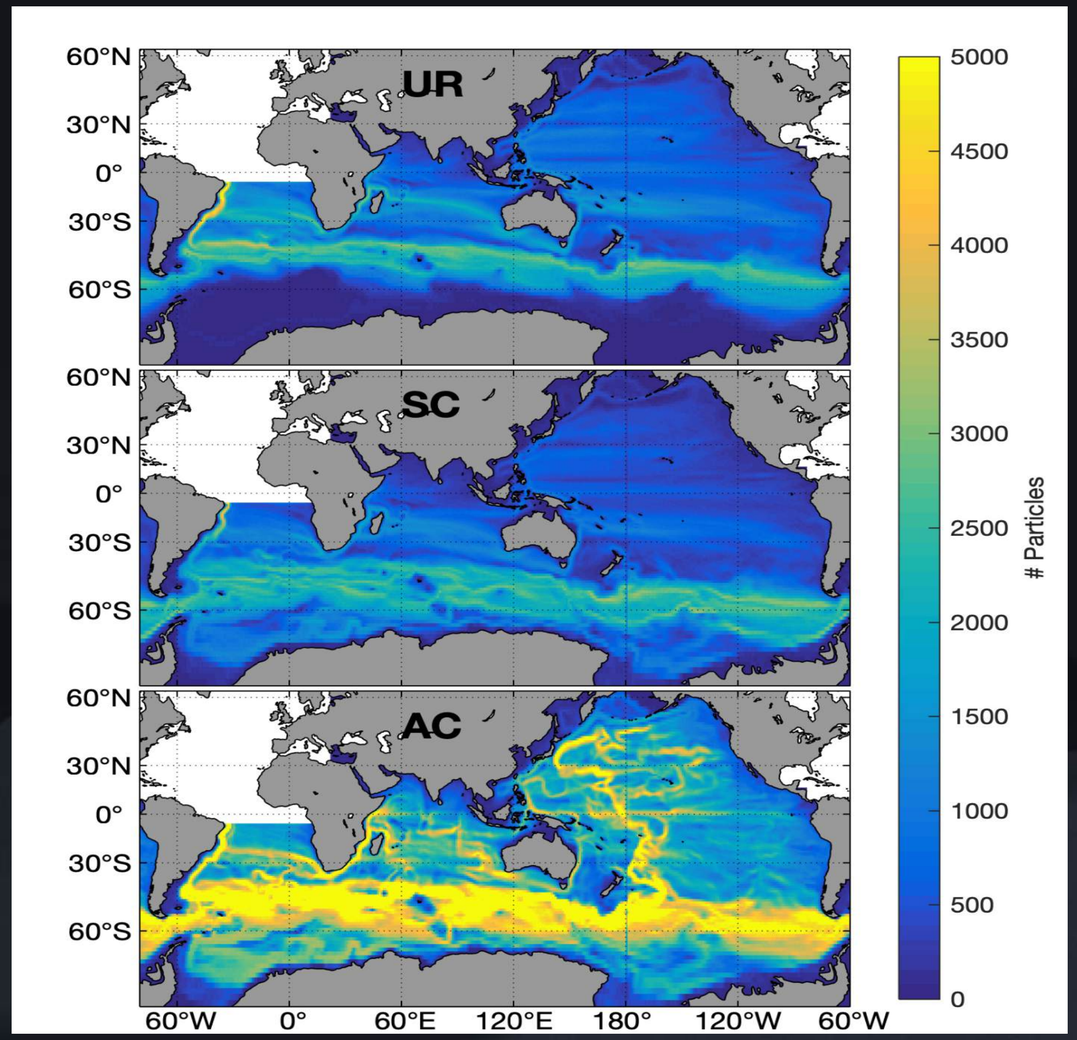
https://doi.org/10.5194/os-11-839-2015



Ocean Circulation Climatology (ECCO4)

e.g. global ocean meridional circulation pathways and time scales





Rousselet, Cessi, and Forget, 2021

https://doi.org/10.1126/sciadv.abf5478

Ocean Heat Transport Climatology

Estimated to balance out air-sea flux climatology (basic method)

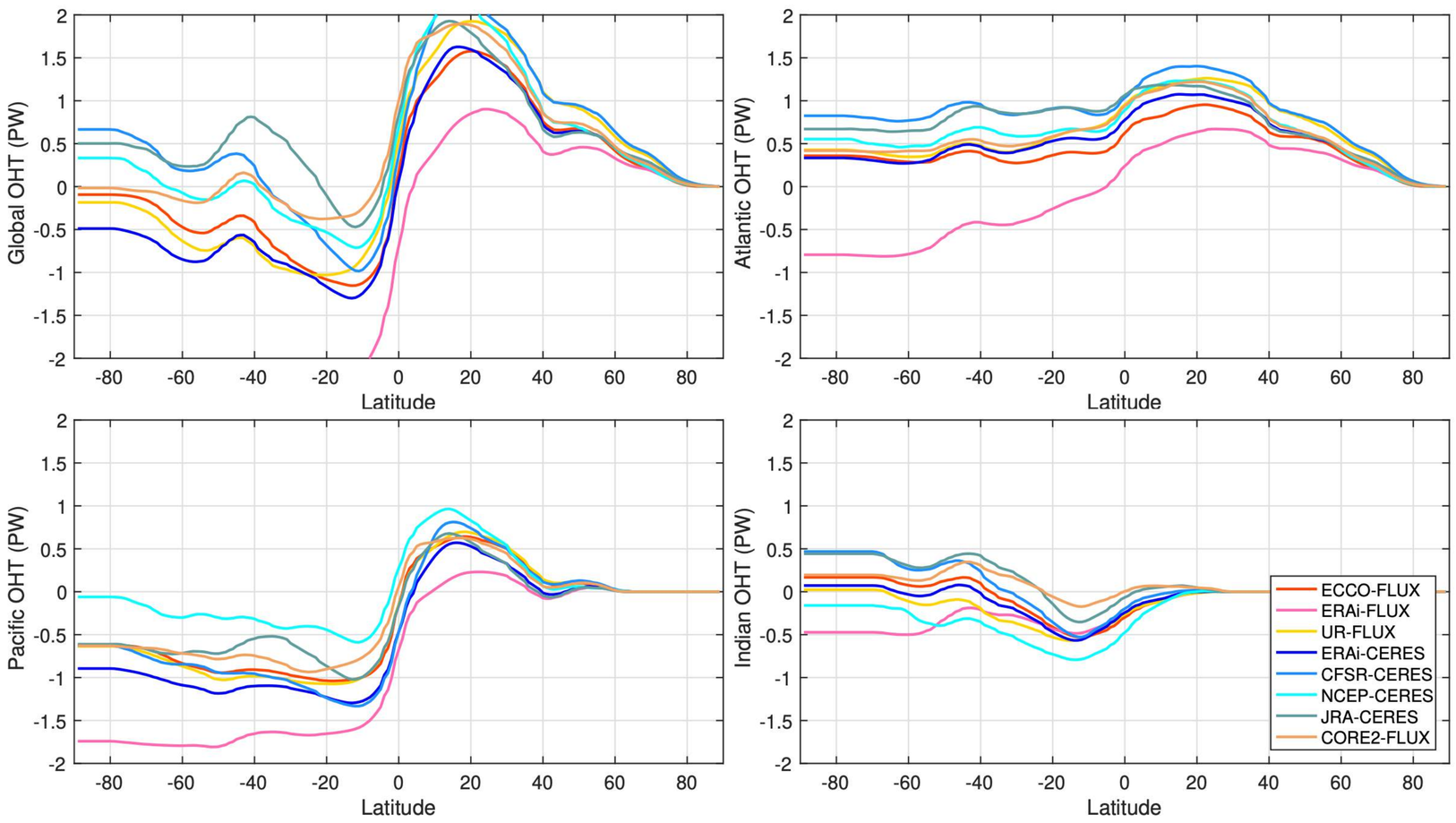


Figure S8: Same as Fig. S7 but based on the ad-hoc integration method discussed in **Methods / Improved Method**.

Supplementary of

Forget & Ferreira 2019

Global ocean heat transport dominated by heat export from the tropical Pacific.

Nat. Geosci. **12**, 2019

https://doi.org/10.1038/s41561-019-0333-7

Ocean Heat Transport Climatology

Estimated to balance out air-sea flux climatology (new method)

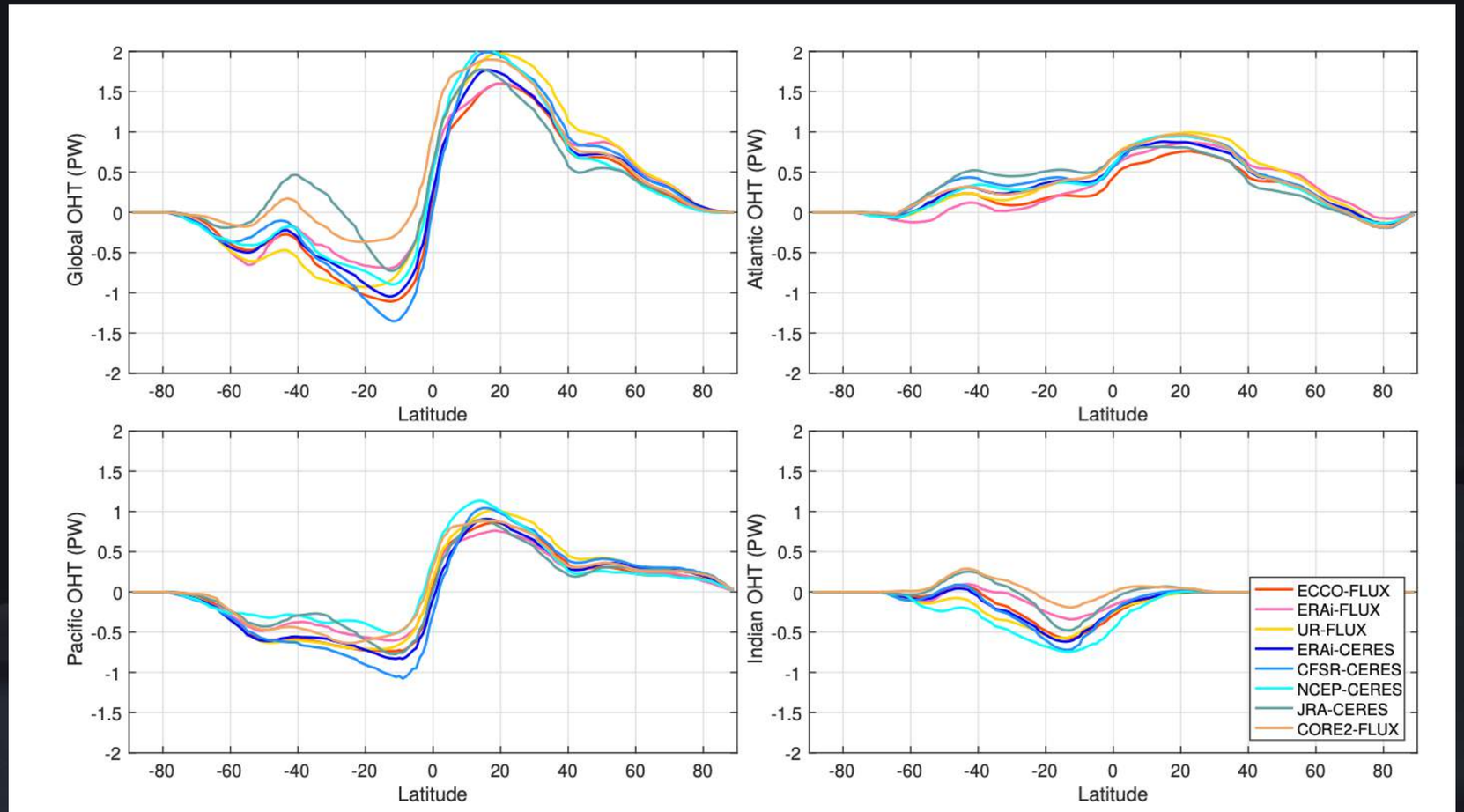


Figure S7: Meridional ocean heat transports (in PW) for the Global Ocean (top left), Atlantic (top right), Pacific (bottom left), and Indian (bottom right) inferred from various air-sea heat flux

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Forget & Ferreira 2019

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Nat. Geosci. **12**, 2019

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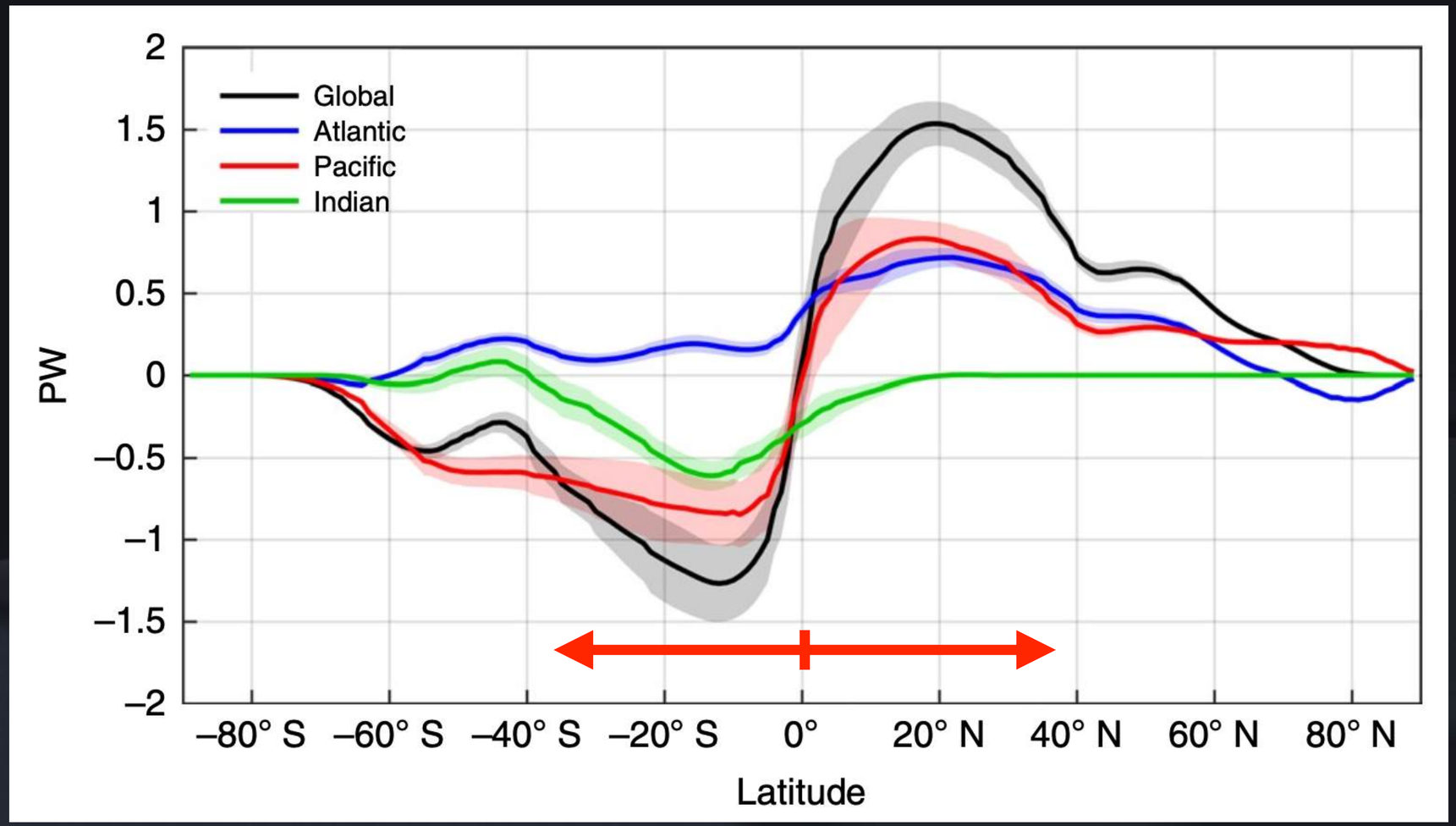
Ocean Heat Transport Climatology (ECCO4)

