Atlantic ocean heat transport enabled by Indo-Pacific heat uptake and mixing

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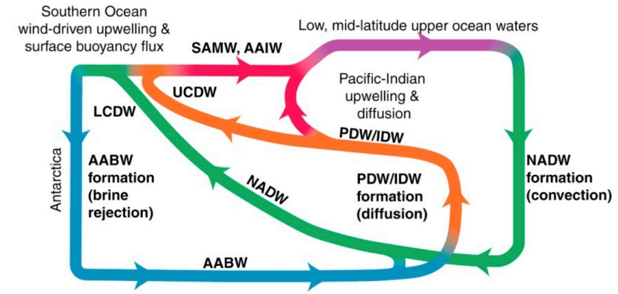
Ocean Heat Transport

Talley (2011)



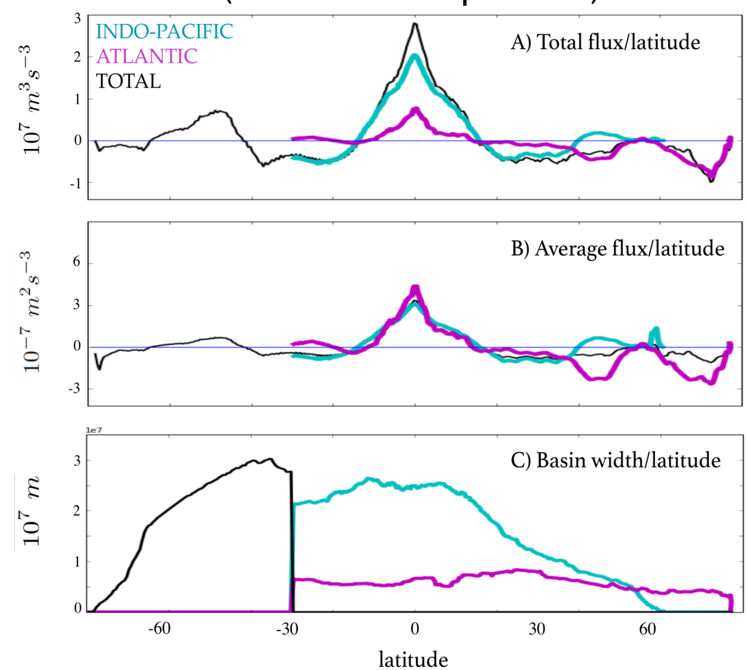
- Ocean heat transport is critical for regulating climate

- Traditionally linked with the general circulation (e.g. density-space MOC). However, reliance on this connection is problematic => sources/sinks, reference energy content

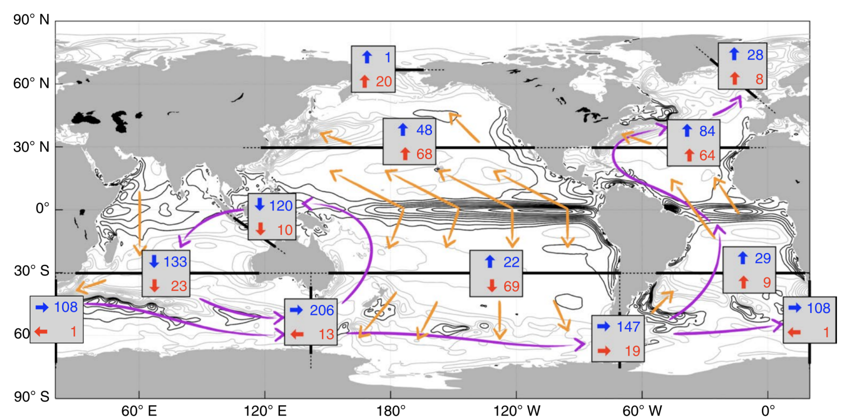
- Recent studies highlight importance of tropical Indo-Pacific

- This study => Precise model heat budget framework independent of reference temperature. Highlights role of mixing and Indo-Pacific - Atlantic connections

Surface buoyancy fluxes in CESM (Newsom and Thompson 2018)

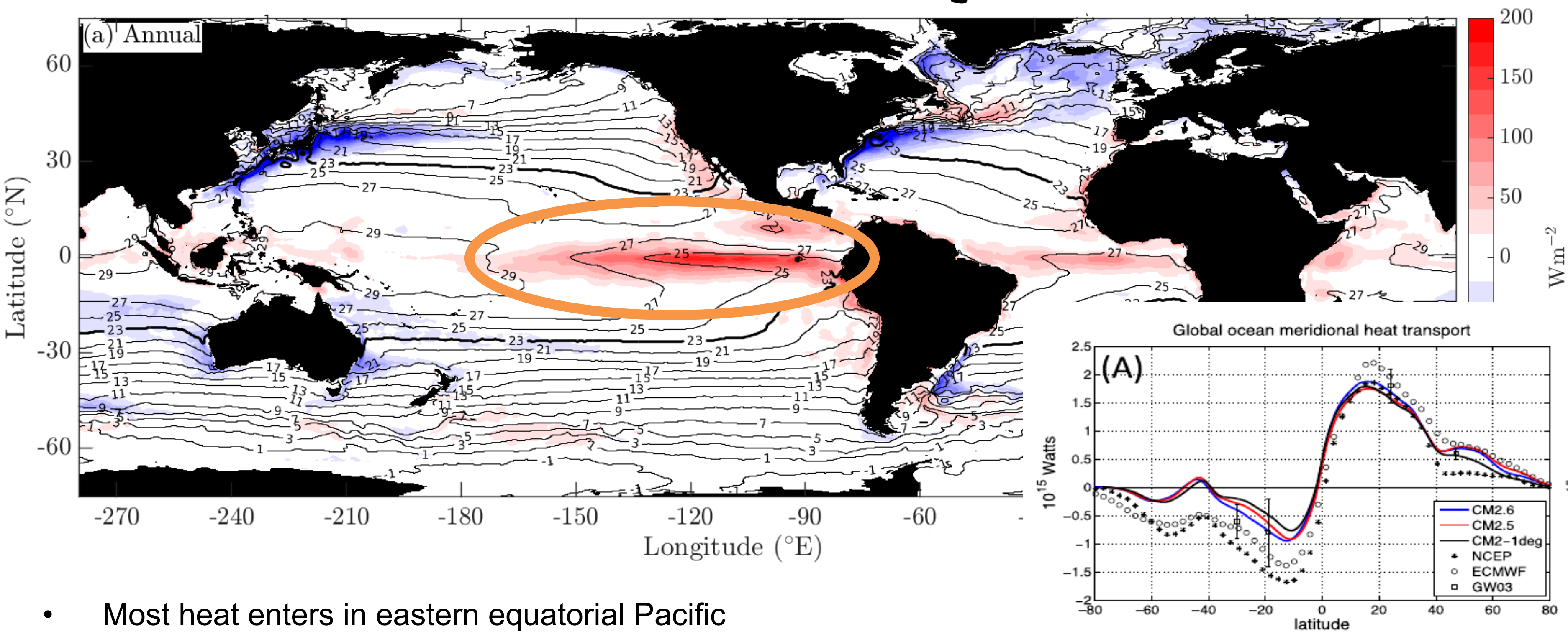


Vertically-integrated divergent heat transport (Forget and Ferriera 2019)



Diathermal Heat Transport

1/4-degree MOM5 Net Surface Heat Flux



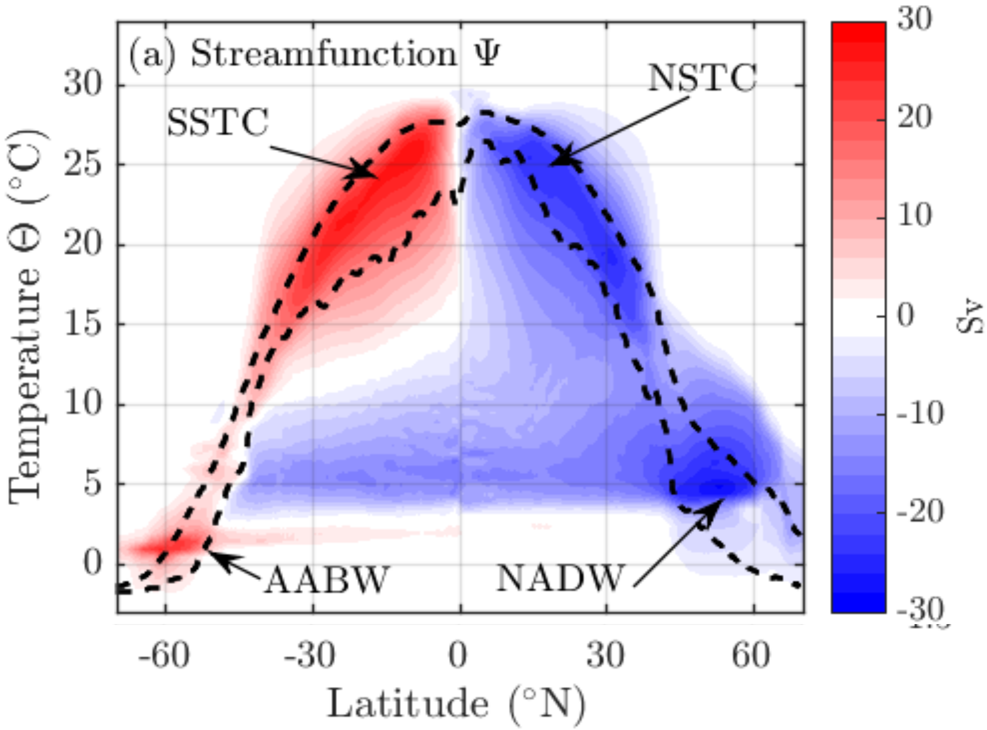
Griffies et al. (2015)

- Most heat enters in eastern equatorial Pacific
- Equatorial heating + mid-latitude cooling => Poleward heat transport (~2PW)
- Heating at SSTs warmer than ~23ºC, cooling at SSTs colder than ~23ºC => Heat transport from warm to cold temperatures (~1.6PW)