Is largely dominated by tropical oceans (sorry AMOC, but you are not #1)



Forget & Ferreira 2019

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Chapter 2

Ocean Heat Transport Under Global Warming

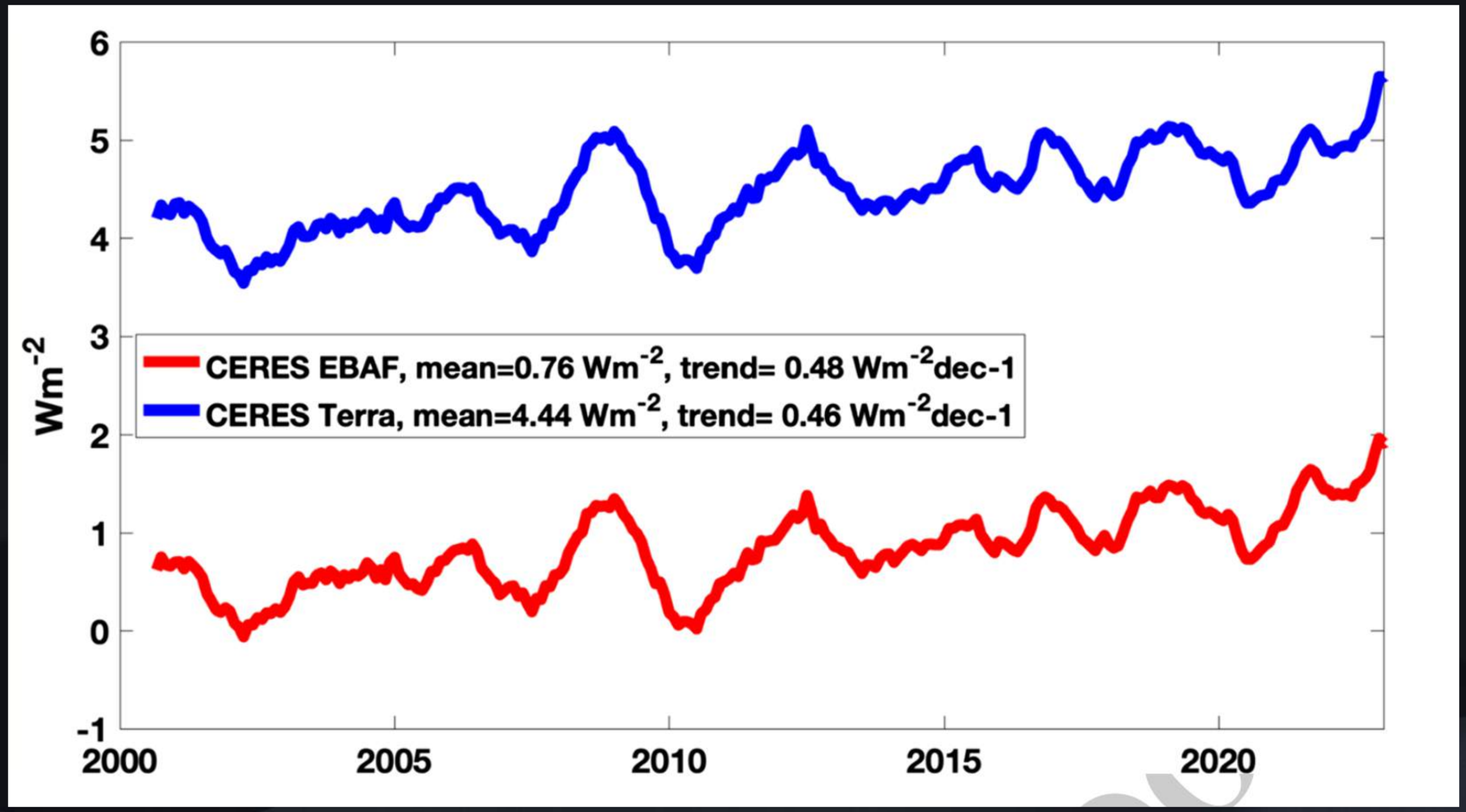
- Global Ocean Heat Content Trends
- Earth Energy Imbalance from Space
- *Let's track EI across the Ocean*
- *Let's pinpoint mechisms*

Earth Energy Imbalance from Space

Earth Energy Imbalance (W/m2)

= incoming - outgoing radiation at top of the Atmosphere

≈ the rate of global warming



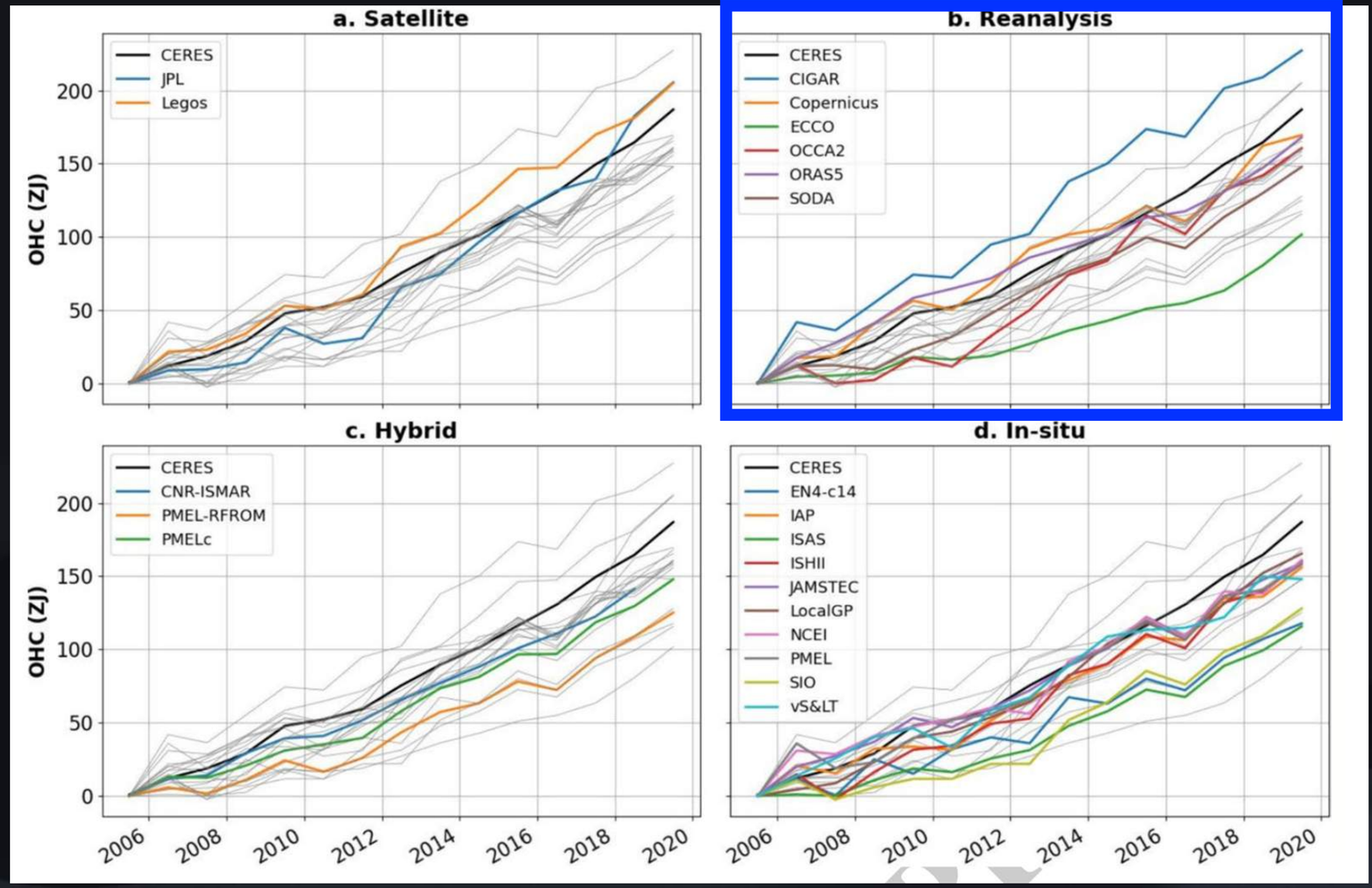
Trends and variability in Earth's energy imbalance and ocean heat uptake since 2005. *Hakuba, Fourest, Boyer, Meyssignac, Carton, Forget, et al.* Surveys in Geophysics, 2024

Rising Ocean Heat Content

Ocean Heat Uptake
(dOHT/dt)

is 90% of
Earth Energy Imbalance

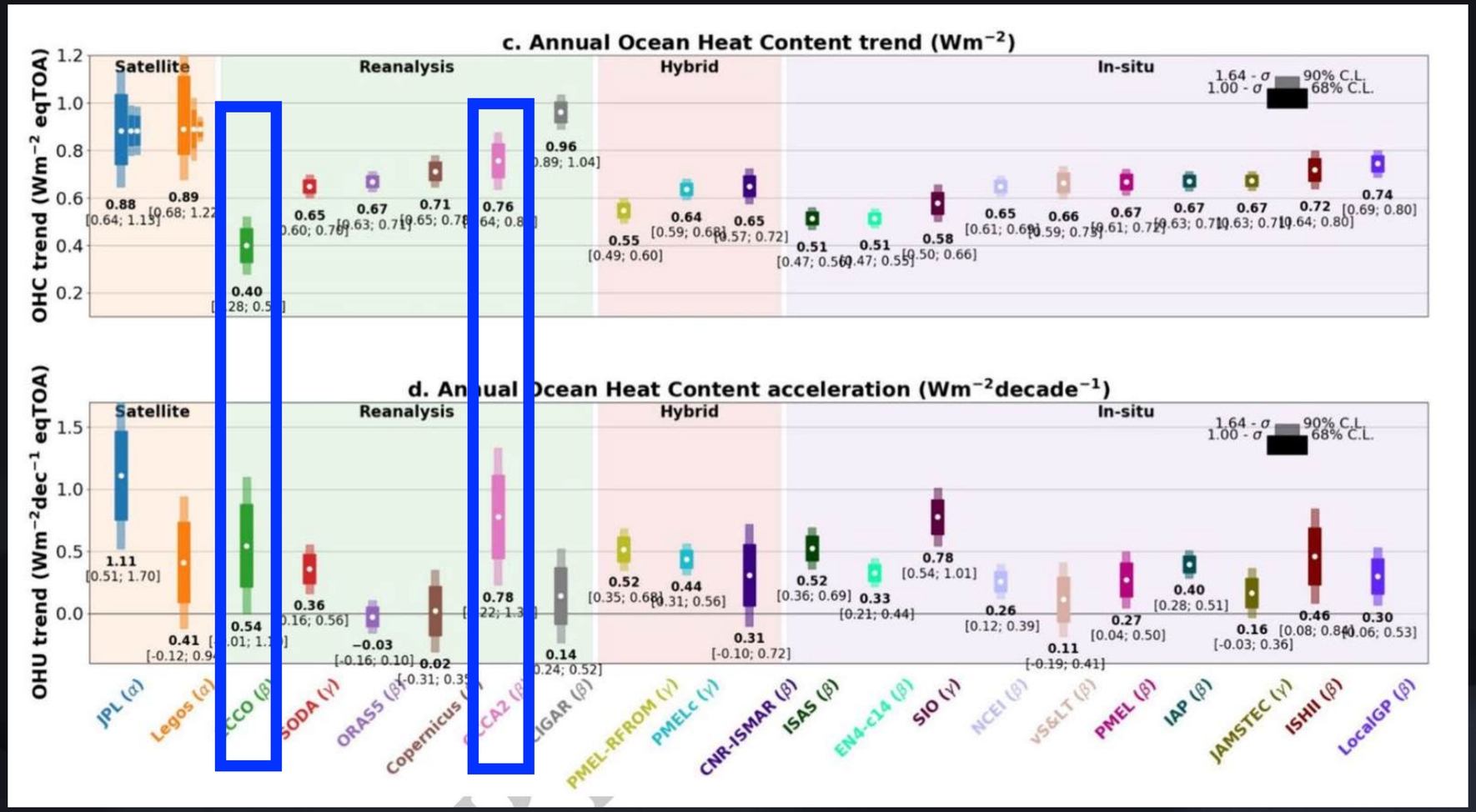
or 90% of the rate of
global warming



Trends and variability in Earth's energy imbalance and ocean heat uptake since 2005. *Hakuba, Fourest, Boyer, Meyssignac, Carton, Forget, et al.* Surveys in Geophysics, 2024

Ocean Heat Uptake and its Acceleration

- Broad agreement amongst estimates
- Heat Uptake of 0.5 - 1 W/m2
- Accelerating by 0 - 1 W/m2/decade



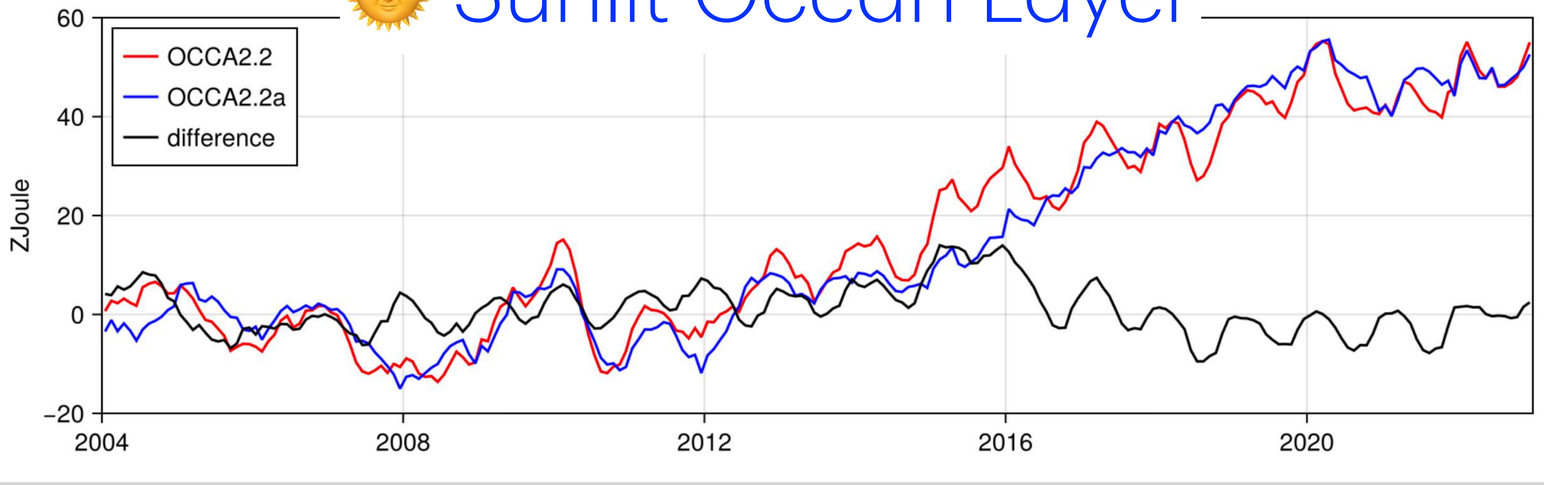
Trends and variability in Earth's energy imbalance and ocean heat uptake since 2005. *Hakuba, Fourest, Boyer, Meyssignac, Carton, Forget, et al.* Surveys in Geophysics, 2024

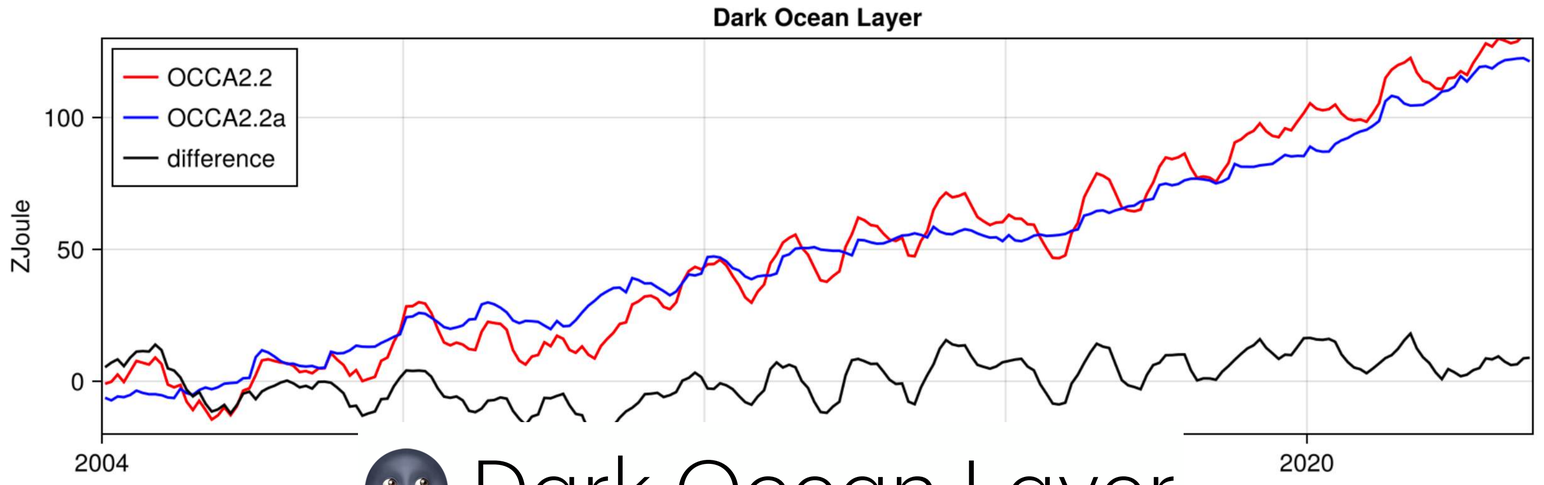
Tracking Earth Energy Imbalance in the Ocean

- OCCA2 is a close relative of OCCA1 & ECCO4
- 1980-2022, ERA5/ECCO4
- Budget : Sunlit v Dark Ocean Layer (200m)
- Two estimates : with Argo increment or not

Forget (in prep.)

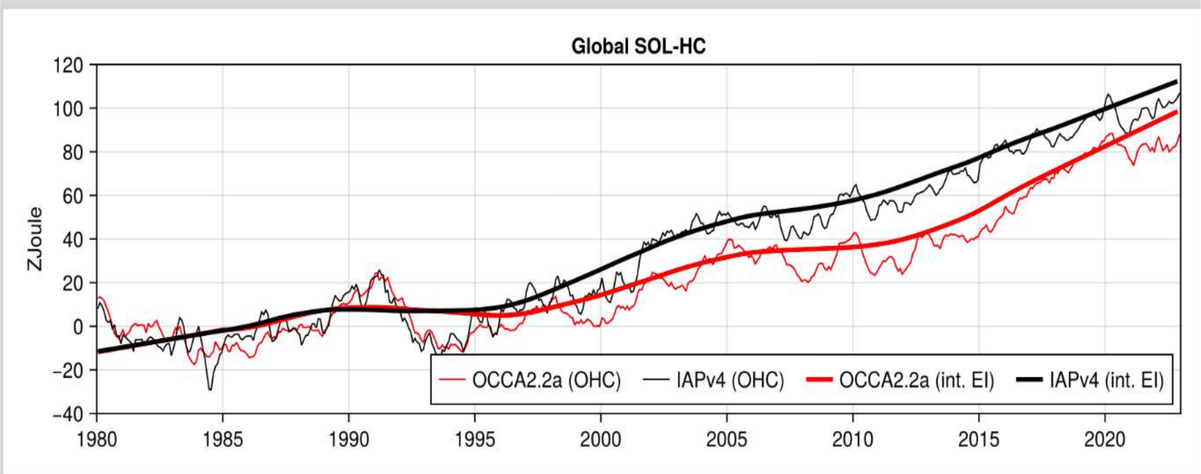
Sunlit Ocean Layer





Dark Ocean Layer

SOL Energy Imbalance (global mean)



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🌞 Sunlit Ocean Layer

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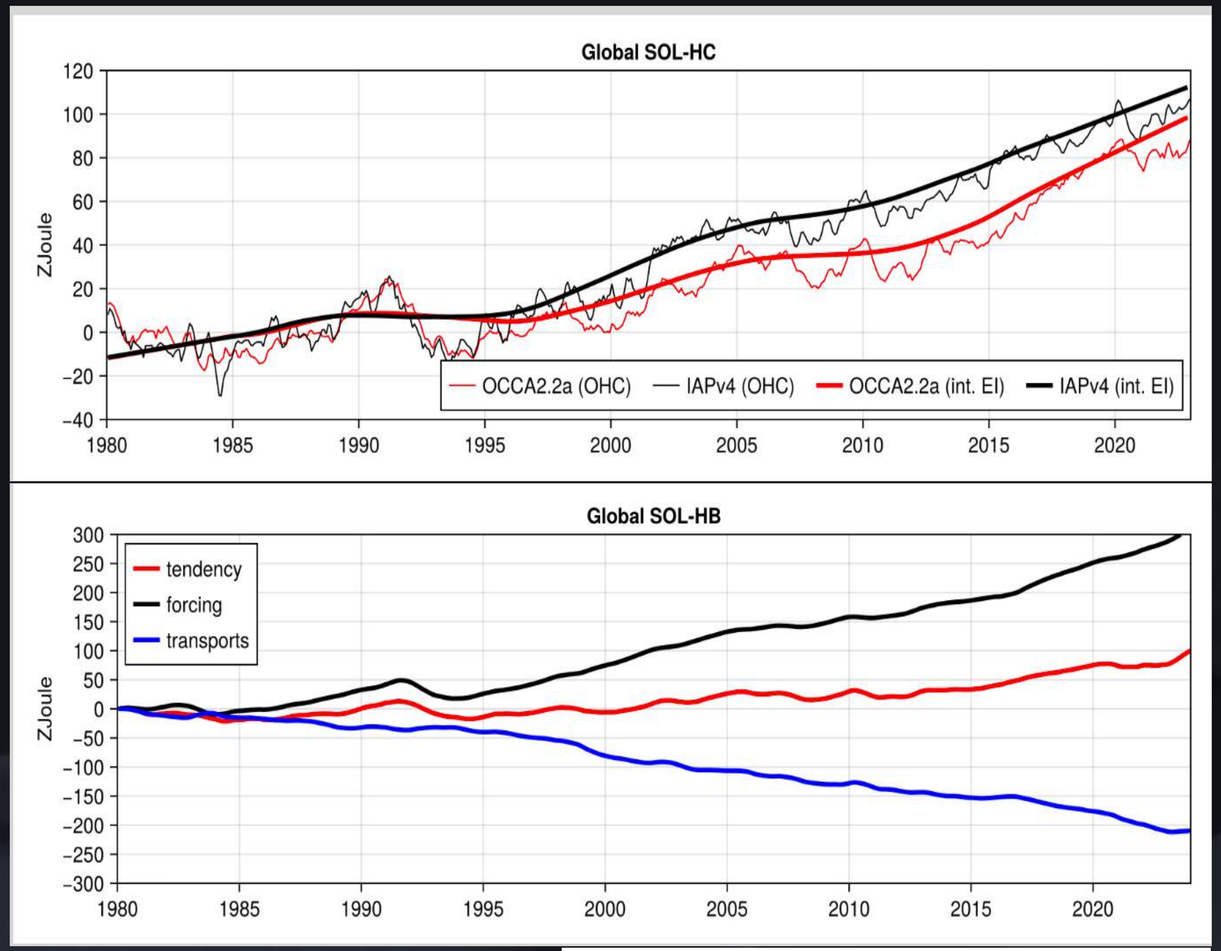

☀️ Sunlit Ocean Layer ☀️ Sunlit Ocean Layer

Forget (in prep.)

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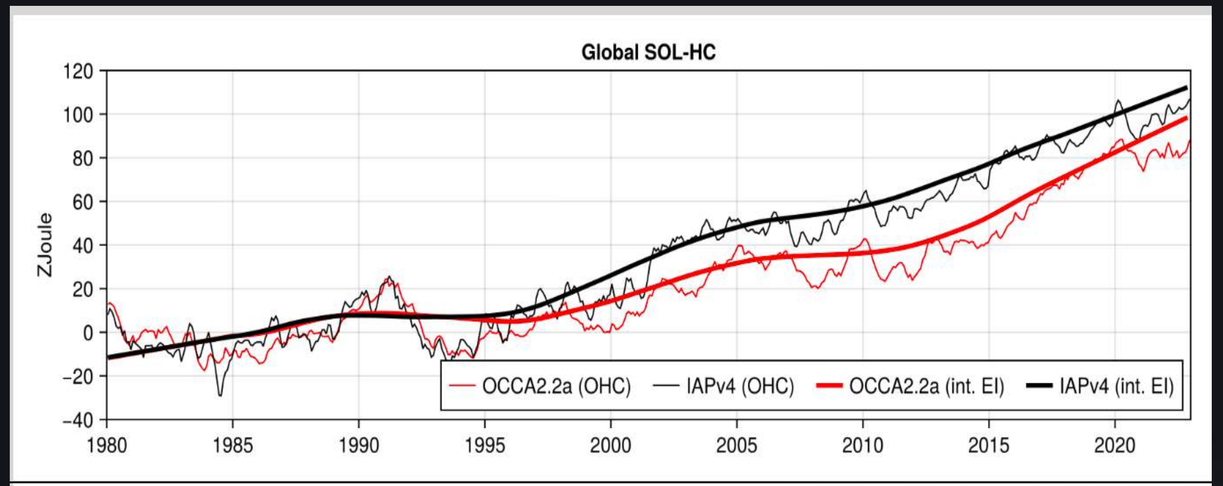

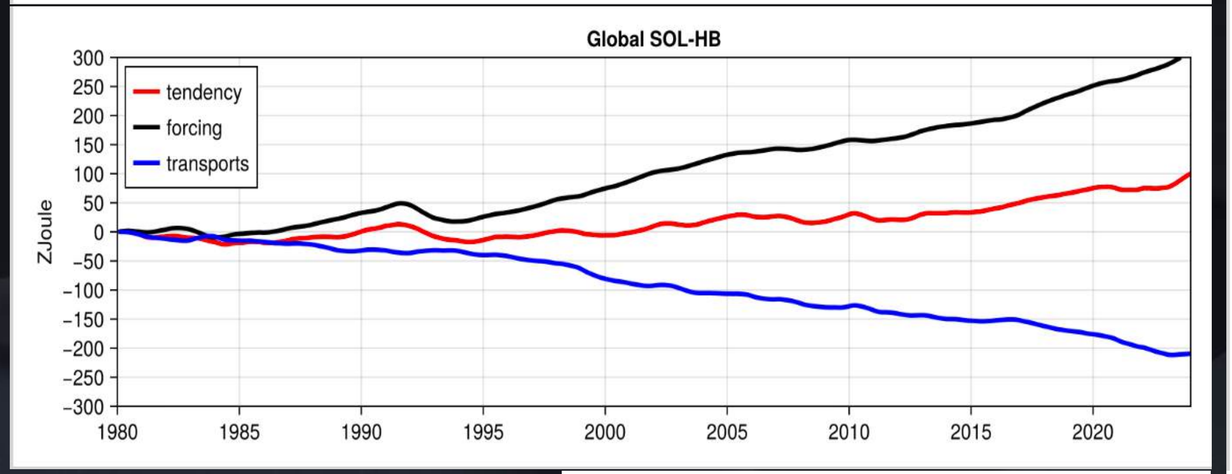

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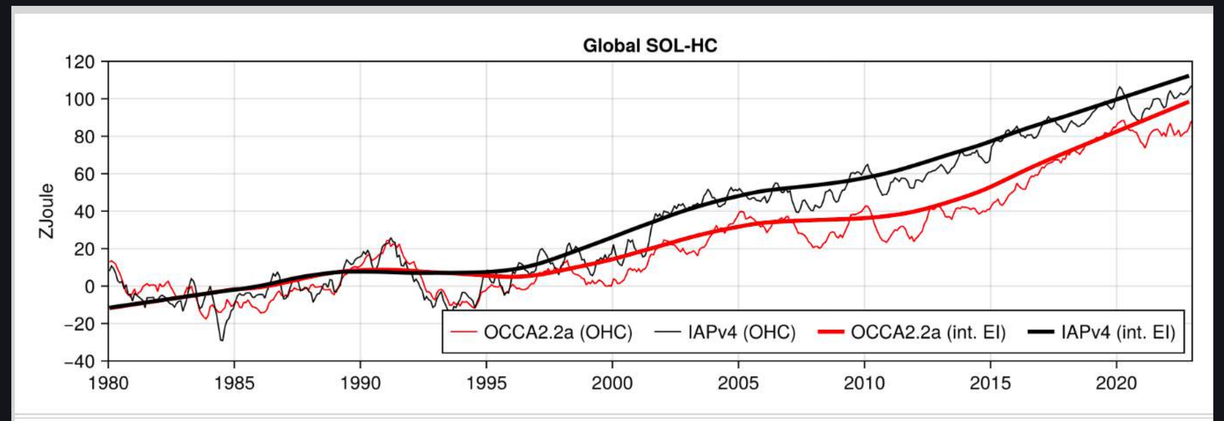
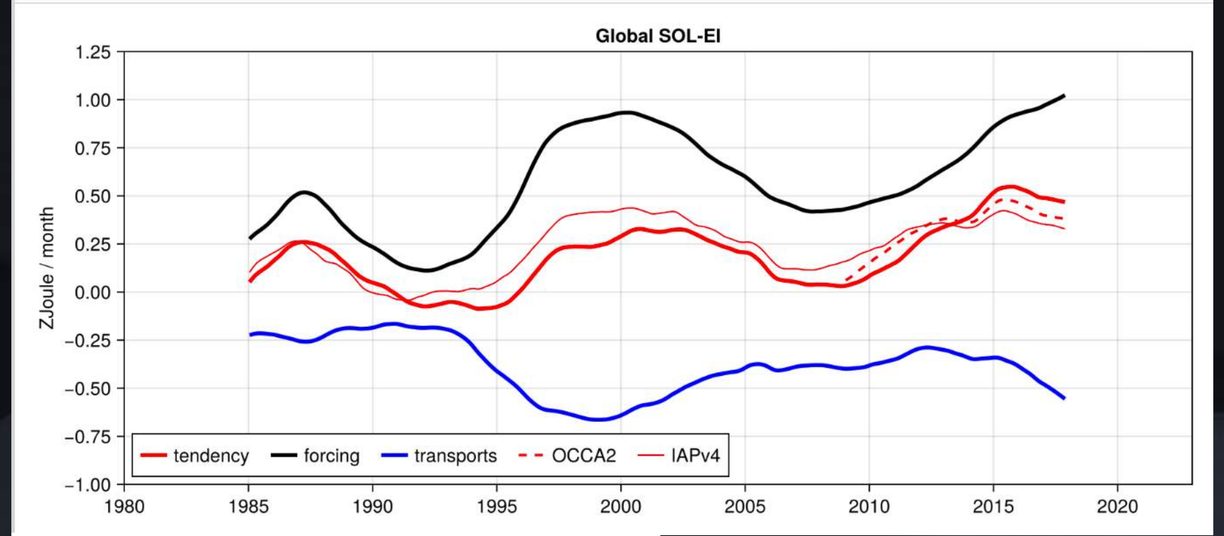