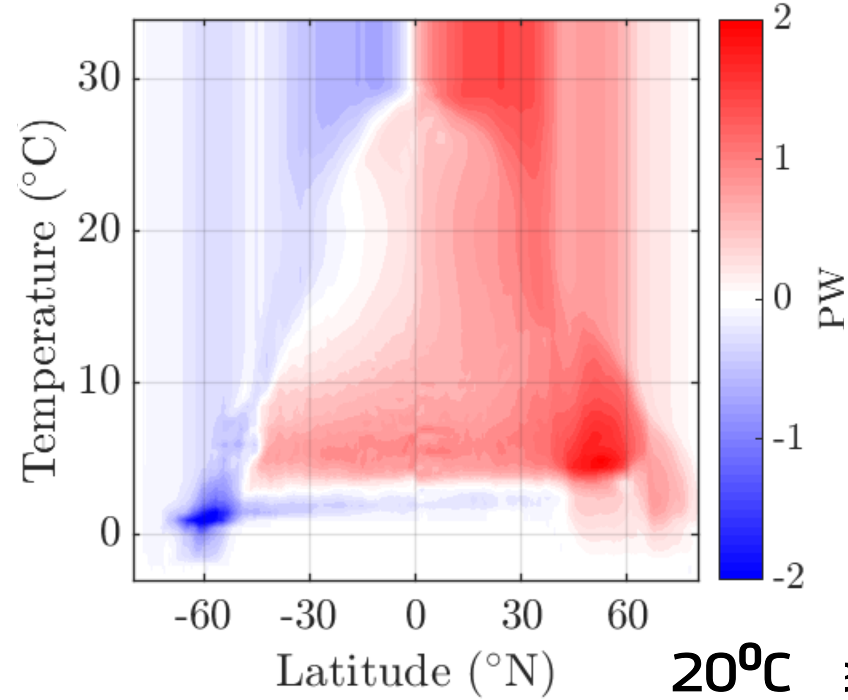
Meridional heat transport is linked to heat transport in temperature space (mixing, surface forcing)

Heat/mass transport in the latitude-temperature plane

Temperature-space MOC



Meridional heat transport



20ºC

Ref

Mass/volume transport below Θ:

$$\Psi(\phi, \Theta, t) = \int \int_{\Theta'(x,\phi,z,t)<\Theta} v(x, \phi, z, t) dx dz$$

Heat transport below Θ:

$$\mathcal{A}(\phi, \Theta, t) = \int_{-\infty}^{\Theta} \rho_0 C_p \Theta' \frac{\partial \Psi}{\partial \Theta} d\Theta'$$

Answer depends on reference temperature

The heat function

$$\mathcal{A} = \int_{-\infty}^{\Theta} \rho_0 C_p \Theta \frac{\partial \Psi}{\partial \Theta} d\Theta'$$

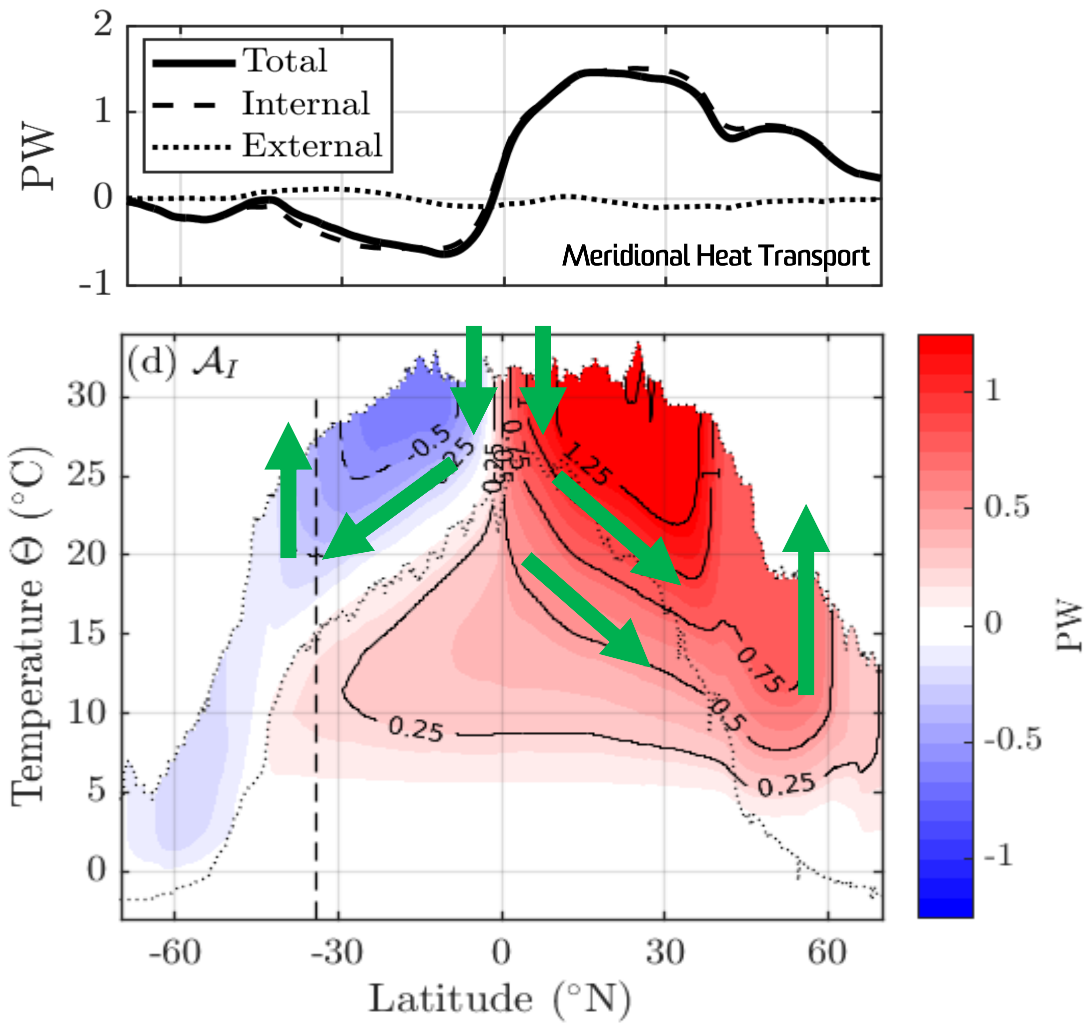
$$= \underbrace{\rho_0 C_p \Theta \Psi}_{\mathcal{A}_E} \underbrace{- \rho_0 C_p \int_{-\infty}^{\Theta} \Psi d\Theta'}_{\mathcal{A}_I}$$

Heat function ($\mathcal{A}_I$, Ferrari and Ferriera 2011) -> heat transport pathways independent of reference temperature

Heat enters at equatorial latitudes and warm temperatures

Moves down-gradient toward cooler temperatures and poleward

Eventually reaching high-latitudes where it is lost back to the atmosphere



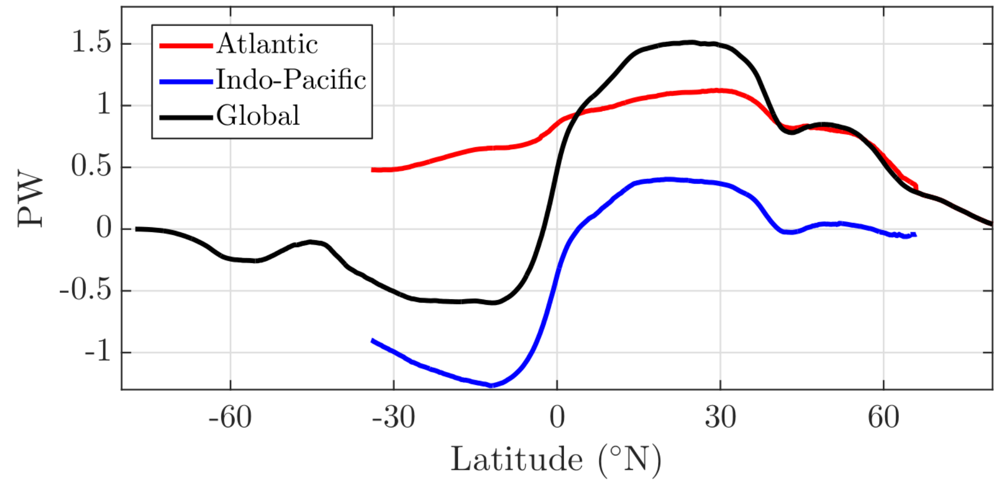
Boccaletti et al. (2005), Czaja and Marshall (2006), Greatbatch and Zhai (2007), Zika et al. (2013)

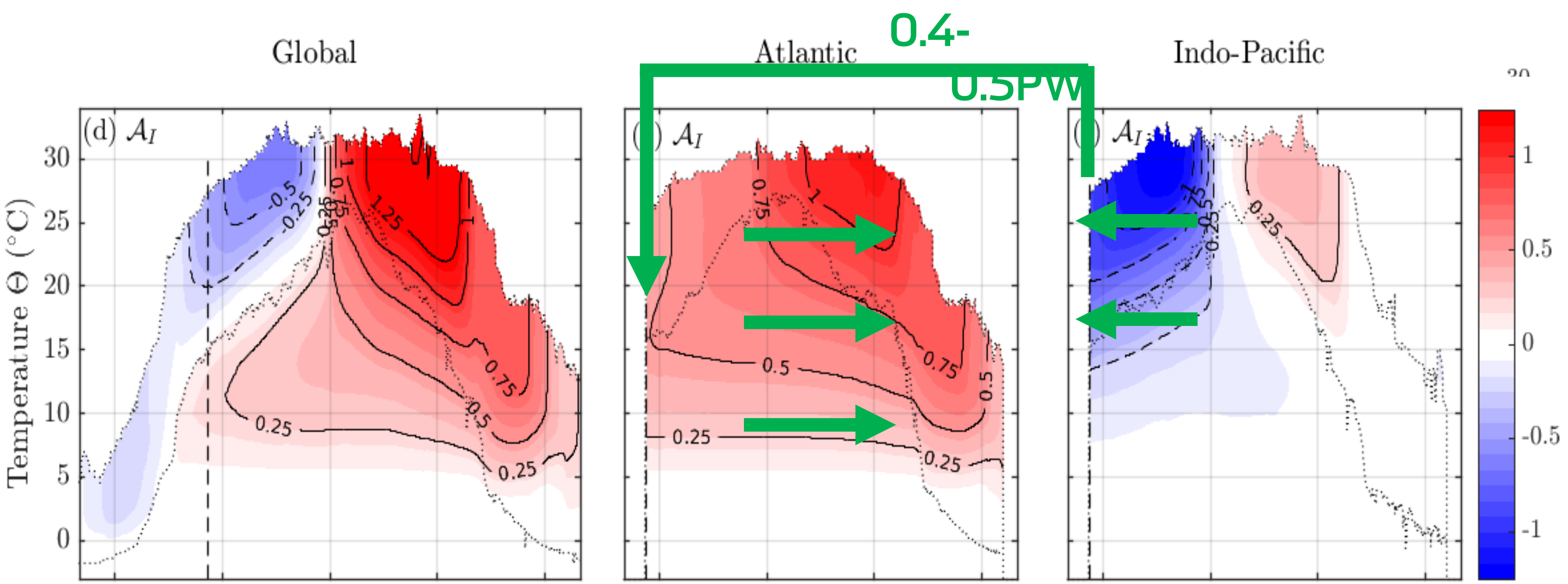
Indo-Pacific and Atlantic contributions

Northward heat transport dominated by Atlantic, relatively uniform with temperature (deep-reaching AMOC)

Indo-Pacific transports heat mainly southward, focused at warm temperatures

Weak transport in Southern Ocean -> large exchange from Indo-Pacific to Atlantic

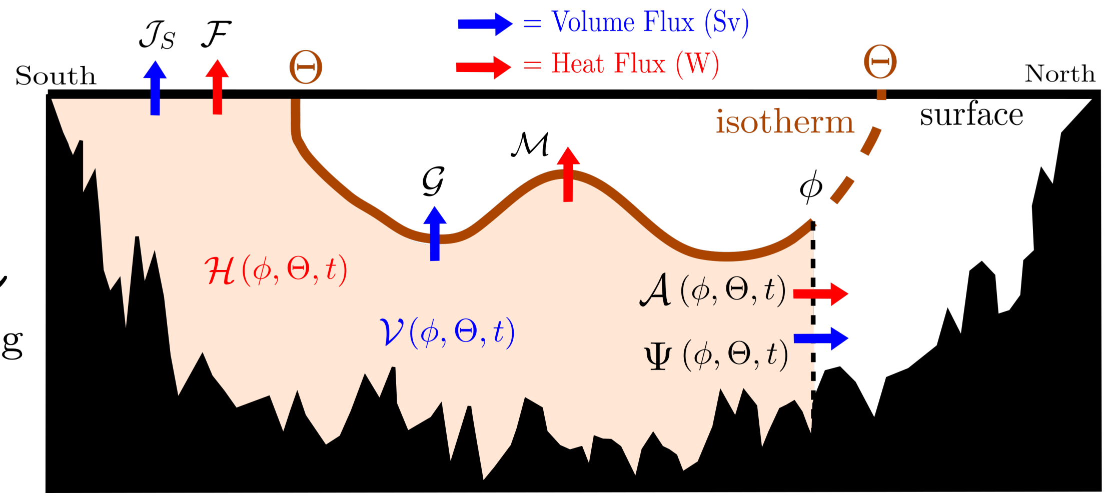




A process-budget for the heat function

A Walin (1982) heat content budget of temperature layers (Watts relative to 0ºC):

$$\frac{\partial \mathcal{H}}{\partial t}(\phi,\Theta,t) = -\underbrace{\mathcal{F}}_{\text{Forcing}} - \underbrace{\mathcal{M}}_{\text{Mixing}} - \underbrace{\mathcal{A}}_{y-\text{Transport}} - \underbrace{\mathcal{G}\Theta\rho_0 C_p}_{\text{Diathermal Advection}}$$



$\mathcal{H}$ can be split into two components:

$$\mathcal{H} = \rho_0 C_p \mathcal{V}\overline{\Theta} = \underbrace{\rho_0 C_p \mathcal{V}\Theta}_{\mathcal{H}_E} + \underbrace{\rho_0 C_p \mathcal{V}(\overline{\Theta} - \Theta)}_{\mathcal{H}_I}$$

internal heat content

$$\mathcal{H}_I = \rho_0 C_p \int_{\Theta}^{\infty} \mathcal{V} d\Theta'$$

Analog with Palmer and Haines (2009)

Internal heat content budget:

- Independent of reference temperature
- Does not include transformation $\mathcal{G}$
- Smoother/more robust (integrated)

$$\frac{\partial \mathcal{H}_I}{\partial t}(\phi,\Theta,t) = -\mathcal{F}_I - \mathcal{M} - \mathcal{A}_I$$

Diathermal transports: Mixing and Surface forcing

All diagnostics binned online into 0.5ºC bins

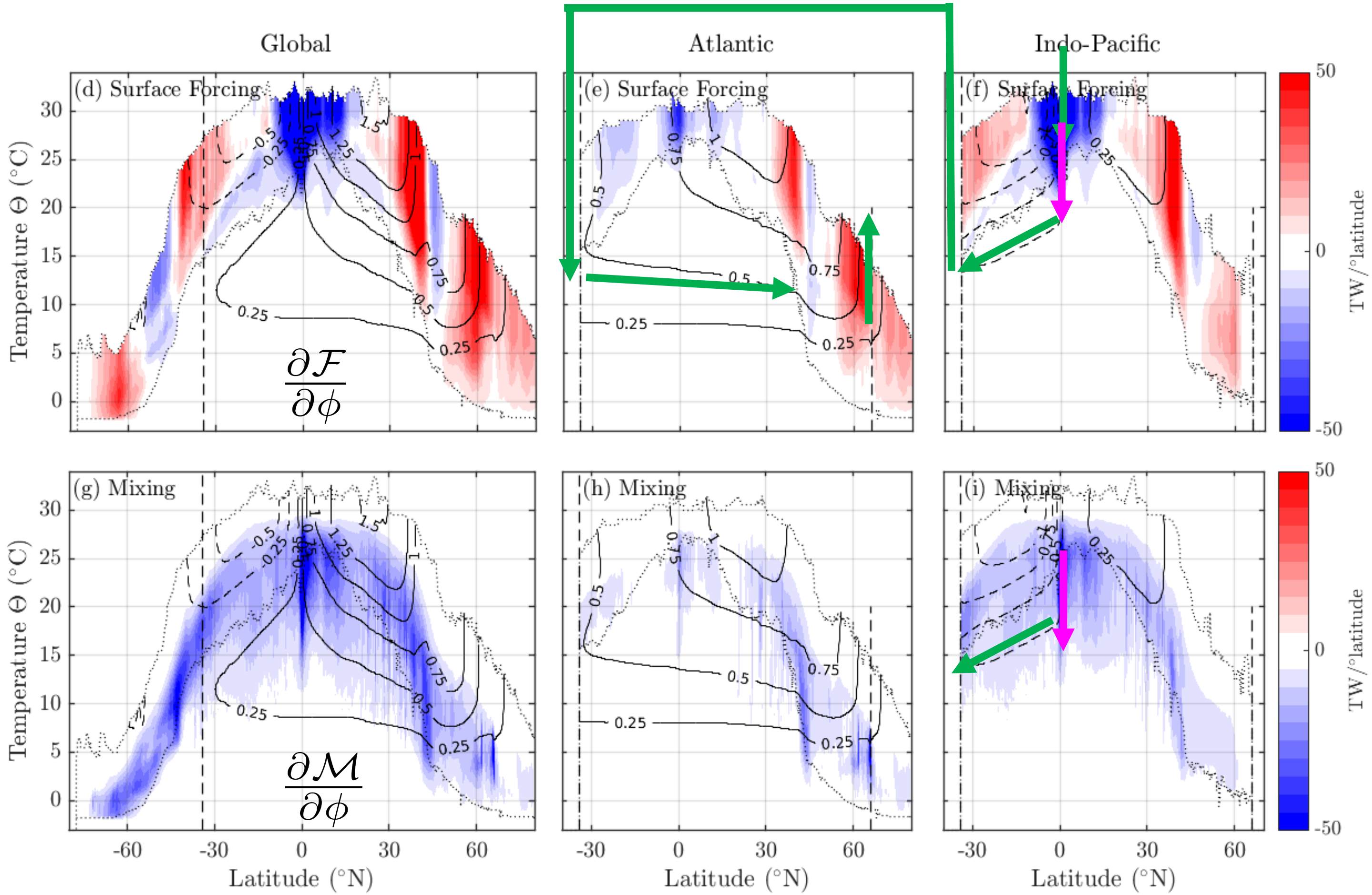
Closed budget for internal heat content: $$\frac{\partial \mathcal{H}_I}{\partial t} = -\mathcal{F} - \mathcal{M} - \mathcal{A}_I$$

Surface heat gain in the *Indo-Pacific* at warm temperatures

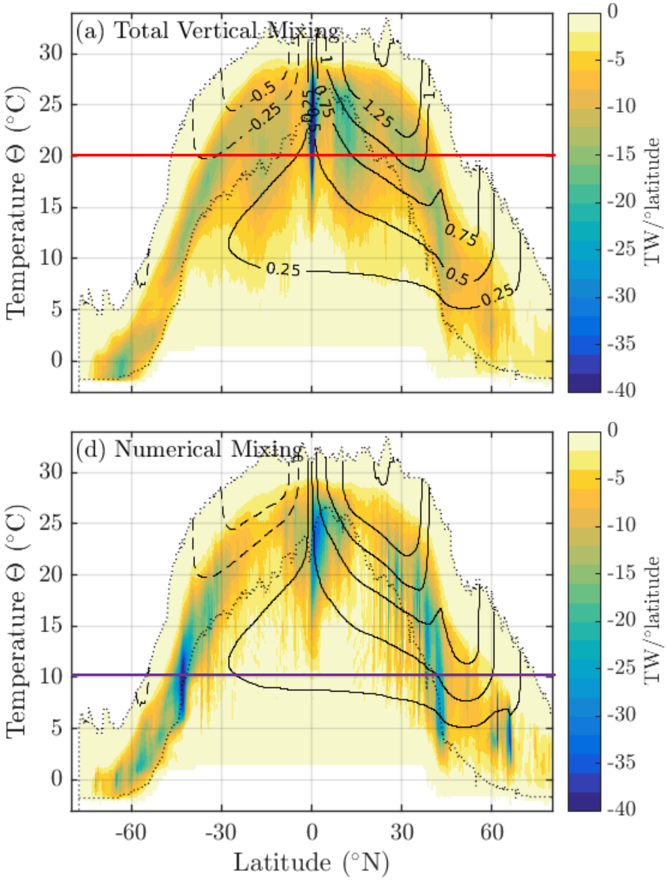
Mixing moves heat toward colder temperatures. Largely in Indo-Pacific

Supplies heat at cool temperatures to the South Atlantic

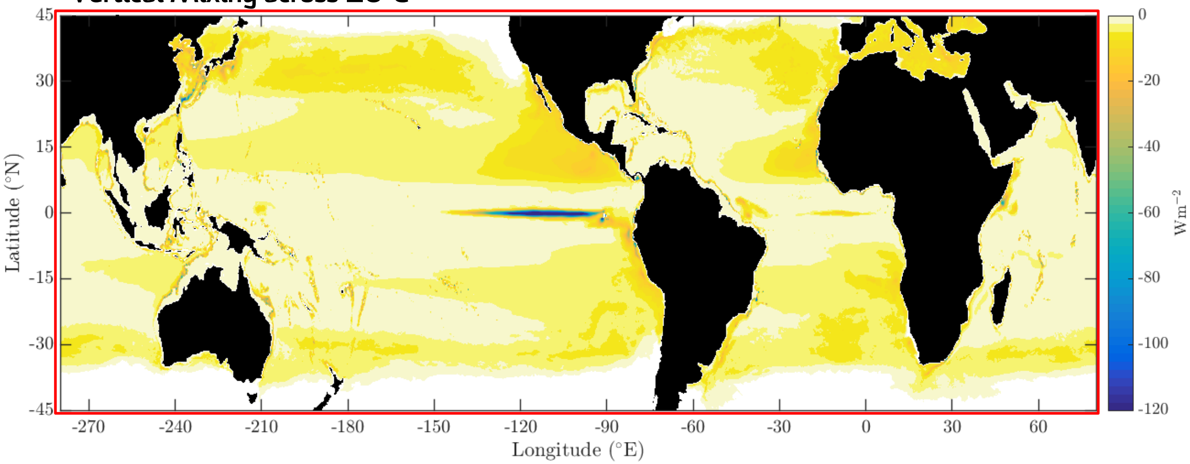
Northward transport through Atlantic to North Atlantic heat loss