☀️ Sunlit Ocean Layer

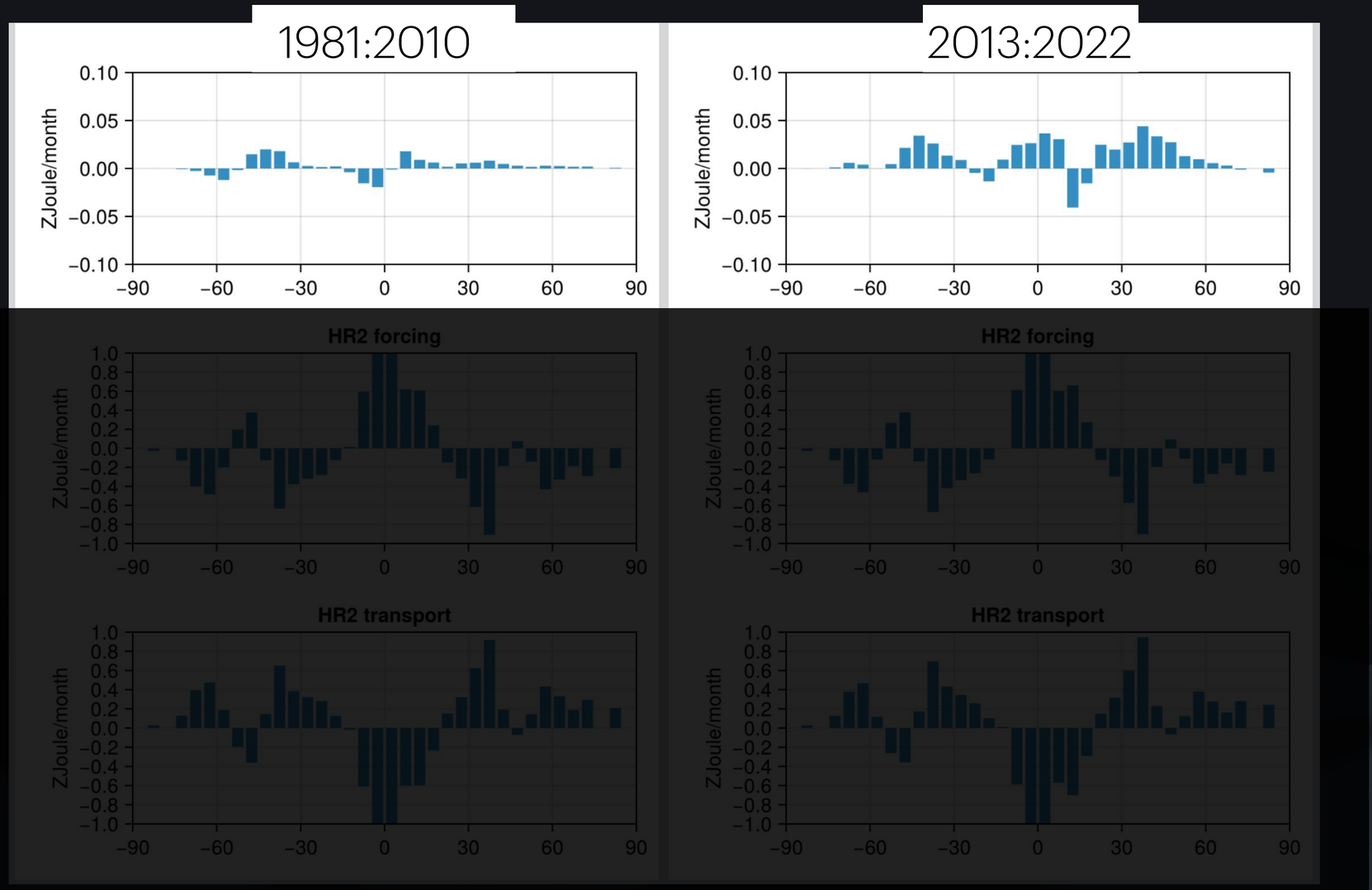
Forget (in prep.)

S.O.L. Heat Budget (geography)

Ocean Heat Content Trend

Net Air-Sea Heat Flux

Ocean Heat Transport Convergence



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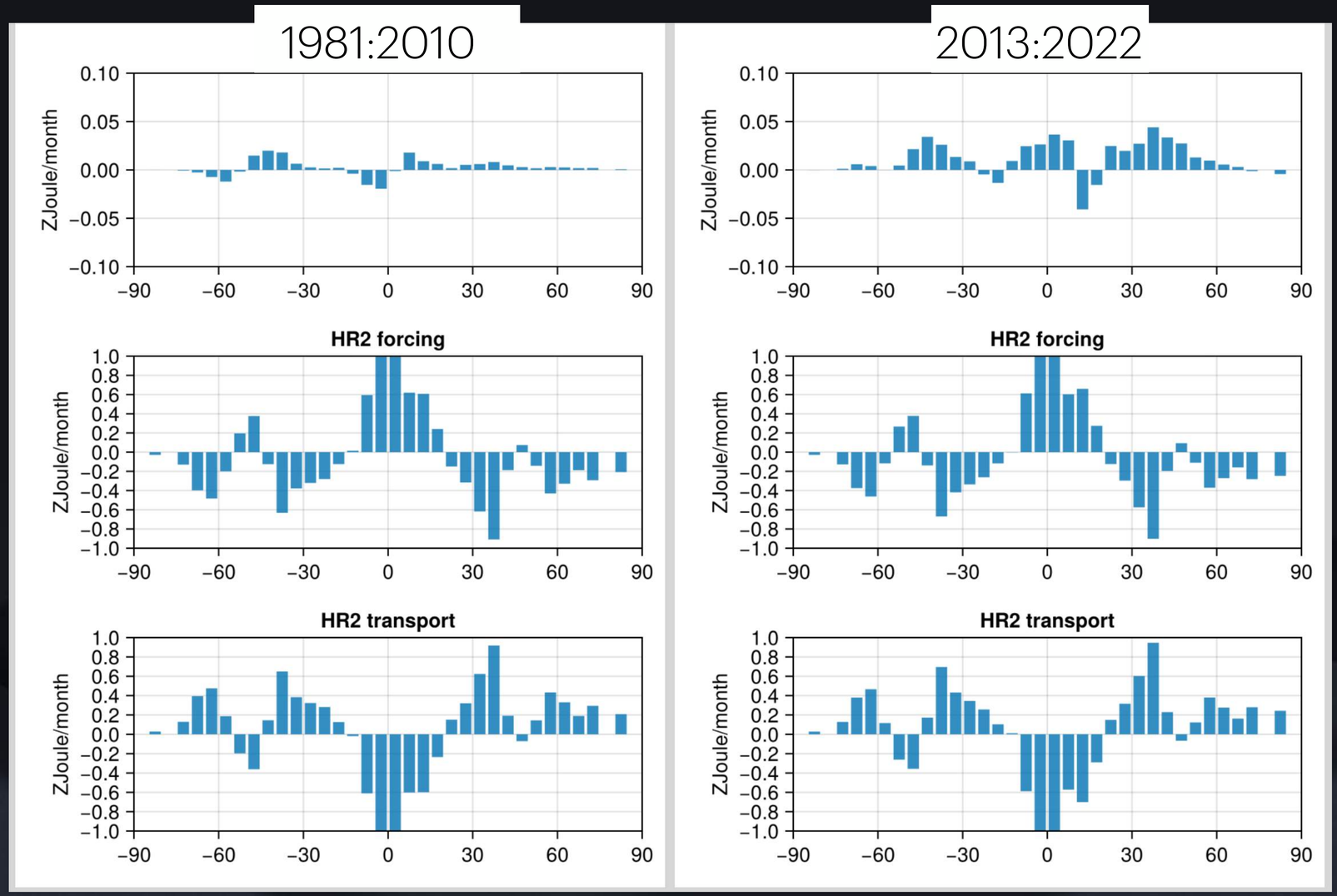

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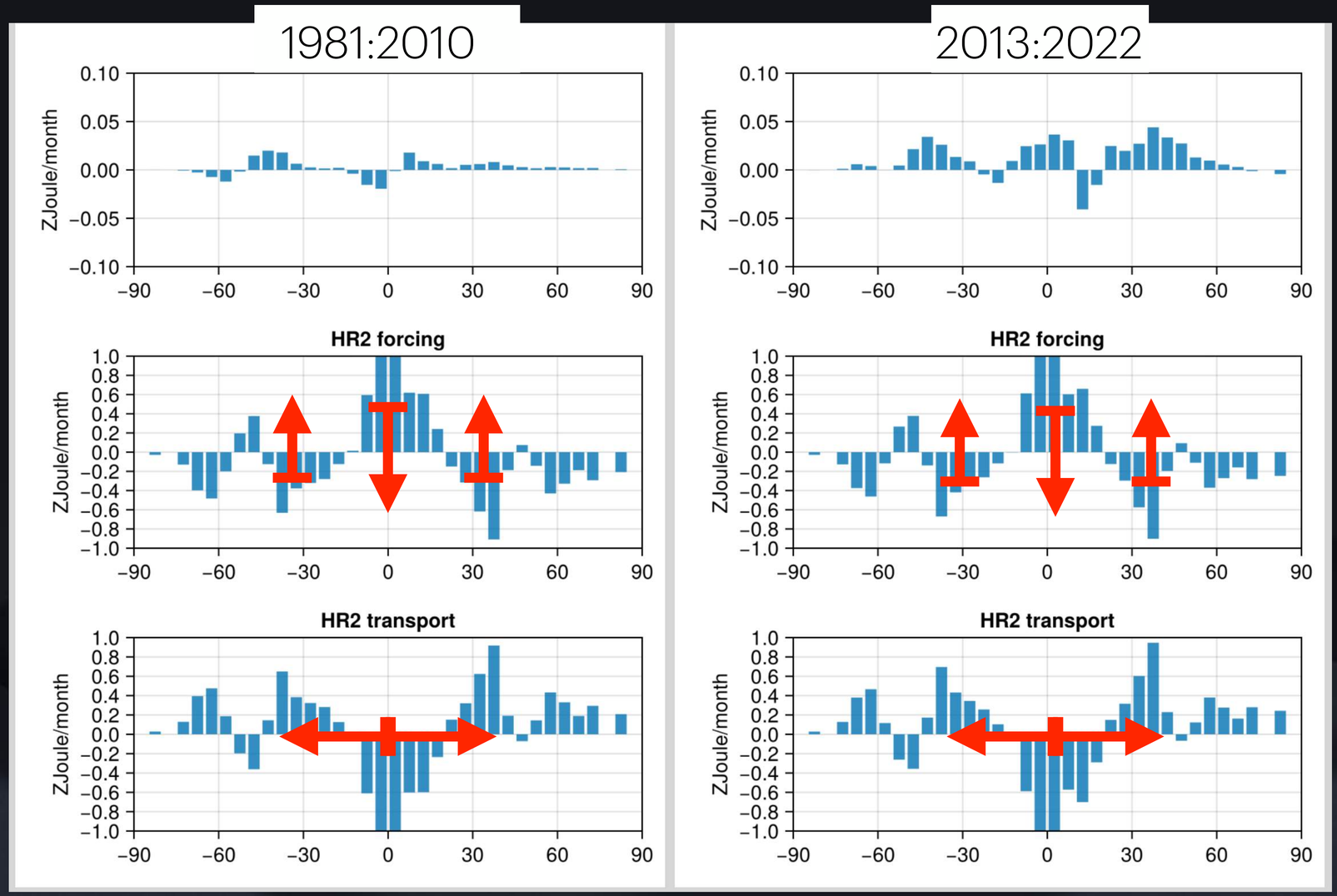

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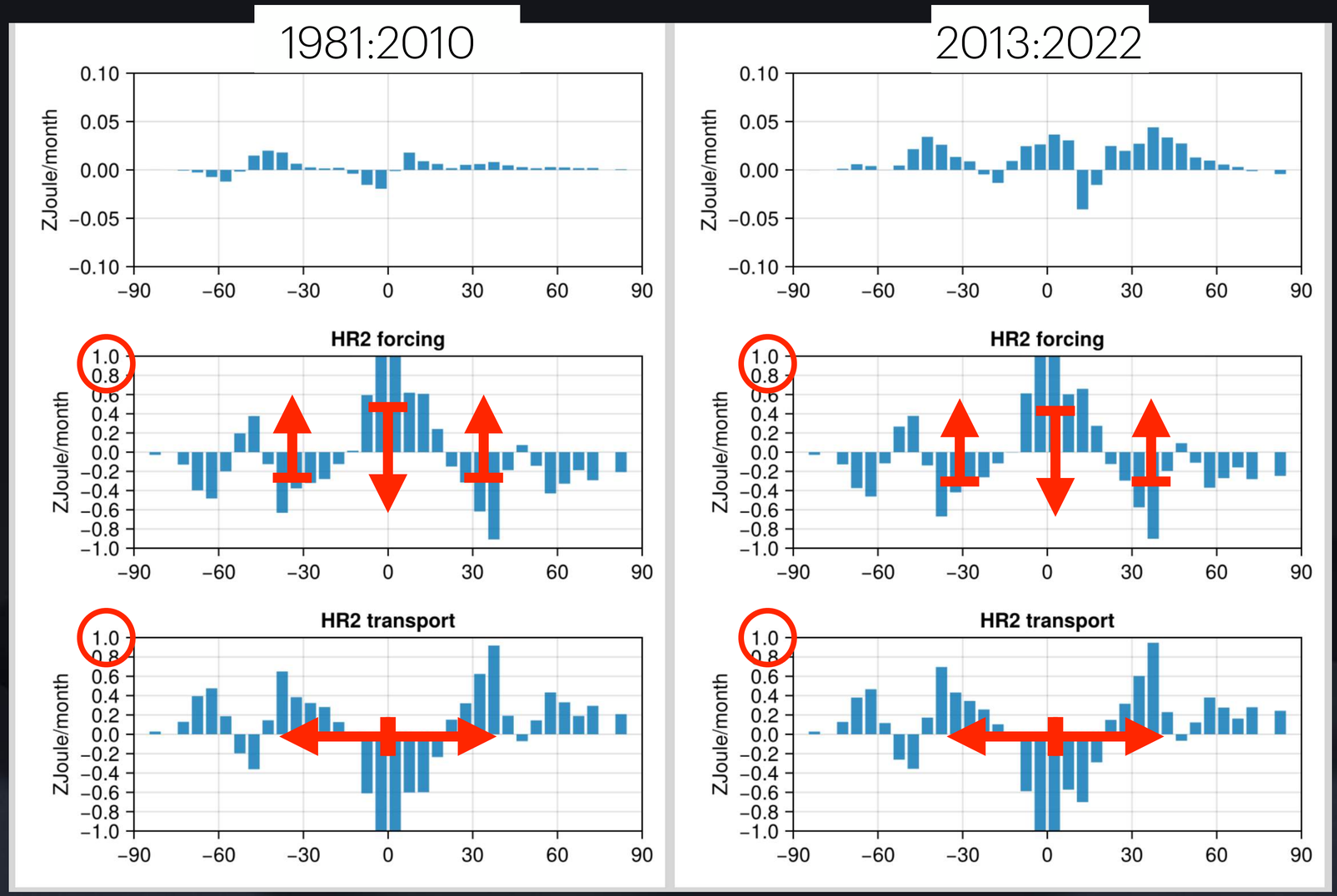


S.O.L. Heat Budget (geography)

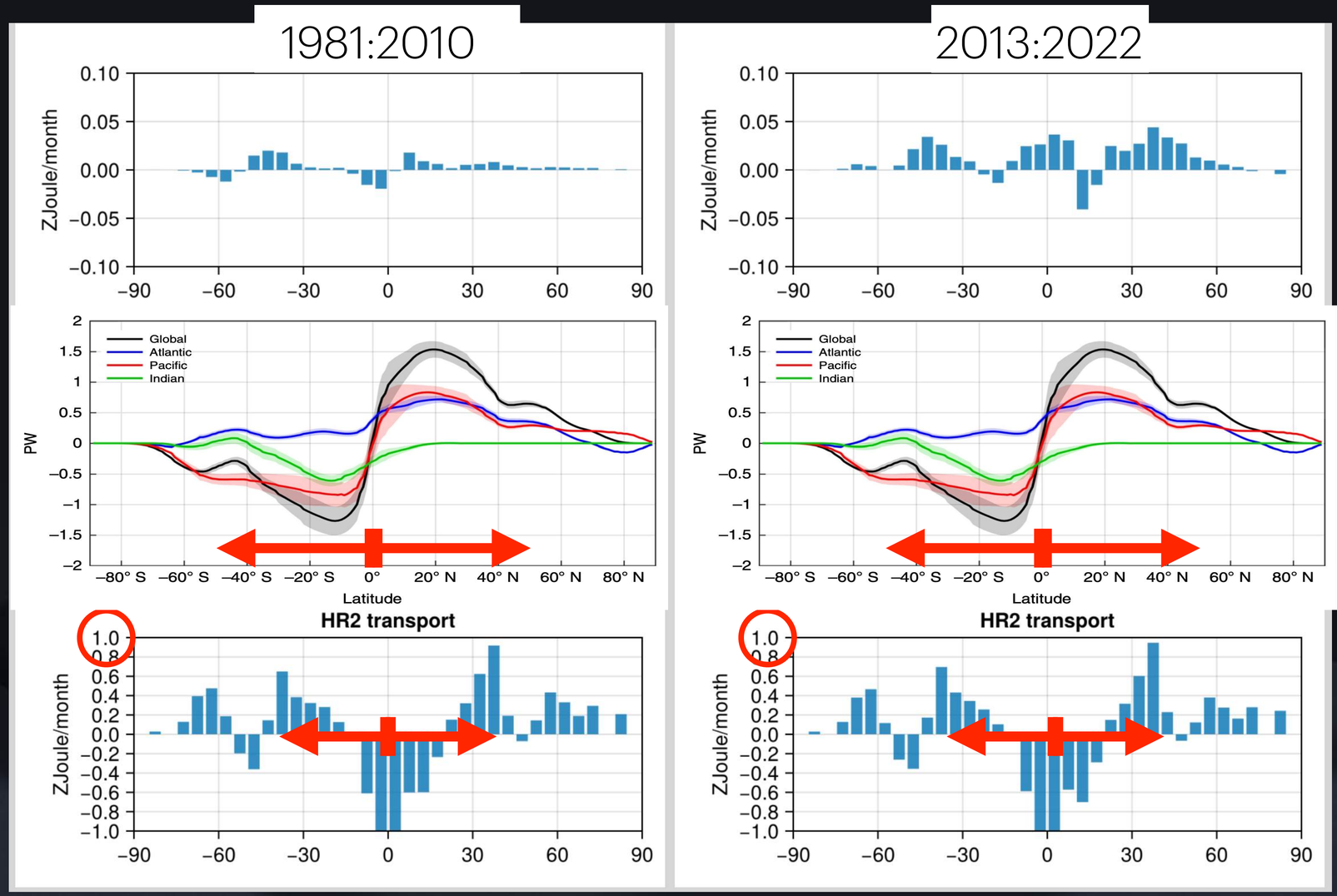
Ocean Heat Content Trend

Forget & Ferreira 2019. (Nat. Geoscience)

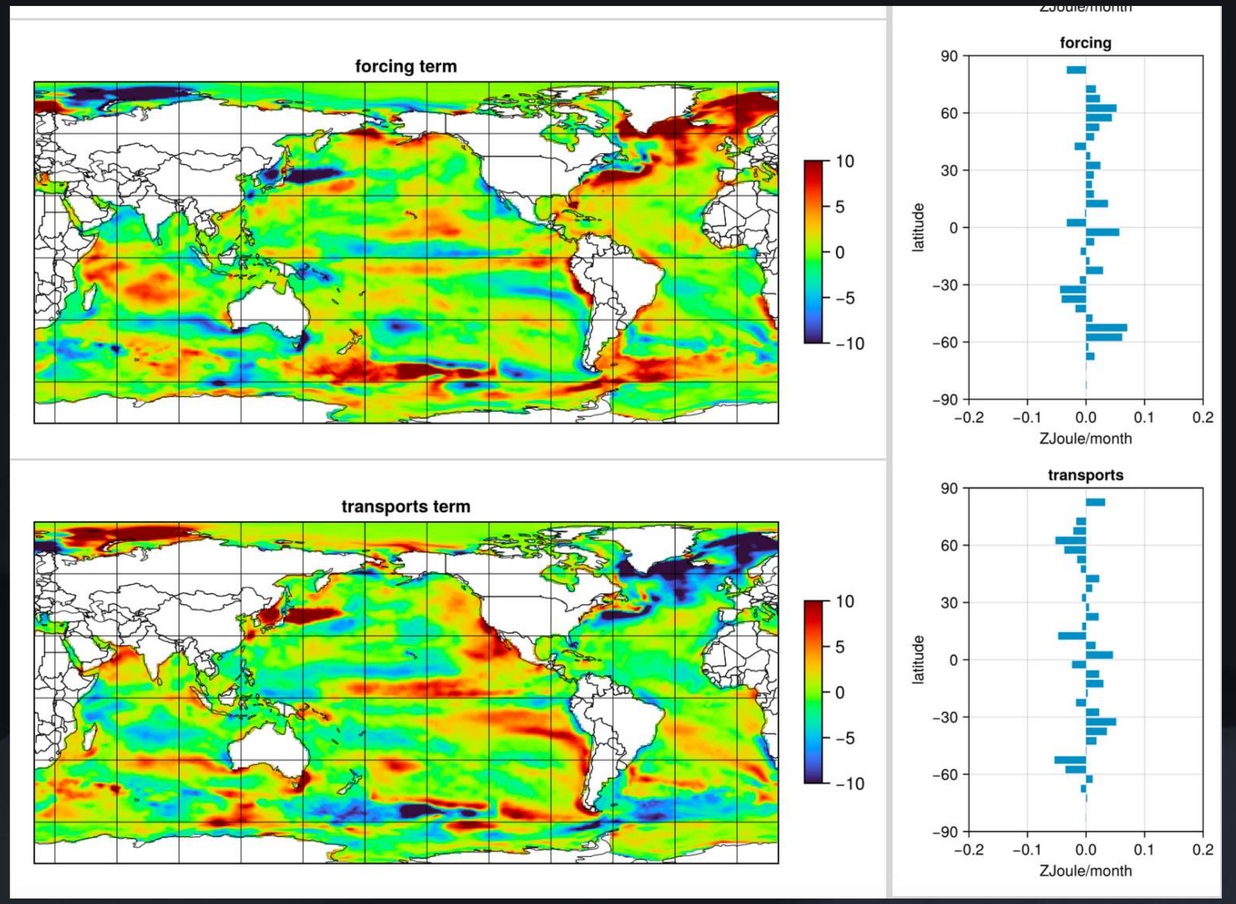
https://doi.org/10.1038/s41561-019-0333-7

Ocean Heat Transport Divergence

Forget (in prep.)



S.O.L. Energy Imbalance (geography)



Forget (in prep.)

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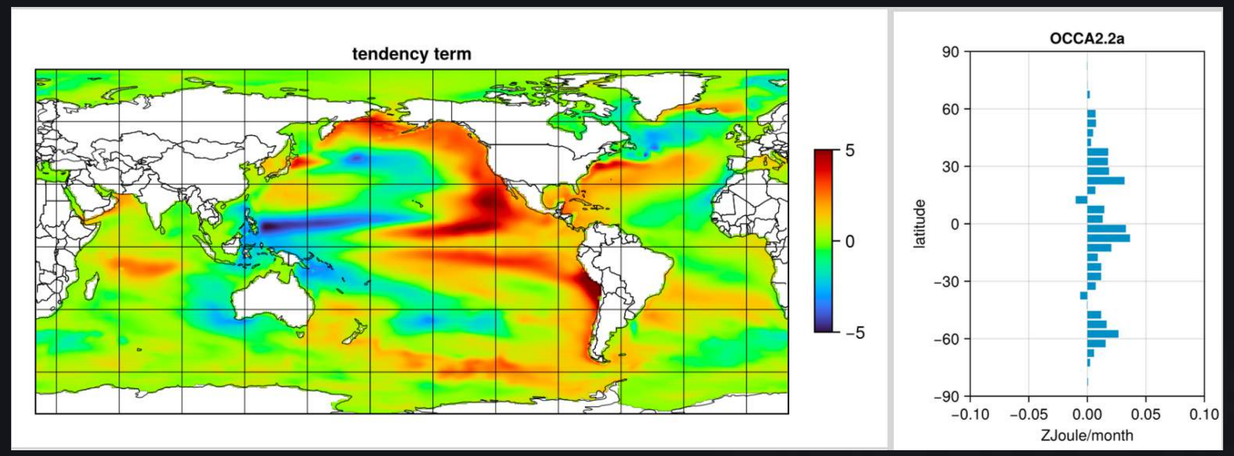