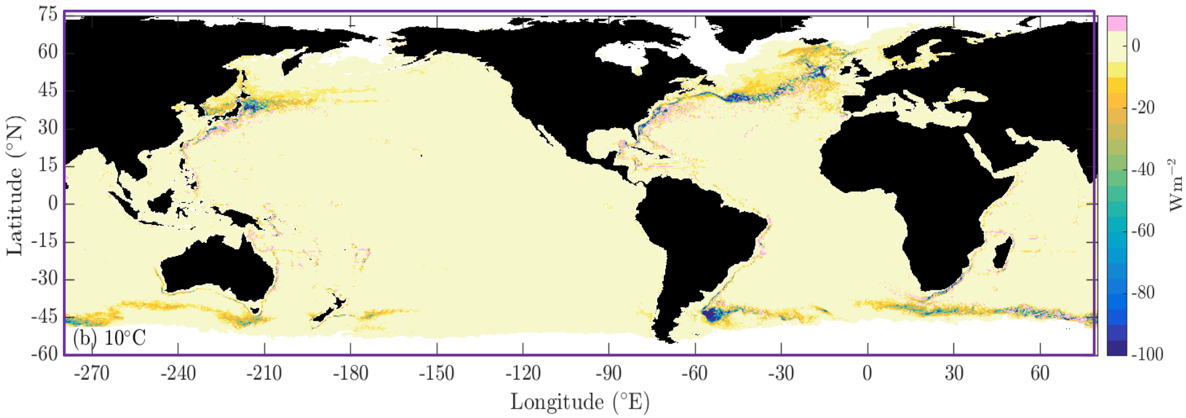
Mixing spatial structure



Vertical Mixing across 20°C



Numerical Mixing across 10°C Isotherm



Numerical mixing spatial structure estimated by applying residual method to each individual fluid column

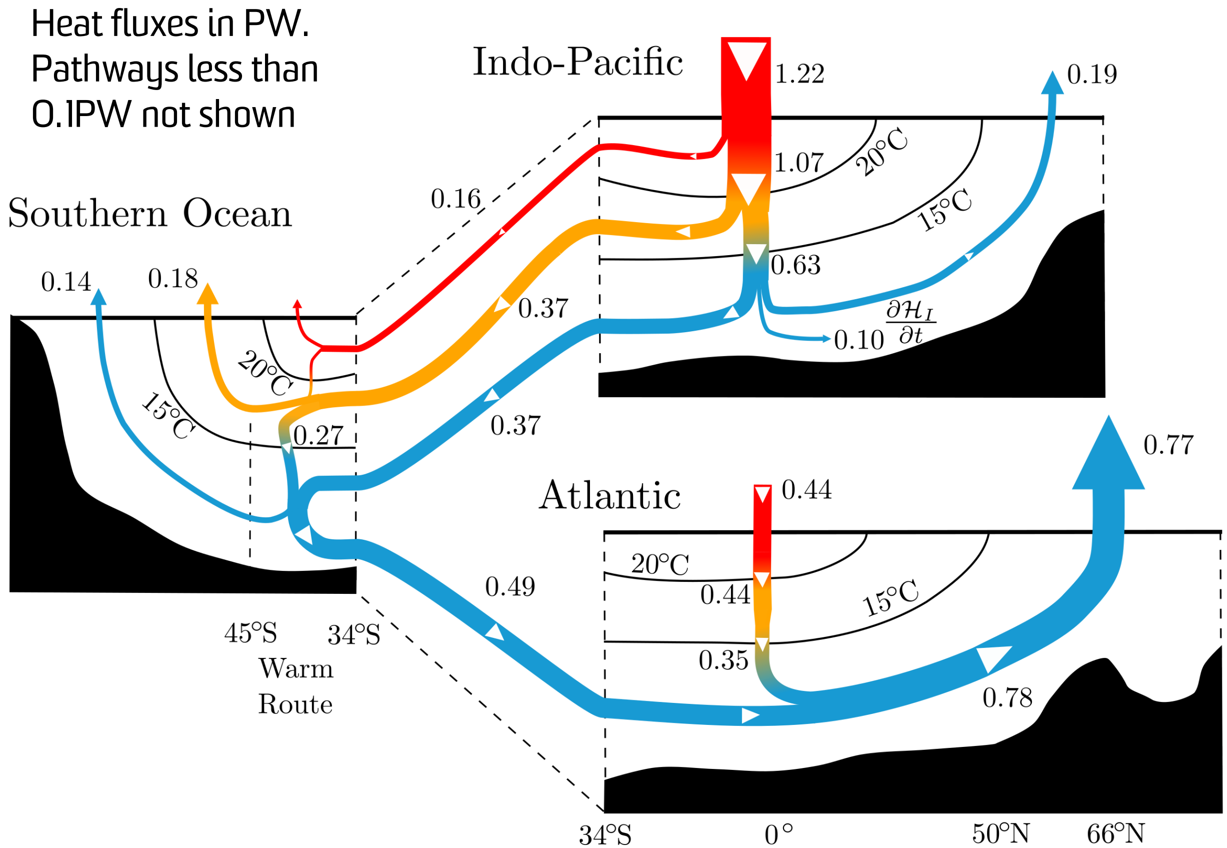
Summary

Internal heat content budget in latitude-temperature plane allows (mostly) unambiguous view of heat flows

60% of the 0.78PW of Atlantic MHT across 50ºN is supplied from Indo-Pacific at temperatures above 15ºC, ultimately from cold tongue heating

Supports recent studies (Newsom and Thompson 2018, Forget and Ferreira 2019) on role of the tropical Pacific

Mixing moves heat from warm wind-driven Indo-Pacific circulation into cold deep-reaching AMOC



Framework has potential applications for ocean heat uptake (work in progress) and for model evaluation

More info: Holmes, Zika and England (2019) J. Phys. Oceanogr., Holmes et al. (2019) submitted to GRL

Other ACCESS-OM2 WMT projects in the pipeline

1. **Idealized climate perturbations:** Apply similar framework to study changes in heat transport under changes in IPO, SAM, an RCP4.5 scenario and AMOC collapse

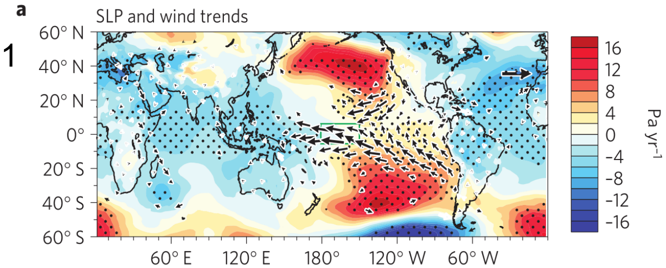
2. **Numerical mixing in the COSIMA model suite:** project held up – still hoping to get back to it

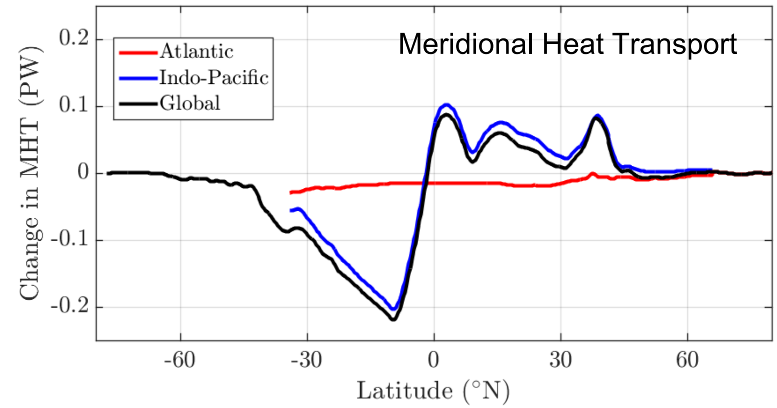
3. **Chris Bladwell** -> similar framework applied to **salt transport**. Future changes in water cycle

4. **Maurice Huguenin-Virchaux** -> Temperature-space WMT applied to **ENSO's warm water volume**. ¼-degree JRA55 IAF 5^{th} cycle will soon be available with full temperature-space heat budget diagnostics

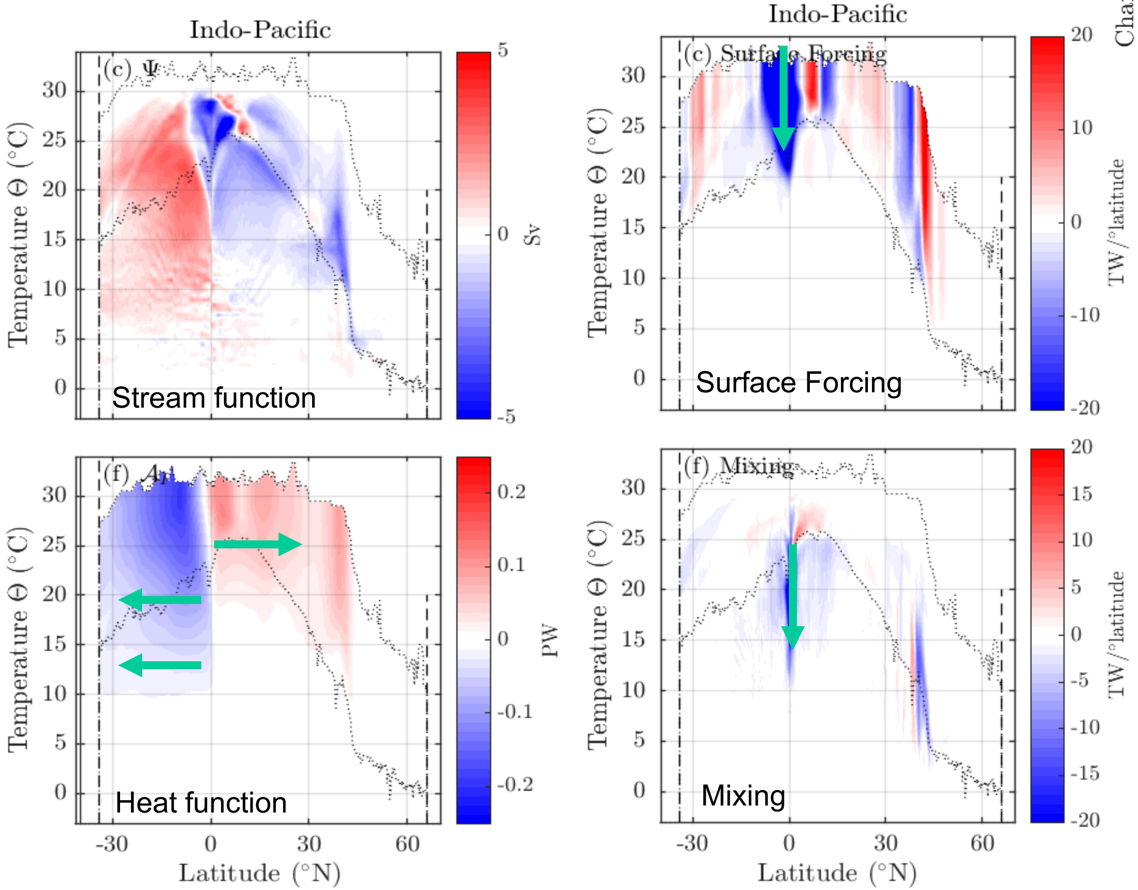
Idealized Perturbations: Trade wind acceleration (-ve IPO, à la England/Maher)