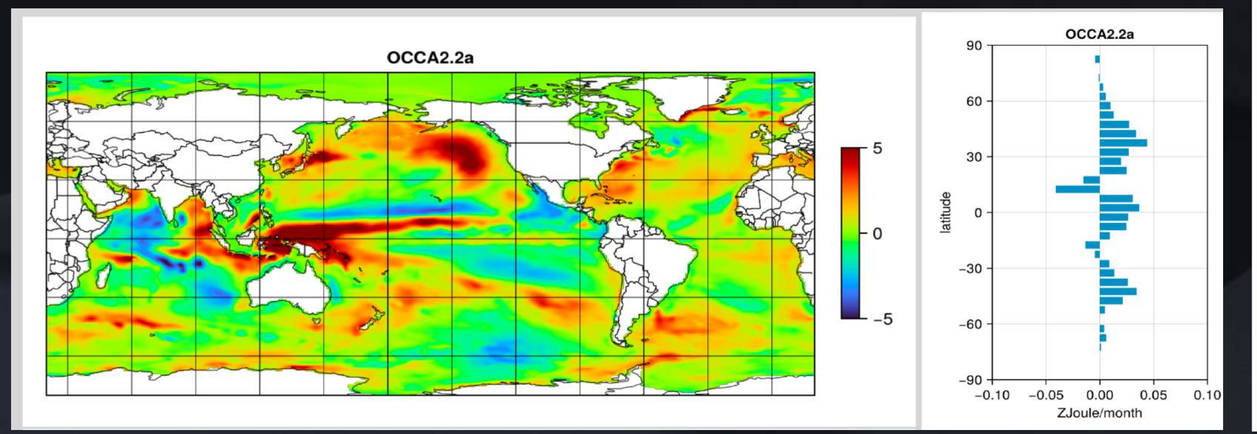

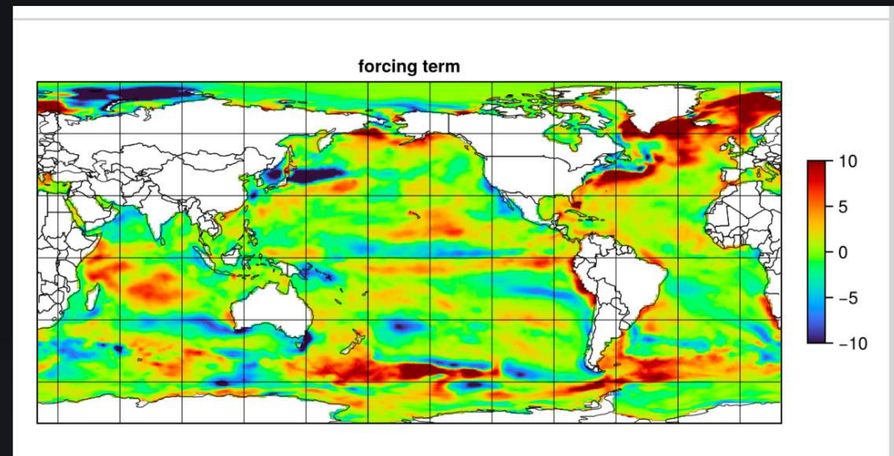

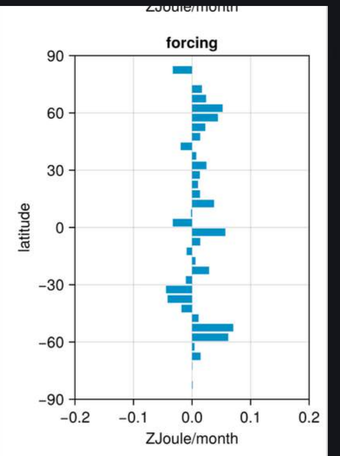

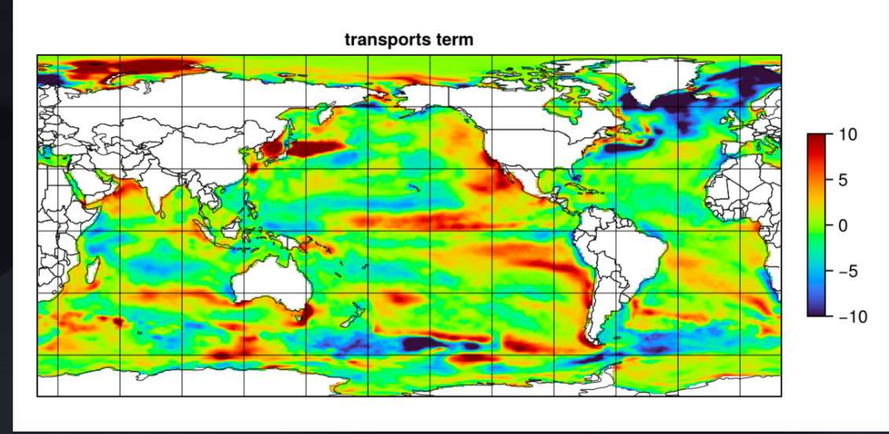

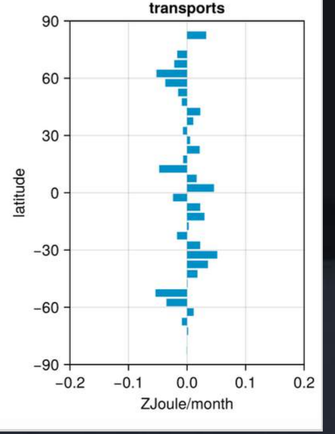

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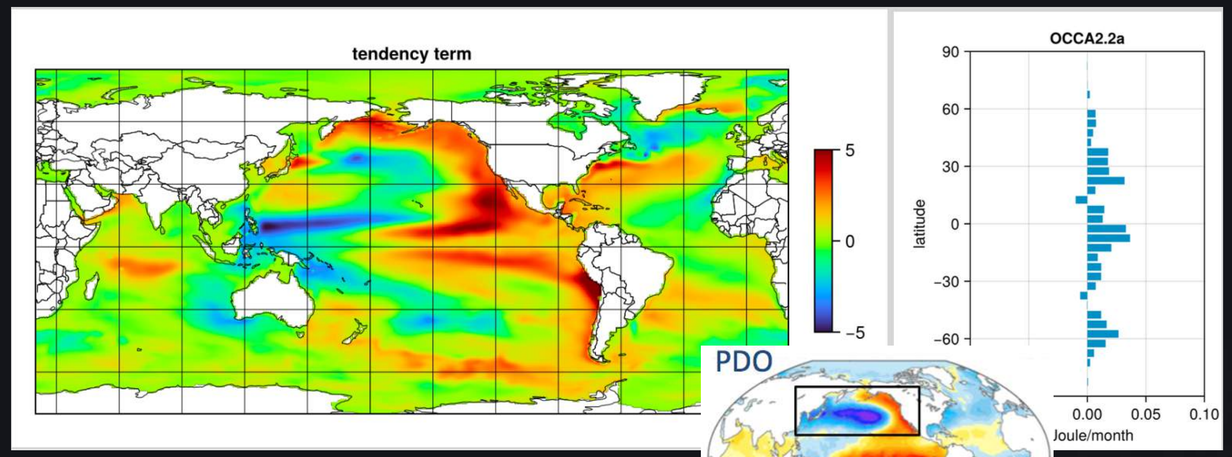
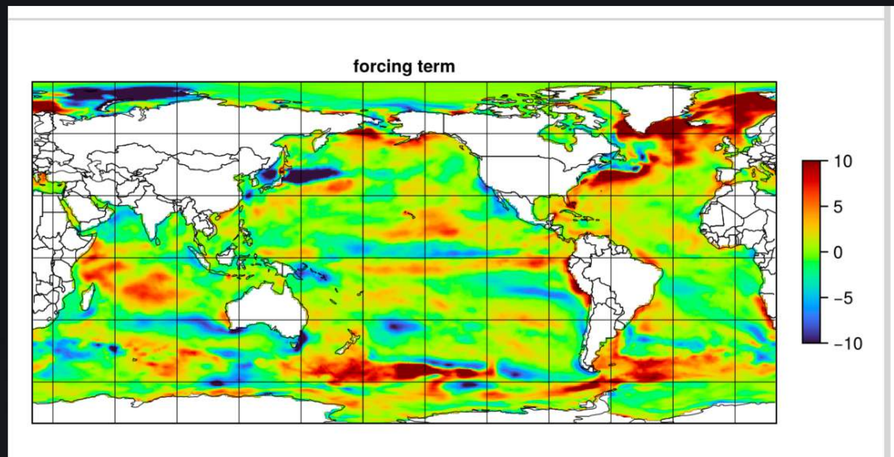
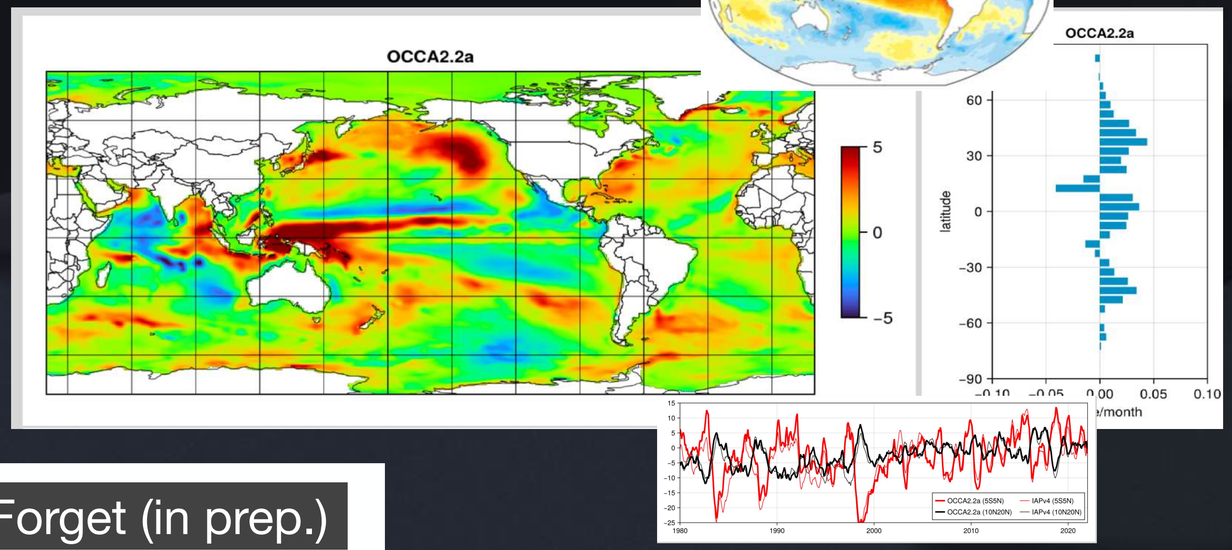
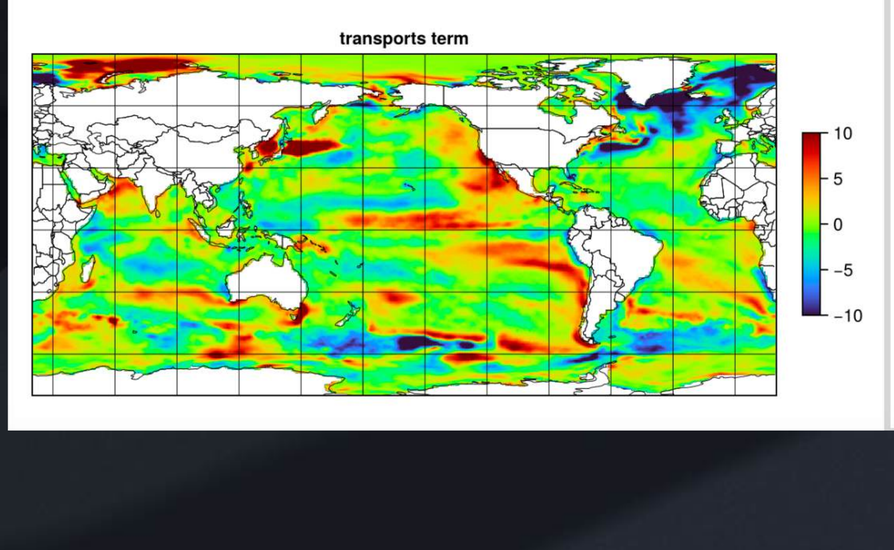




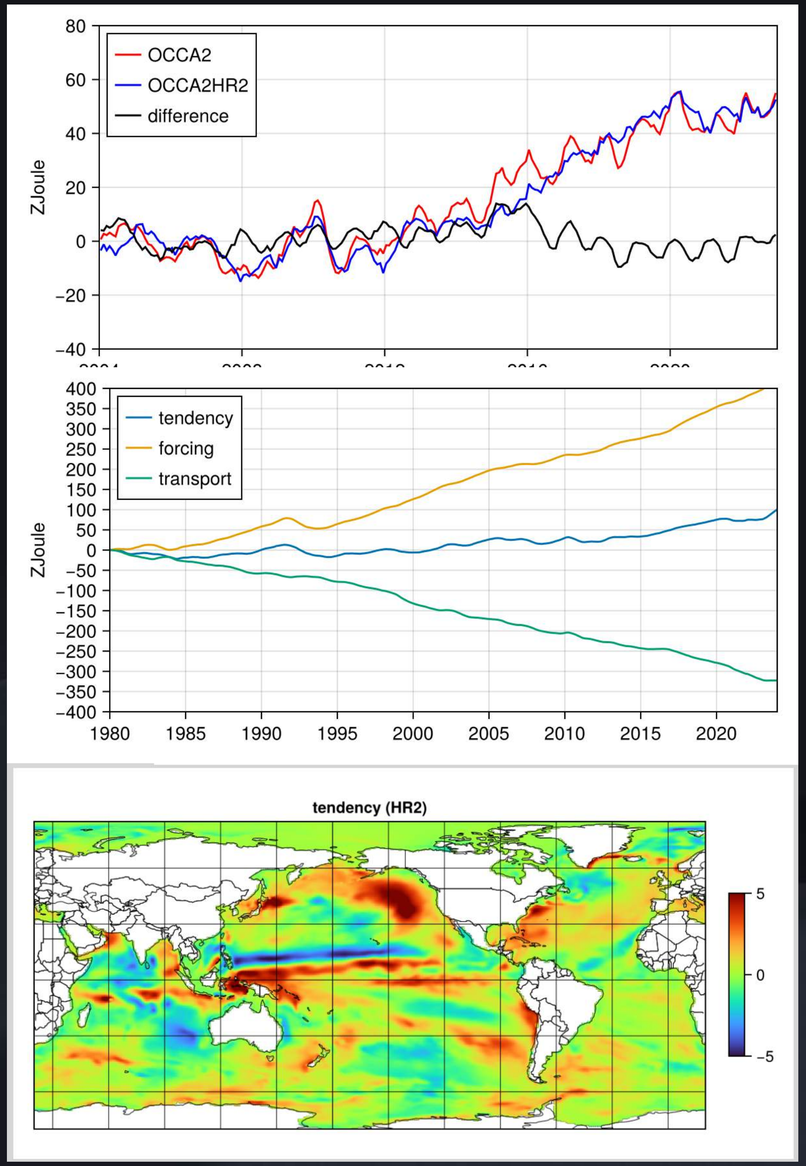




Forget (in prep.)

Take Aways

- Increased accumulation of Energy Imbalance in the Sunlit Ocean Layer in past decade
- Reflects the unabated rate of Energy imbalance (between Qnet & OHT divergence)
- The geography of SOL-EI is complex but can only be elucidated by subtracting mean budget
- Regions that show prominent warming are not necessarily those where air-sea heat flux is increasing
- Moving forward we must better account for dQnet/dt and dOHT/dt, which cannot just be backed out from dOHC/dt

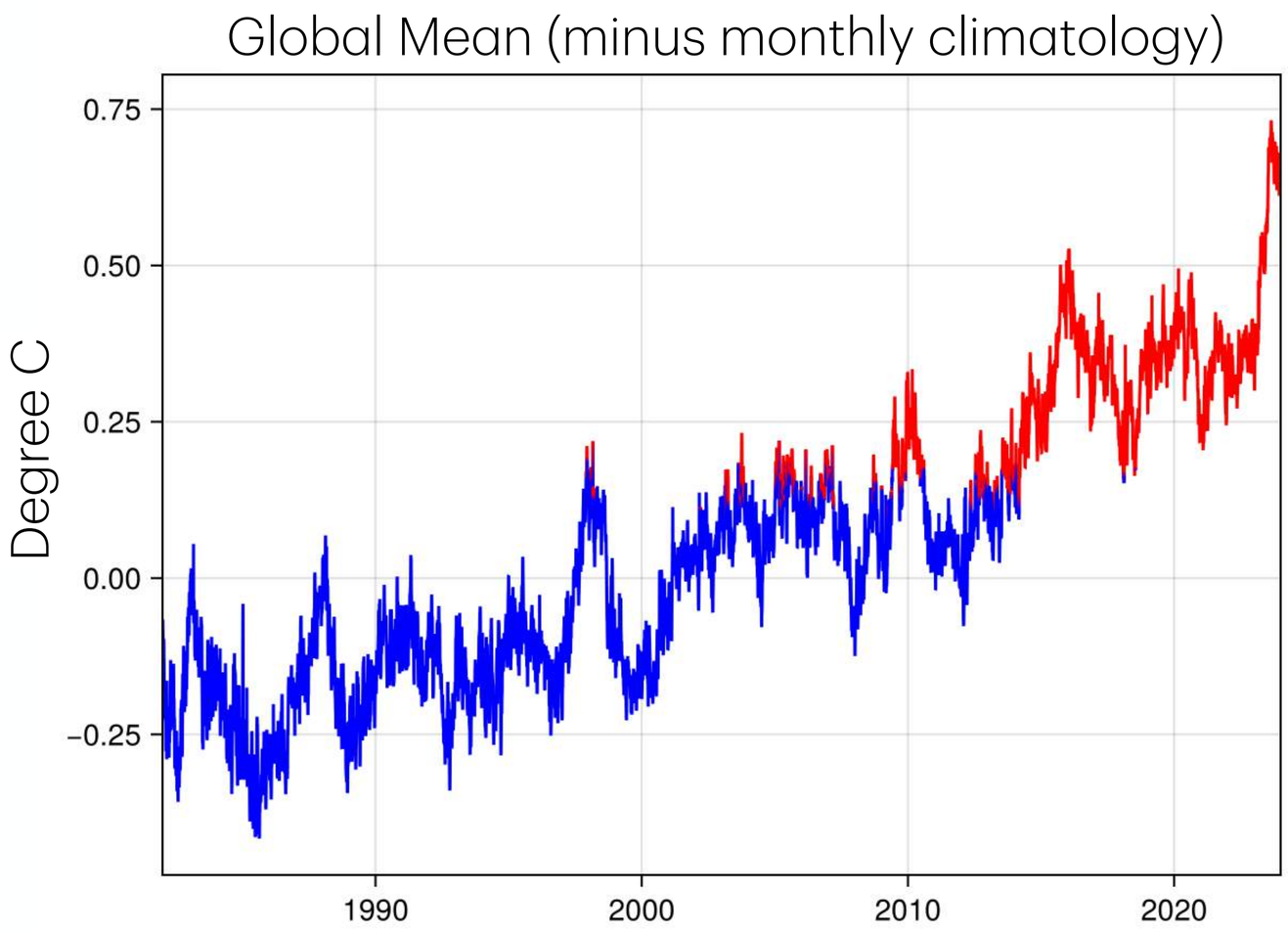


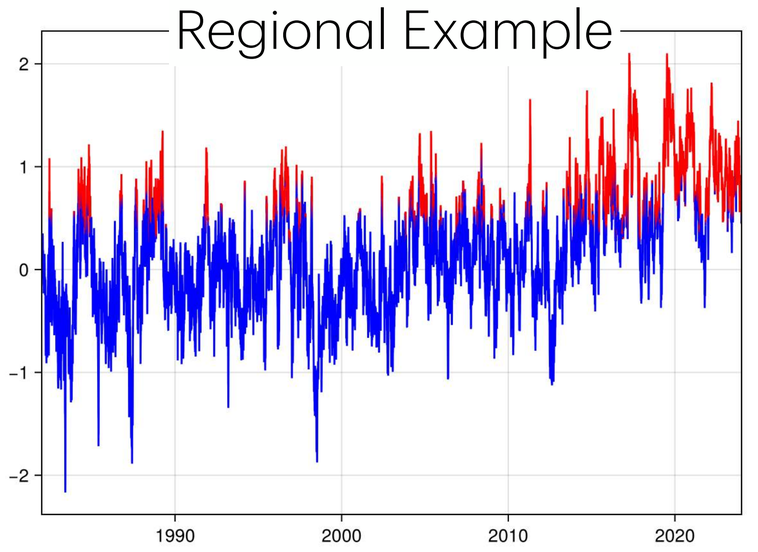
Chapter 3

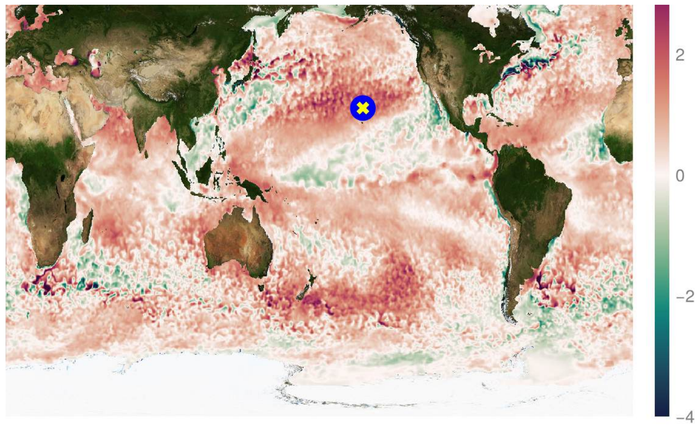
Tracking marine heat waves and water masses

1. Sea Surface Temperature Anomalies
2. Volume Budgets for Marine Heat Waves
3. Lagrangian Budgets for Marine Heat Waves
4. Tracking Subducted Anomalies
5. Mode Water Source Regions

Sea Surface Temperature Anomalies



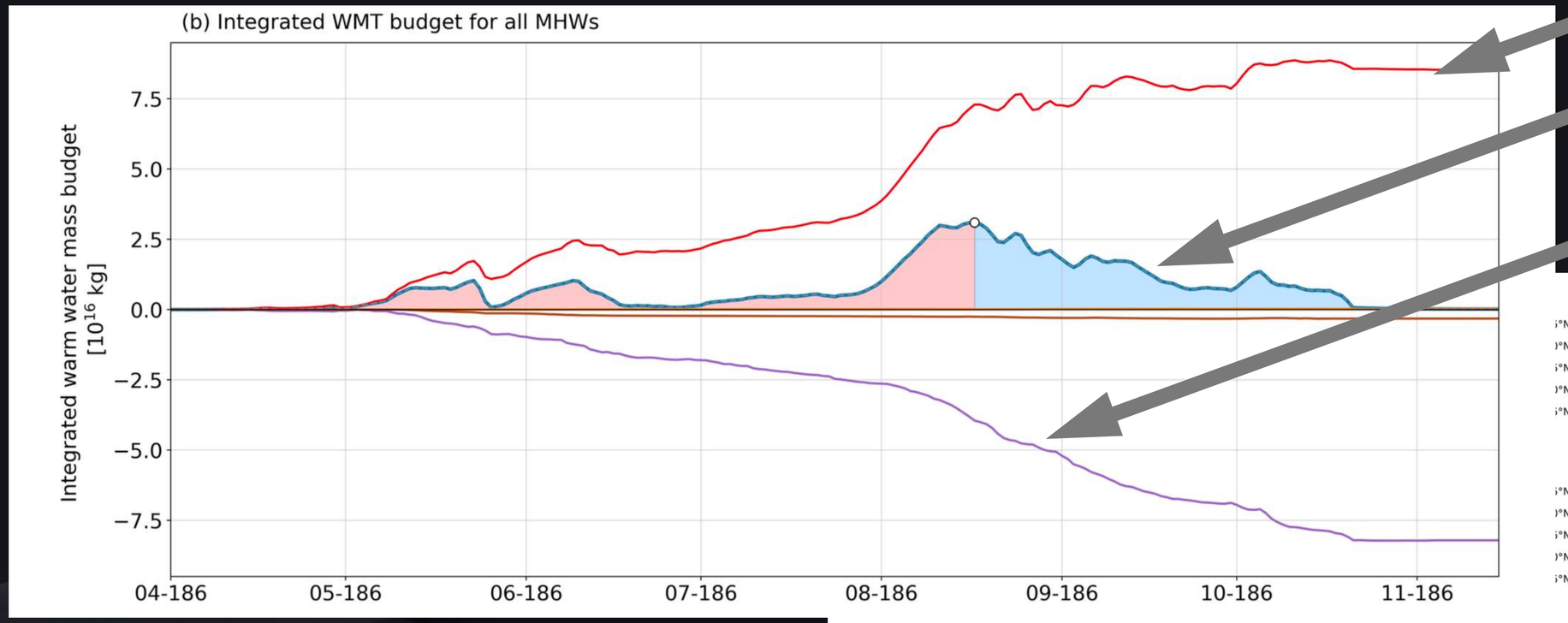




Clear warming trend and possible acceleration. Data Source : NOAA NCEI.

Volume Budgets for MHWs

Torres, Drake, Forget, et al (in prep)



- Air-sea flux
- Mass / Volume
- Mixing

Volume budget for these marine heatwaves (T>29)

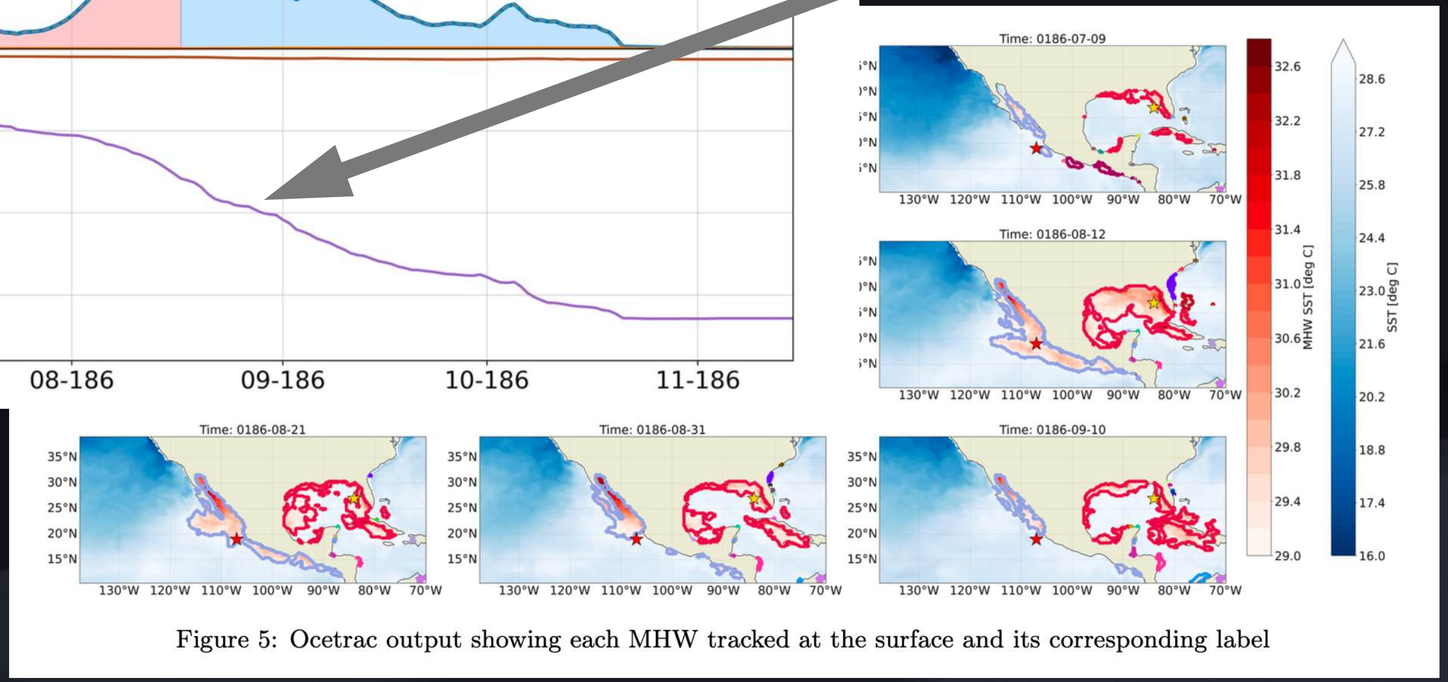


Figure 5: Ocetrac output showing each MHW tracked at the surface and its corresponding label

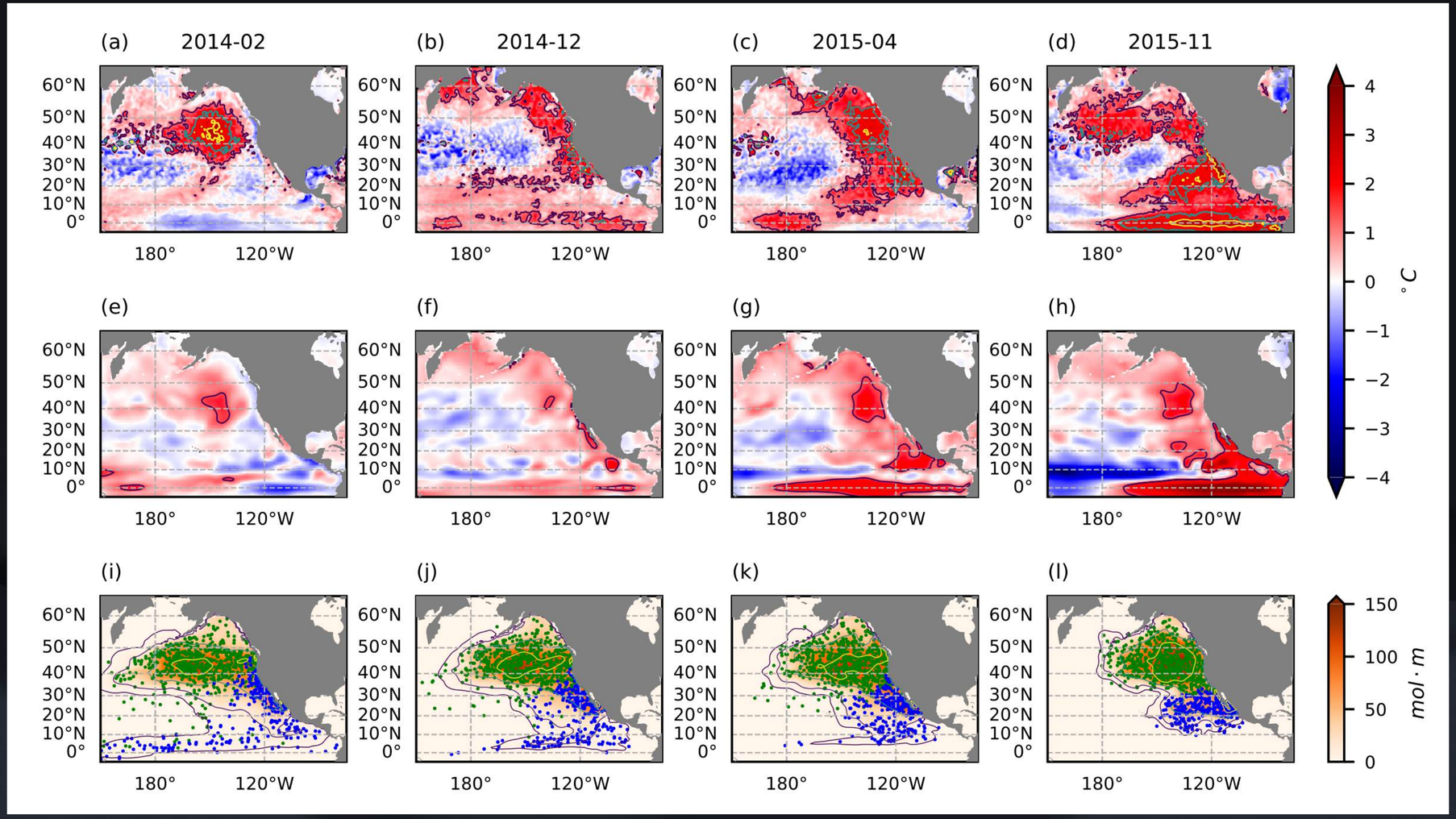
Lagrangian Marine Heat Wave Budgets

Jiang, Forget, Song, Haine (in prep)