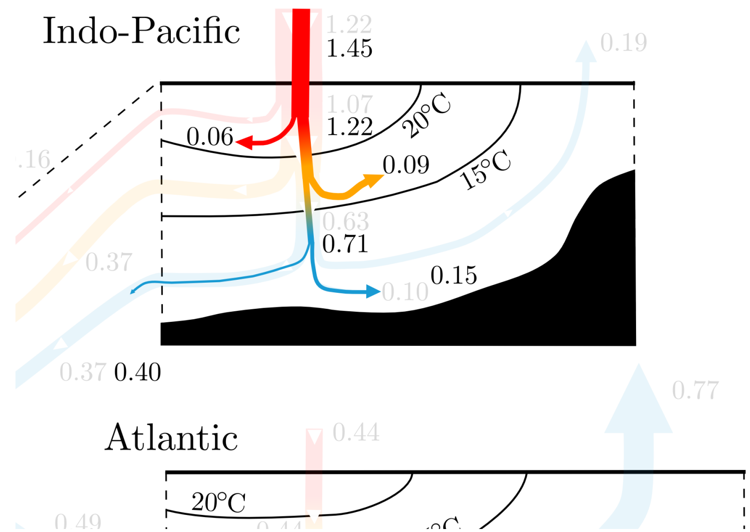
Pacific wind trends 1992-2011
(England et al. 2014)





Anomalies years 10-20

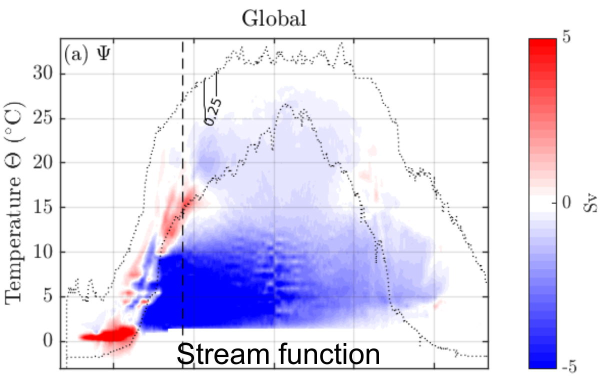


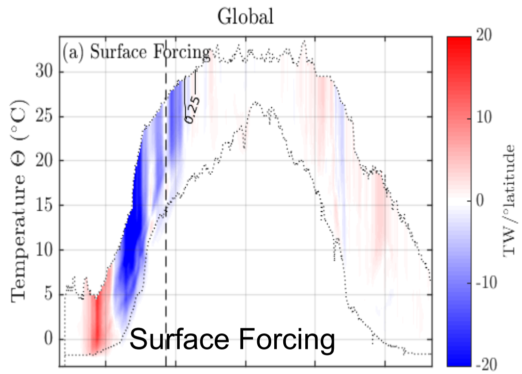


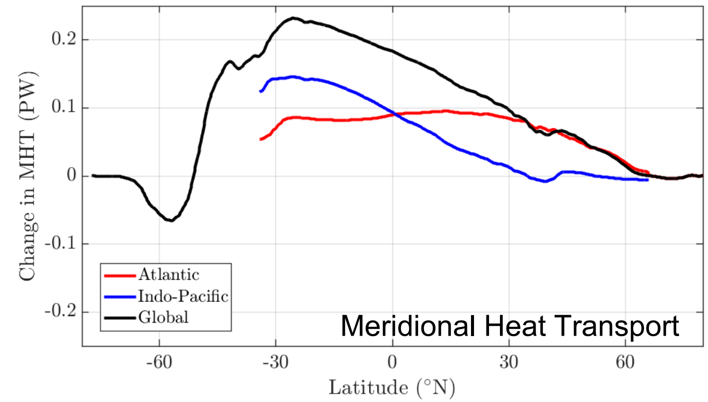
0.2PW accumulating in Indo-Pacific

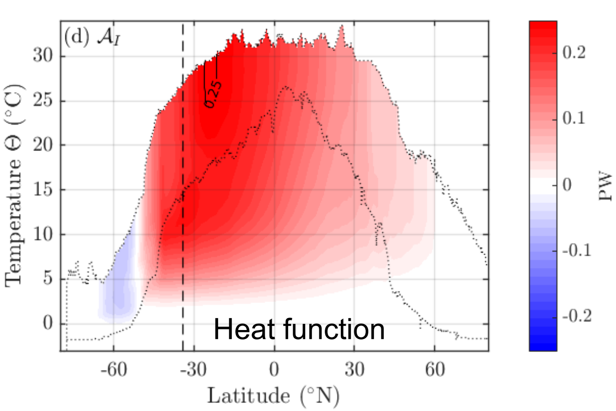
Idealized Perturbations: Southern Ocean wind acceleration (à la Spence)

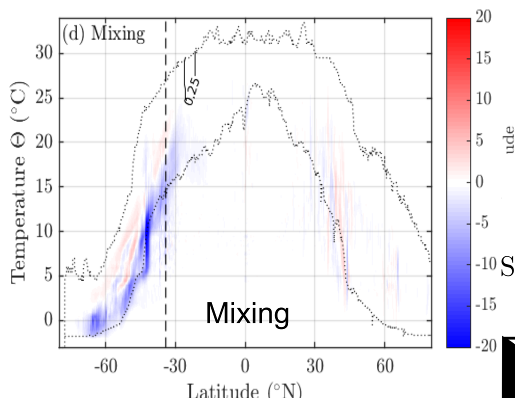
Southern Ocean winds intensified by 15% (Spence et al.)