SST anomalies

0-150m depth temp. anomalies

Particle Tracking & Passive Tracers



Tracking Subducted Anomalies

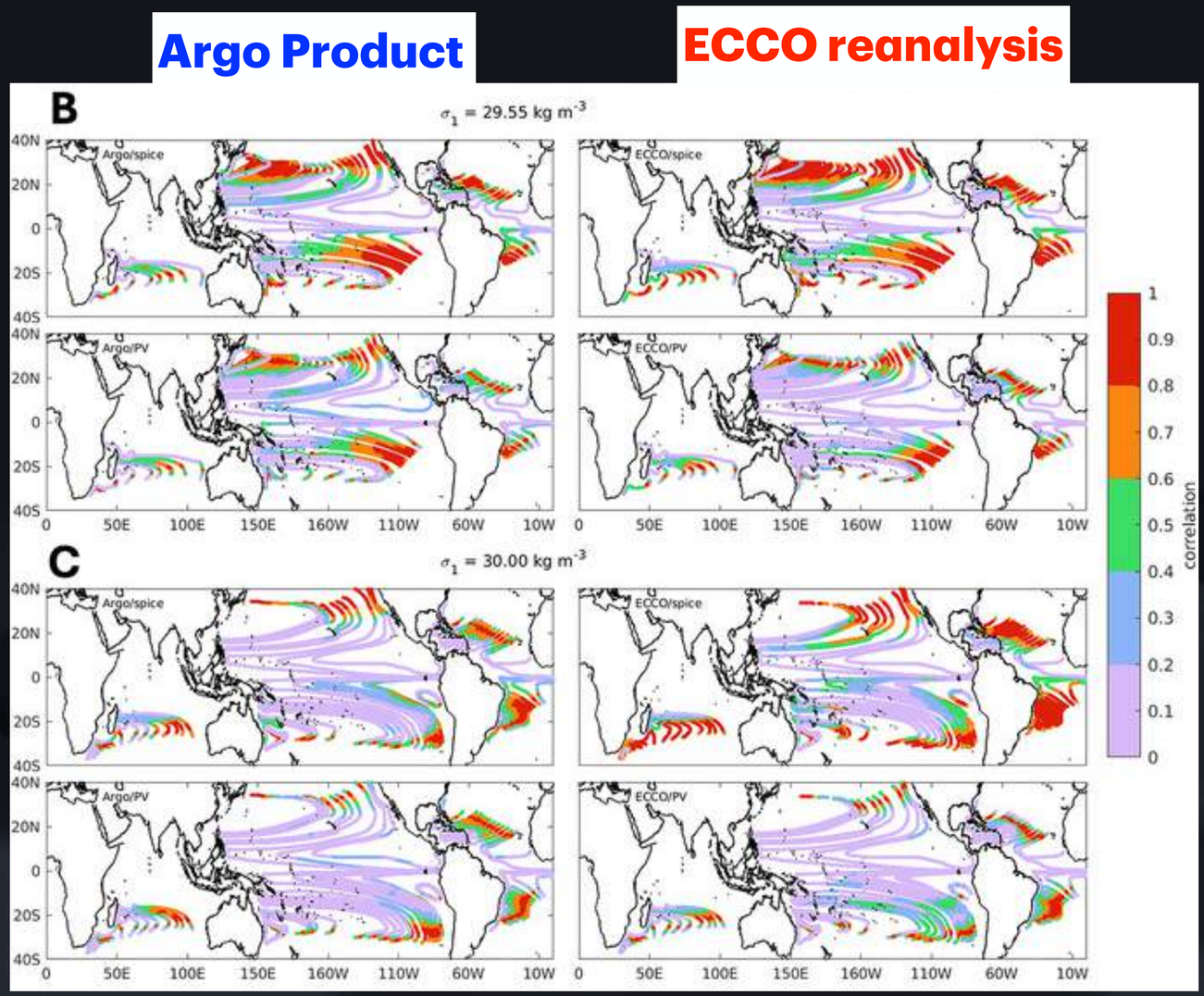
Hersh, Wjiffels, Gebbie, Forget 2025

Spice Anomalies

PV anomalies

Spice Anomalies

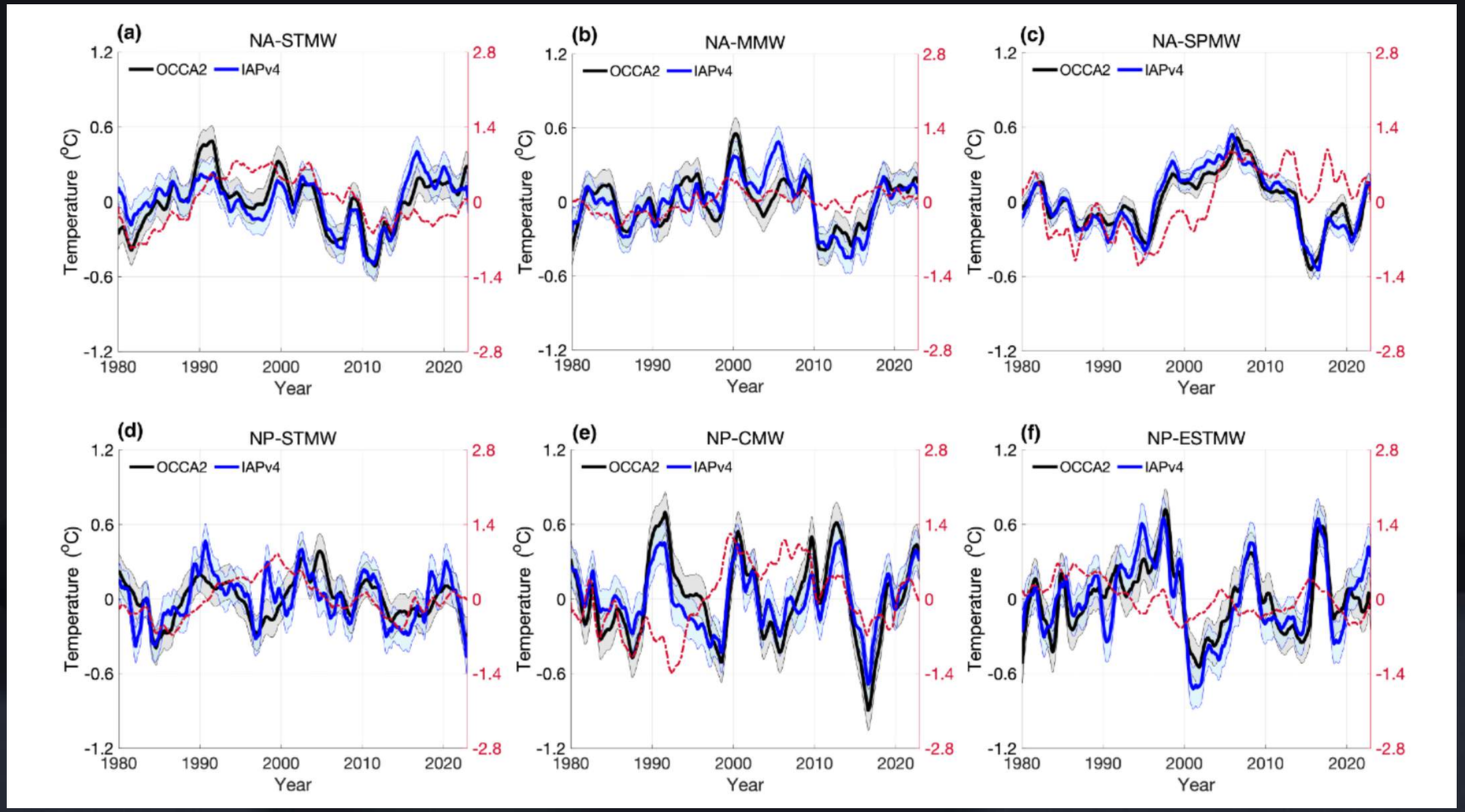
PV anomalies



Mode Water Source Regions

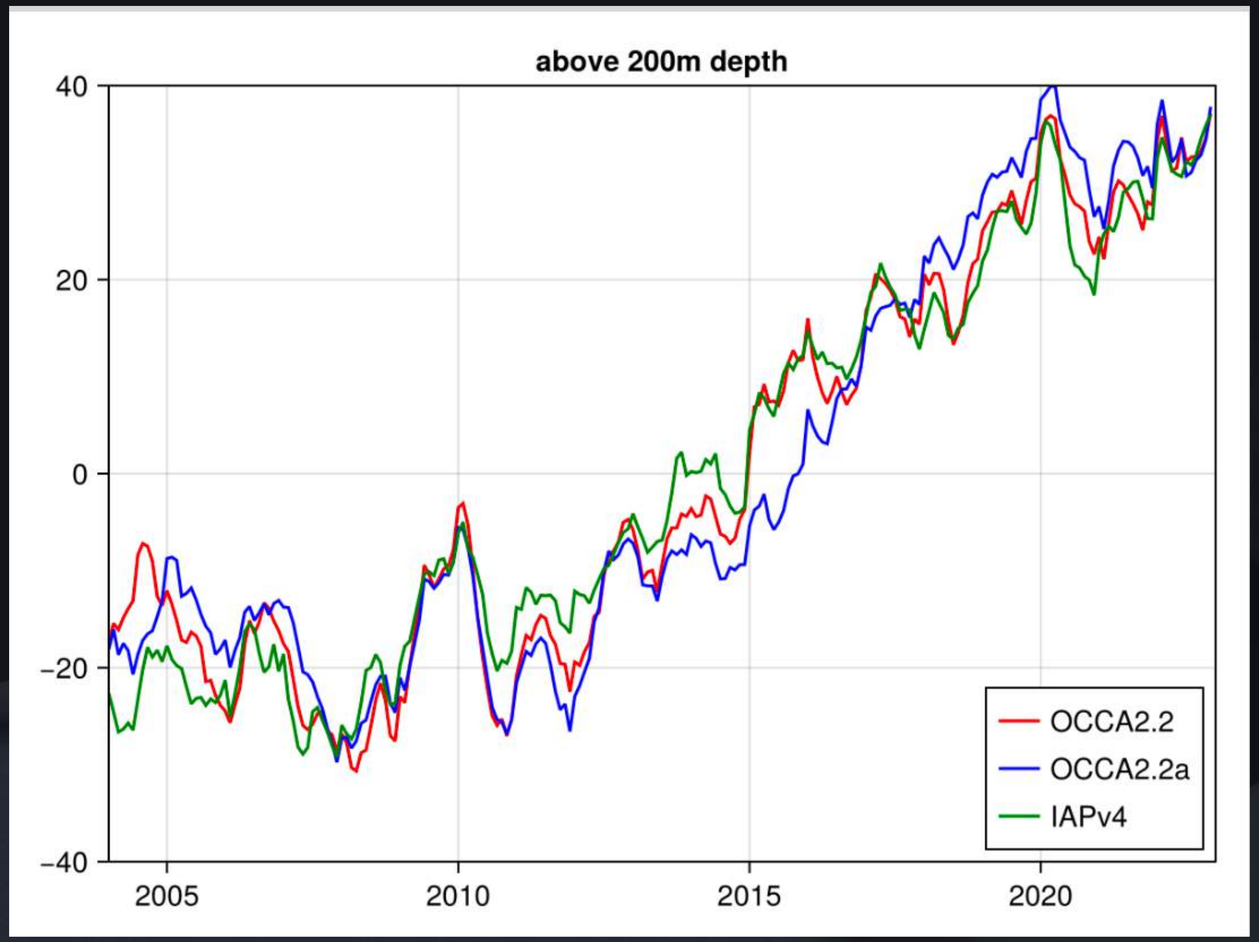
Song, Yuanyuan and Forget, Gaël (in prep)

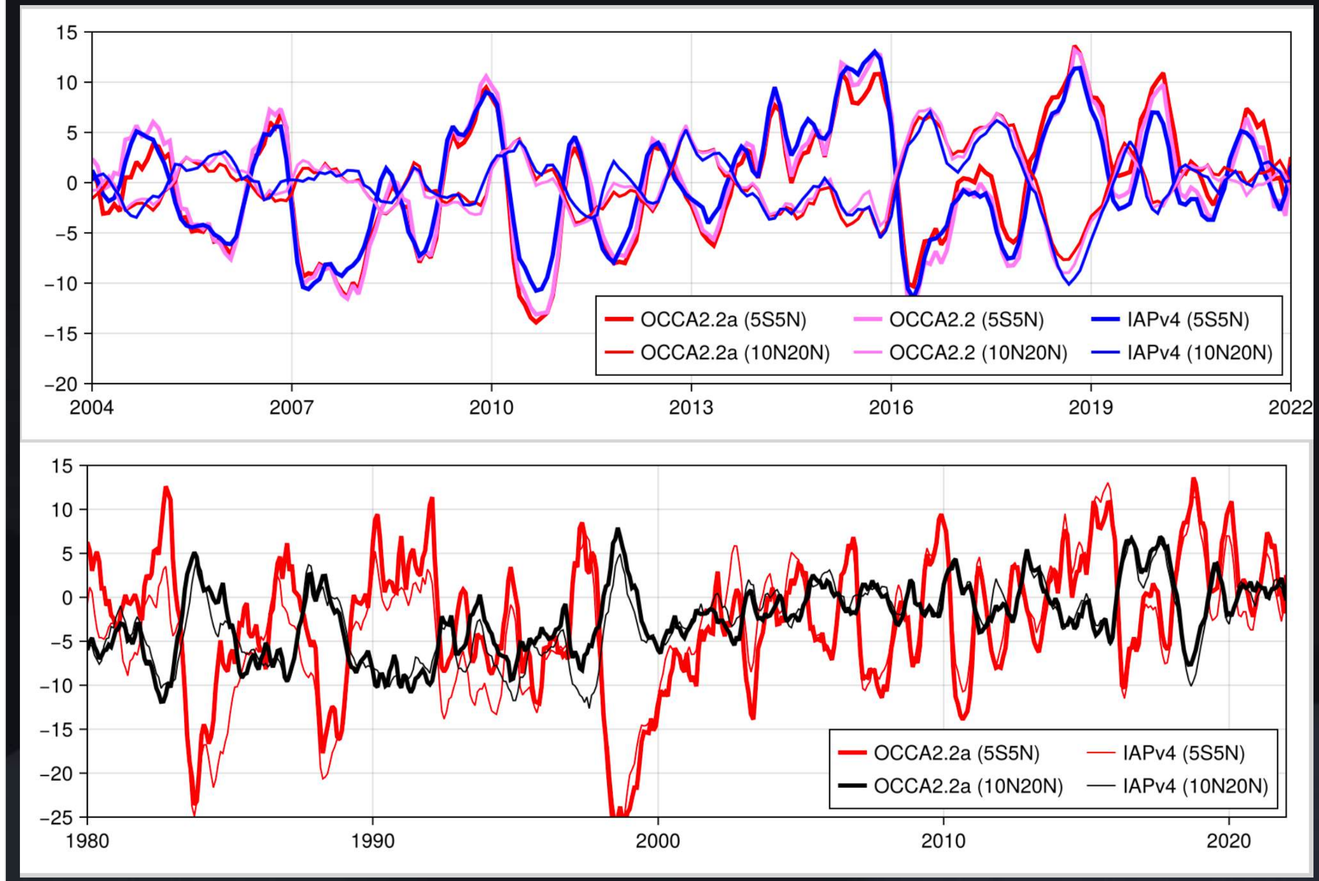
- Detrended temperature anomalies
- 100m just below max(clim(MLD))
- Top : N. Atl.
- Bottom : N. Pac.



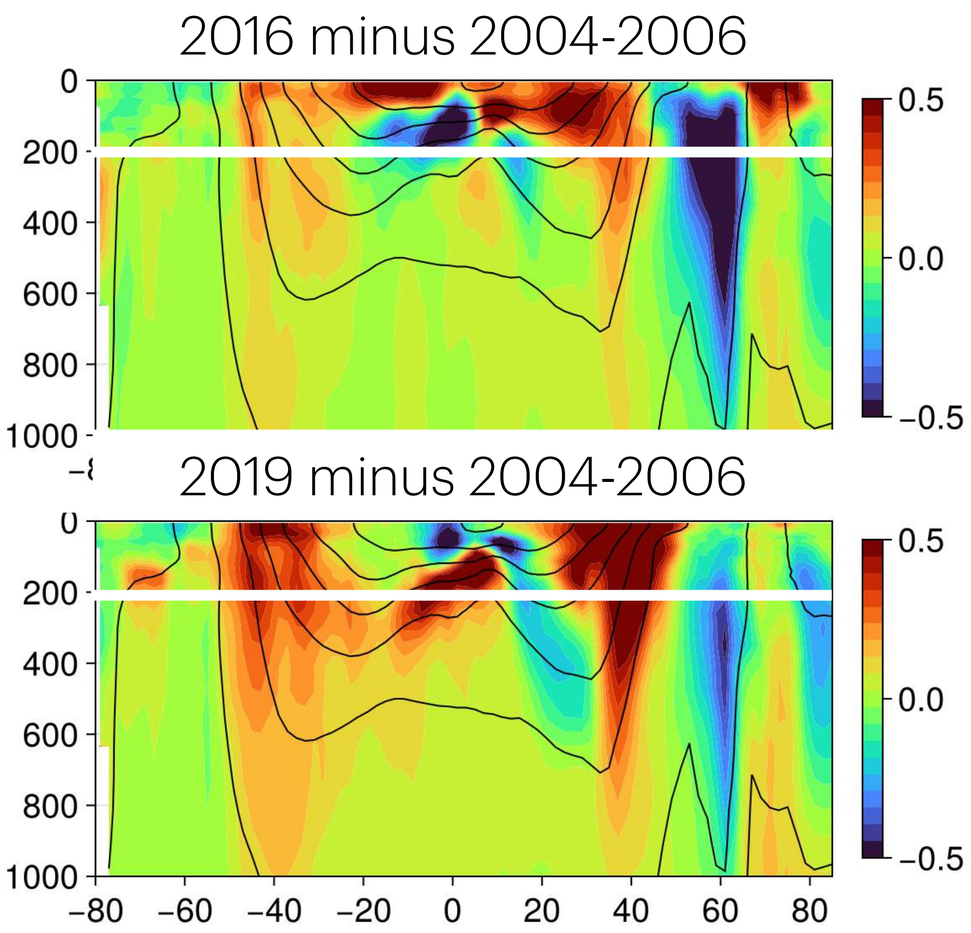
Extra slides

Global Mean , and Tropical Variability

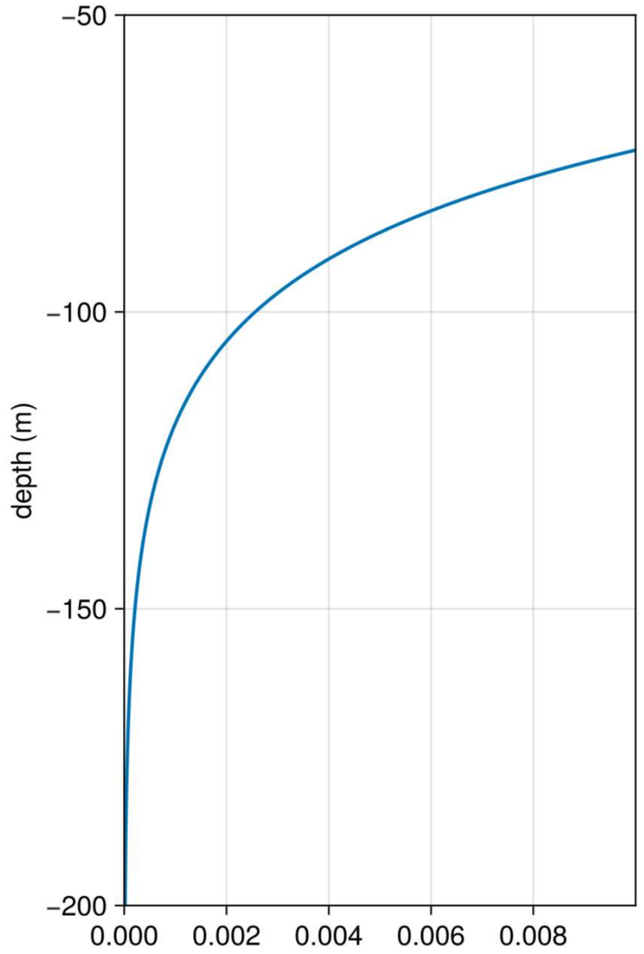




Sunlit Ocean Layer (SOL) = 0-200m Layer



Zonal Mean Temperature Anomalies computed from the 2004-2006 mean



Fraction of downward shortwave radiation reaching depth D as approximated in model

- **Why focus on 0-200m?**
  - Proxy for SST
  - Euphotic Depth
  - Radiative transfer profile
  - Ekman layer depth ~ 100m
- **Not a unique choice!**
  - Why not 0-10m? 0-100m? Ekman Layer? 0-MLD?
  - Easy to change later (OCCA2 is a full 3D, global estimate)