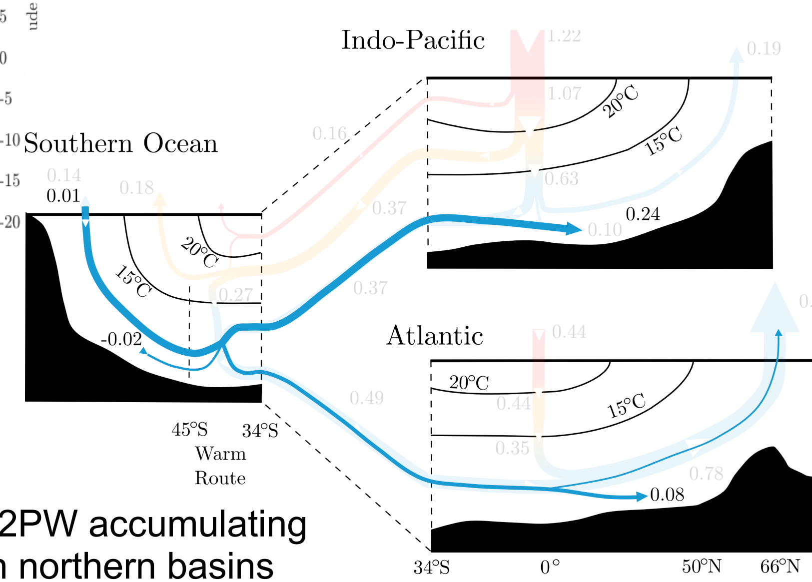




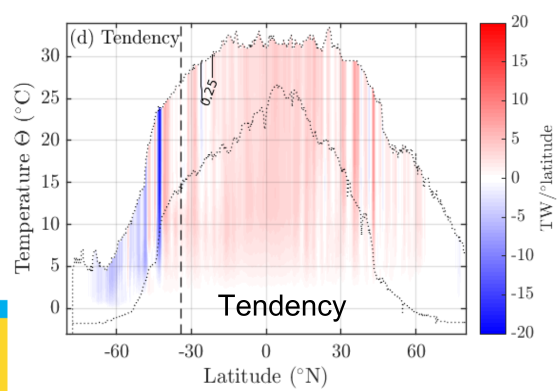








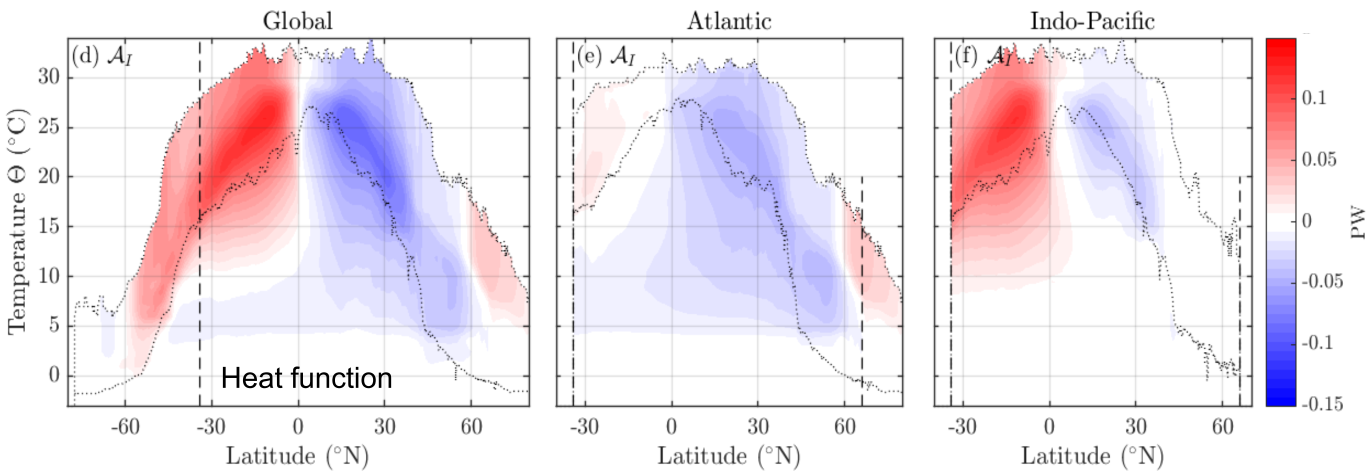
Anomalies years 10-20

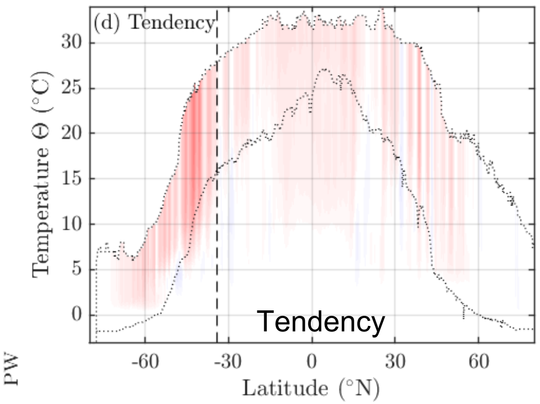


0.22PW accumulating in northern basins

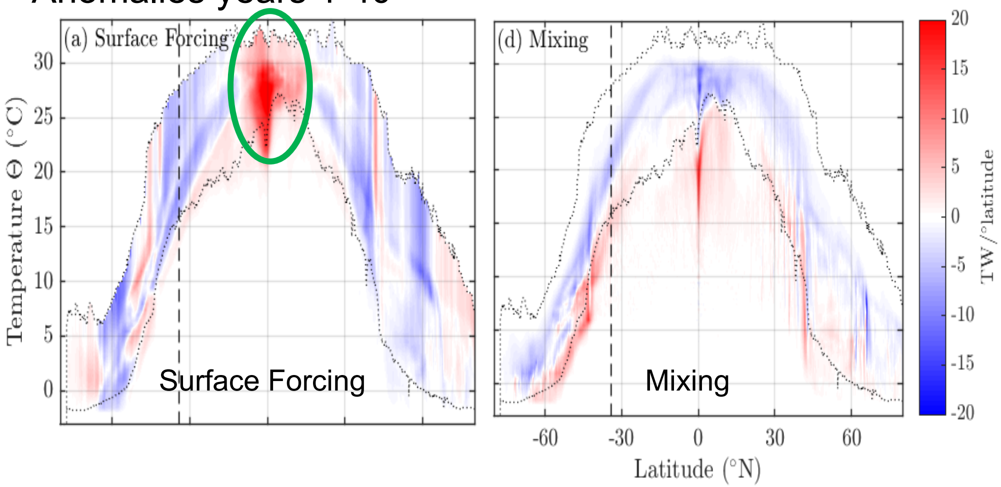
Idealized Perturbations: Idealized RCP4.5 (à la Stewart)

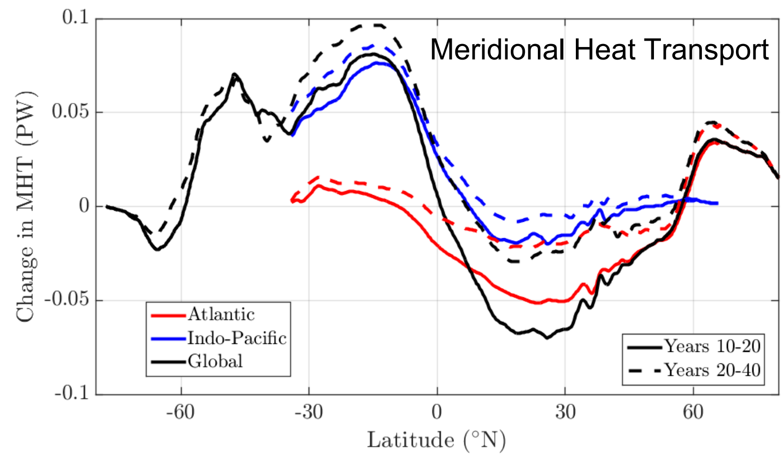
+1.5°C air temperature, +8Wm^{-2} downward longwave (Stewart and Hogg 2019)





Anomalies years 1-40





Shift of cell locations in temperature-space

Net *surface heat loss* from equatorial regions – latent heat flux changes

Perturbations - Initial results

Trade wind acceleration/-ve IPO: Diathermal analysis isolates diabatic rearrangement. Accumulation of heat in colder temperature classes highlights potential for long-lasting heat uptake.

Southern Ocean wind acceleration: Enhanced overturning circulation drives accumulation of heat below 15C in northern basins

RCP4.5: Net equatorward heat transport associated with rapid equatorial adjustment / slower mid-latitude adjustment. Heat loss from equator may be due to relative humidity changes.

Would be great to consider an AMOC-off simulation – but how would this be done in an ocean-only model given dependence off heat fluxes on air temperature?

Questions?

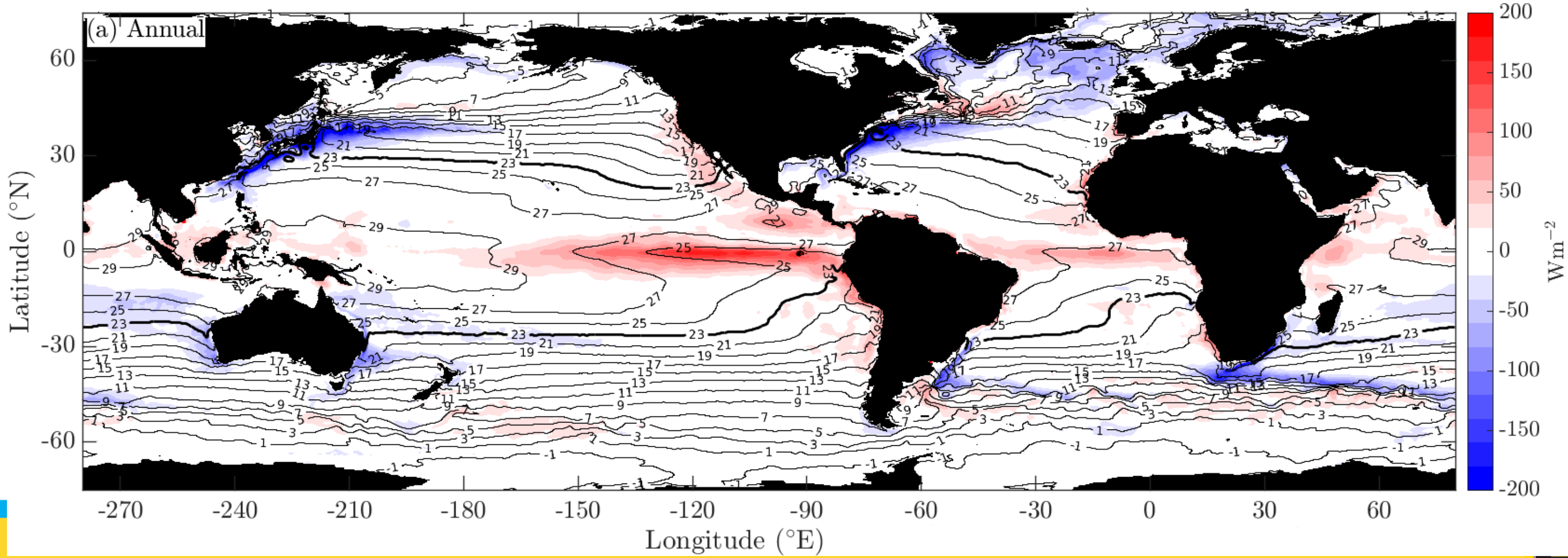
Modelling details

MOM5-SIS global ocean sea-ice model. Will focus on a 1/4º, 50 vertical levels configuration (MOM025). CORE-NYF climatological forcing

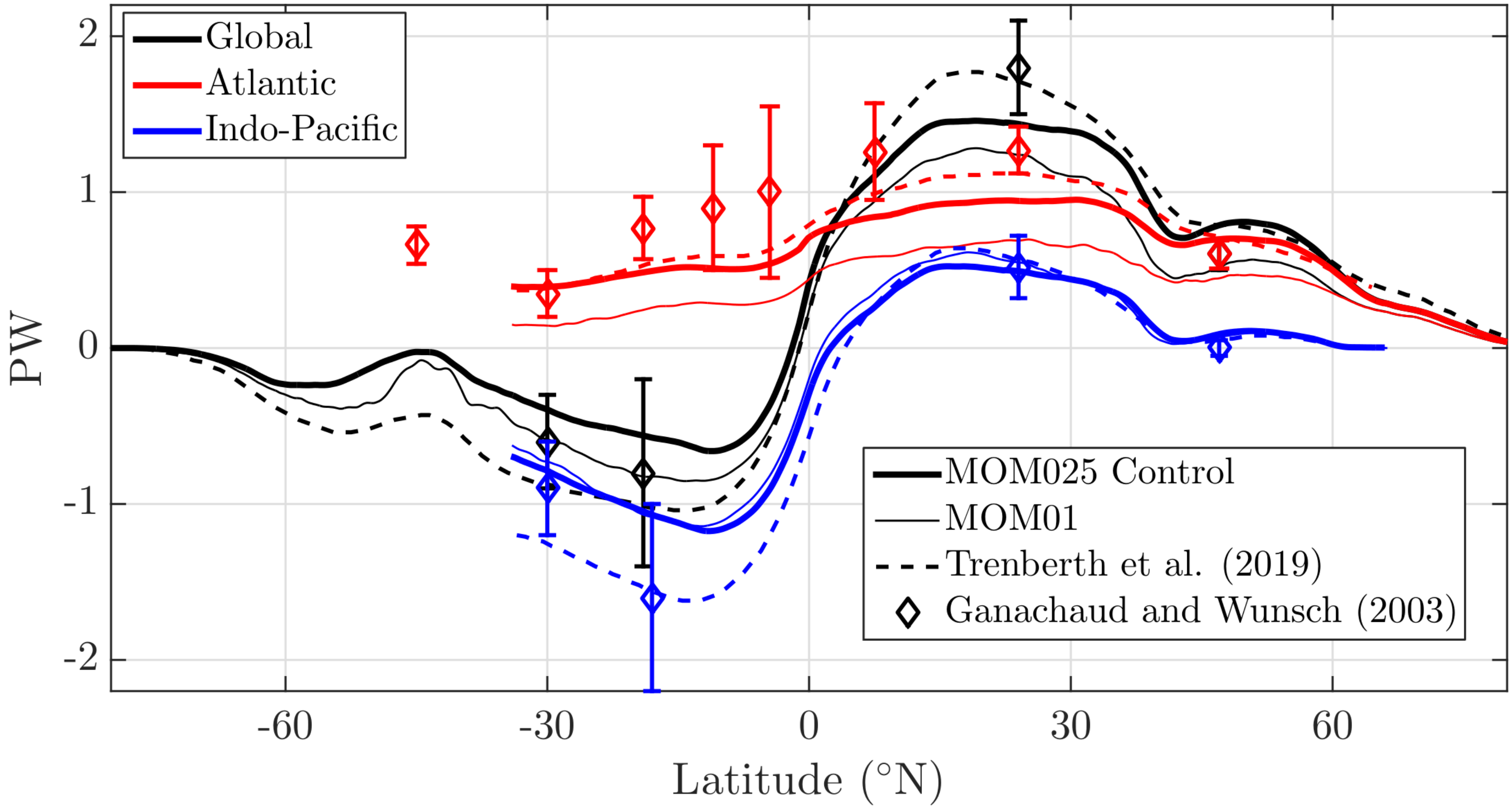
KPP boundary layer/shear vertical mixing, Simmons et al (2004) tidal mixing and $10^{-5}m^2s^{-1}$ ($10^{-6}m^2s^{-1}$ at Equator) background diffusivity

Heat budget tendency diagnostics binned into 0.5ºC temperature bins online

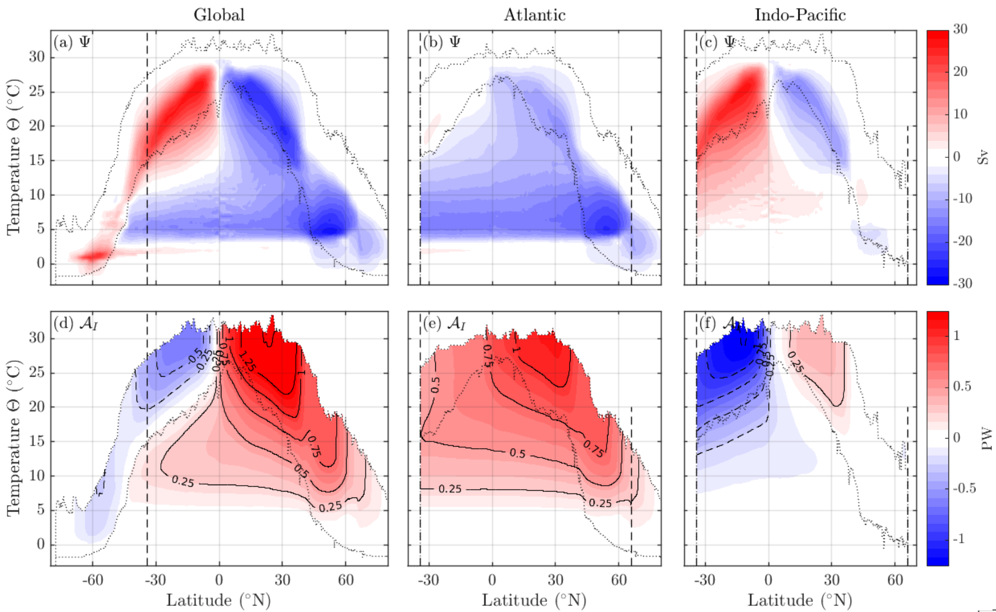
No explicit lateral or along-isopycnal diffusion – lateral gradients dissipated through *numerical mixing* (MDPPM + flux-limiters advection scheme)



Meridional Heat Transport Comparison

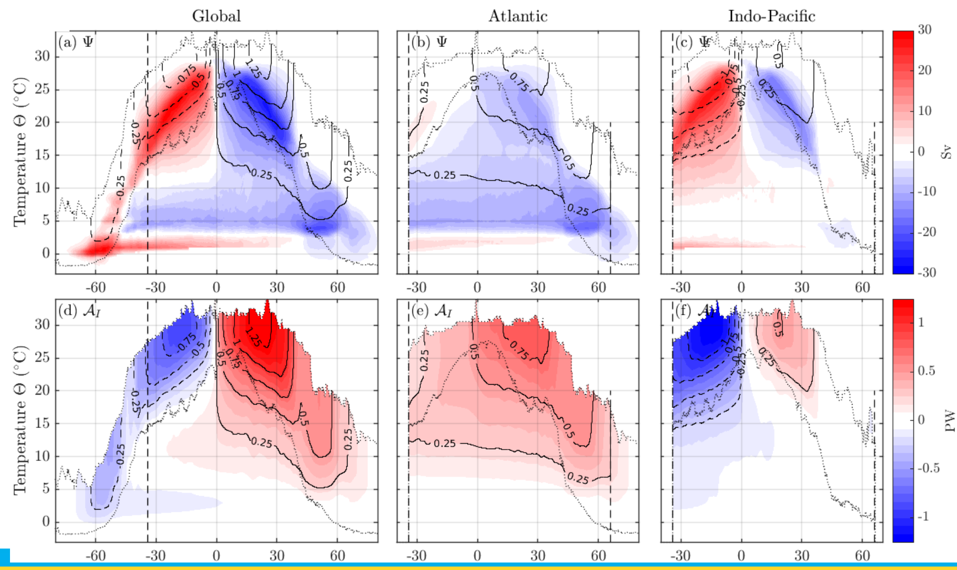


Comparison to MOM01

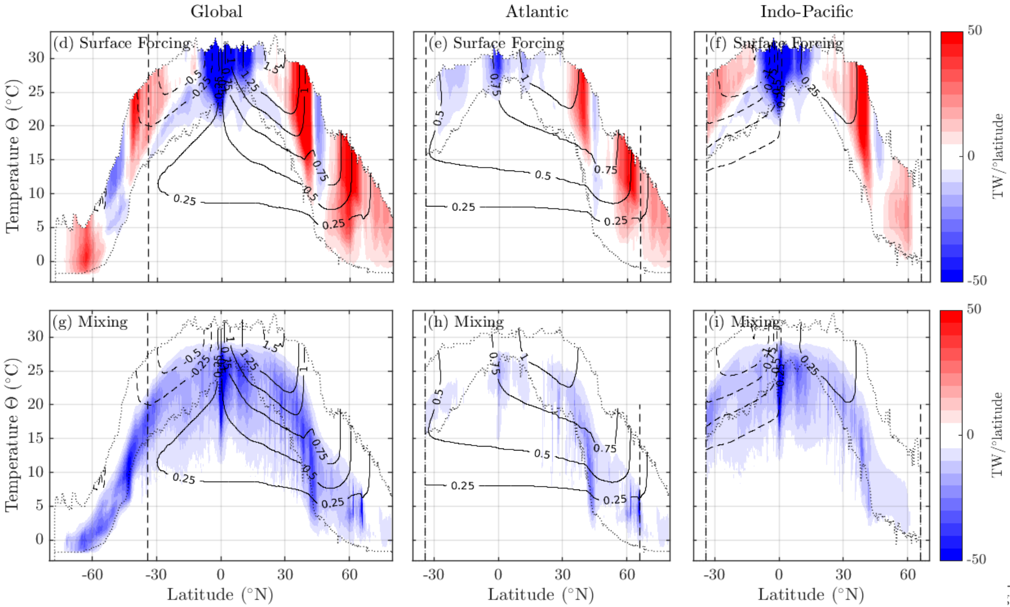


MOM025 (1/4-degree, 5-levels with background diffusivity)

MOM01 (1/10-degree, 75-levels with no background diffusivity)

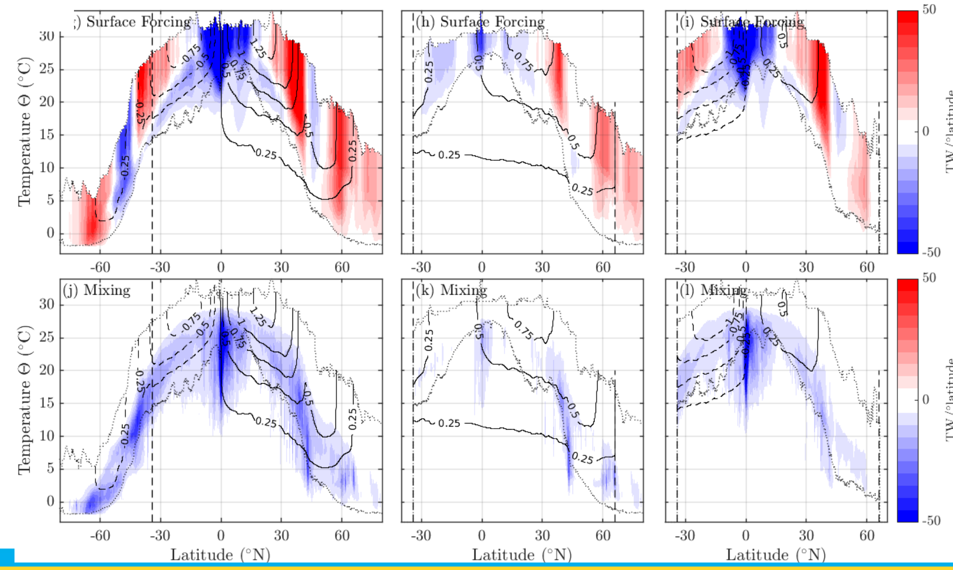


Comparison to MOM01

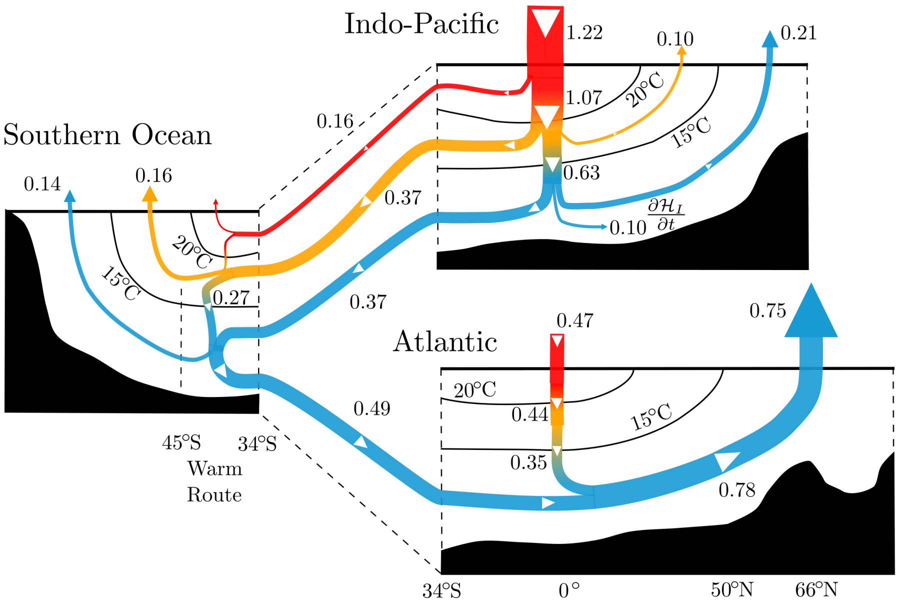


MOM025 (1/4-degree, 5-levels with background diffusivity)

MOM01 (1/10-degree, 75-levels with no background diffusivity)

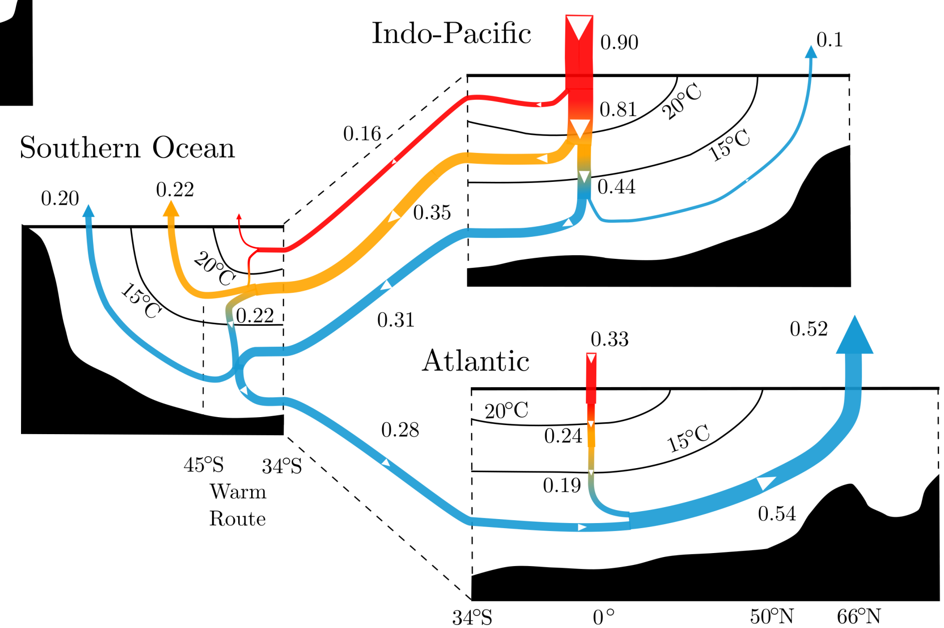


Comparison to MOM01

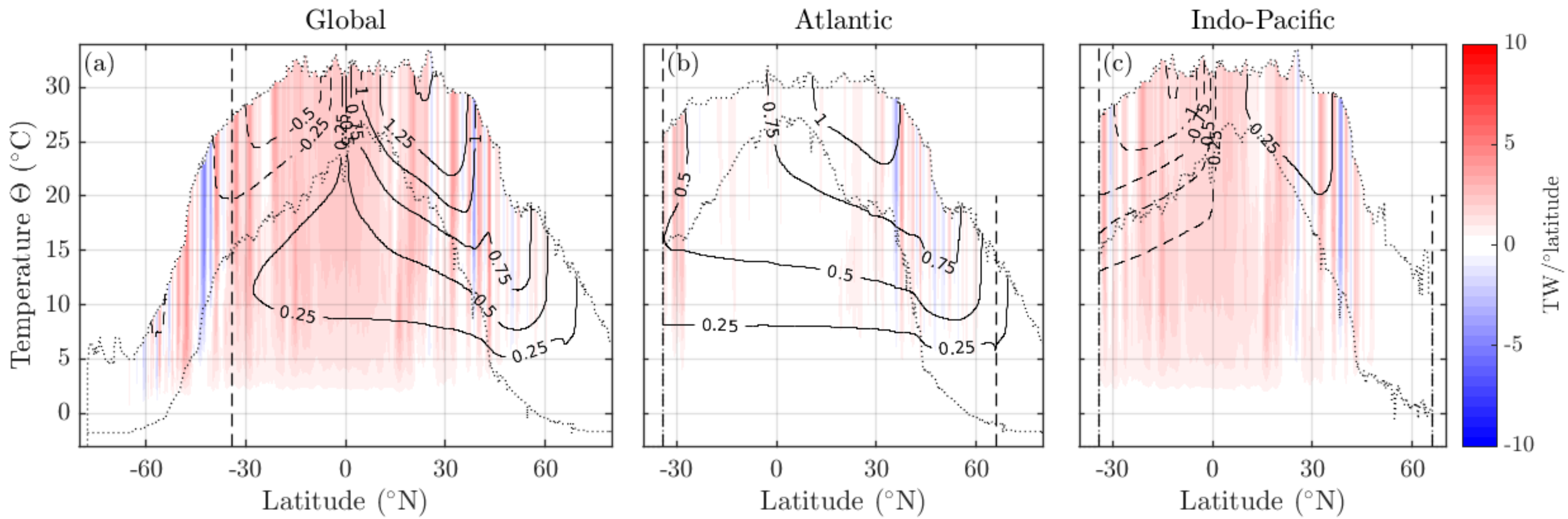


MOM025 (1/4-degree, 5-levels with background diffusivity)

MOM01 (1/10-degree, 75-levels with no background diffusivity)

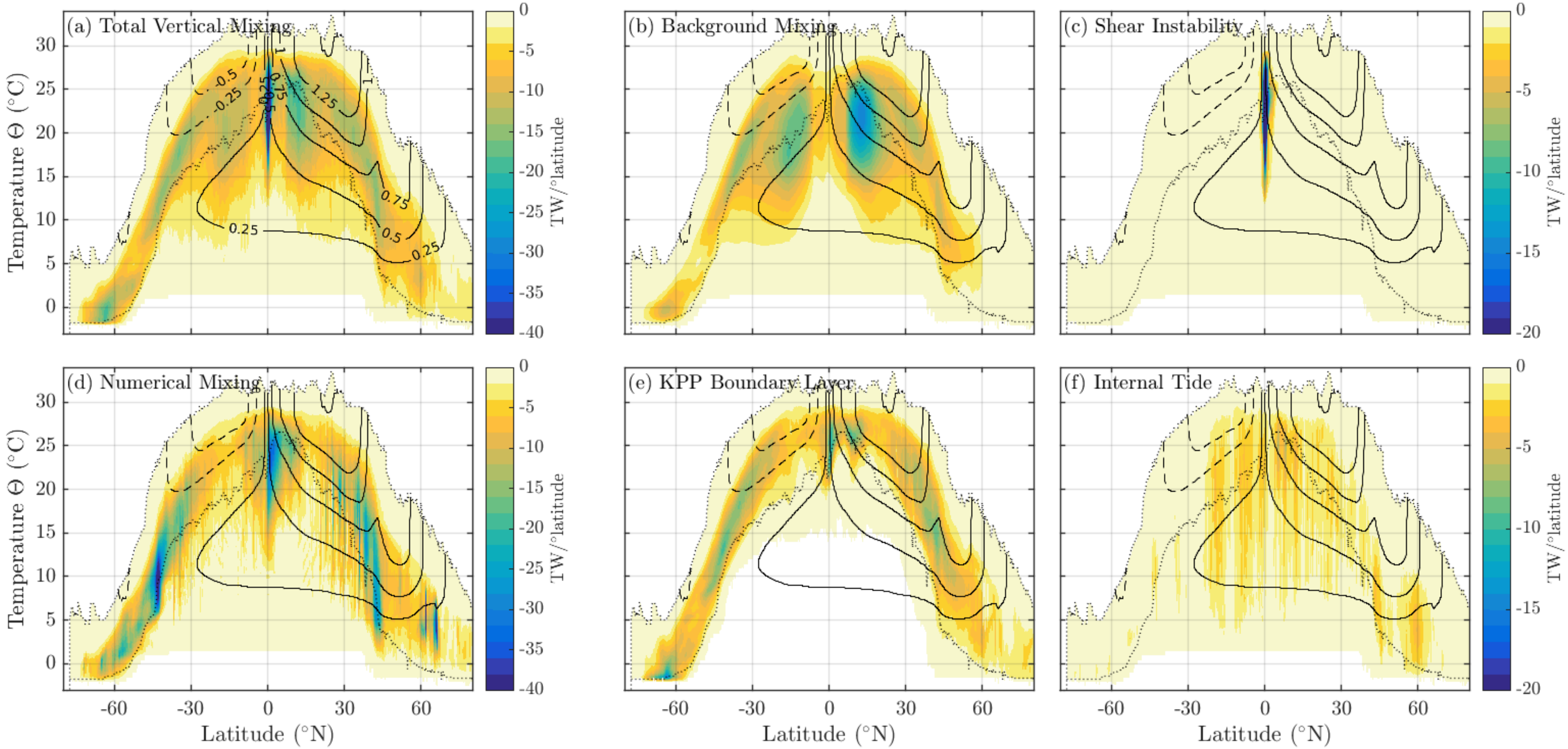


Internal heat content tendency in MOM025



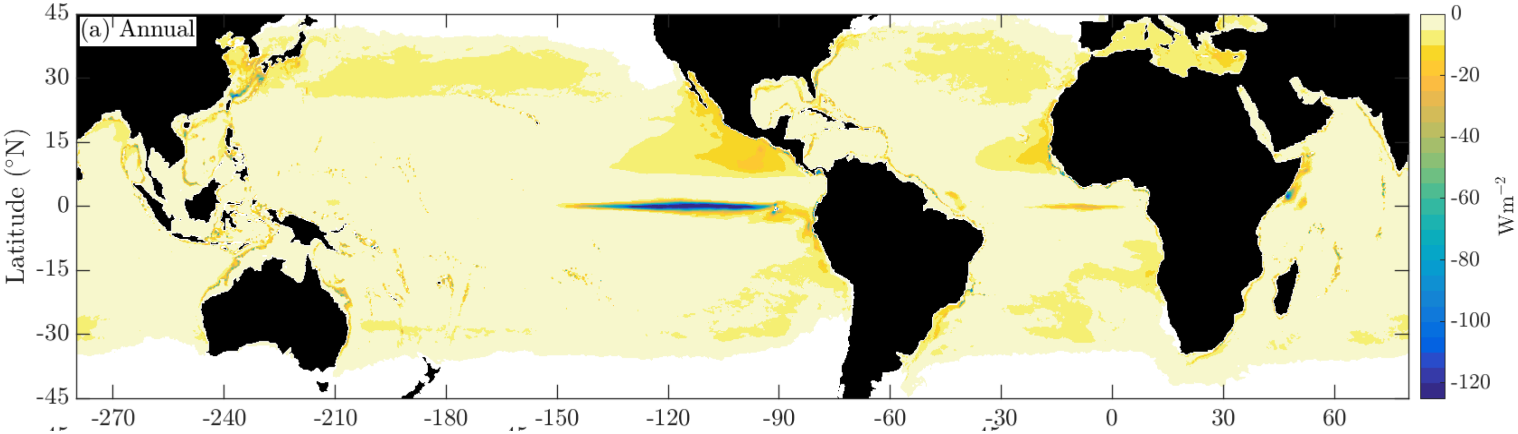
Process contributions to mixing

Components of Vertical Mixing



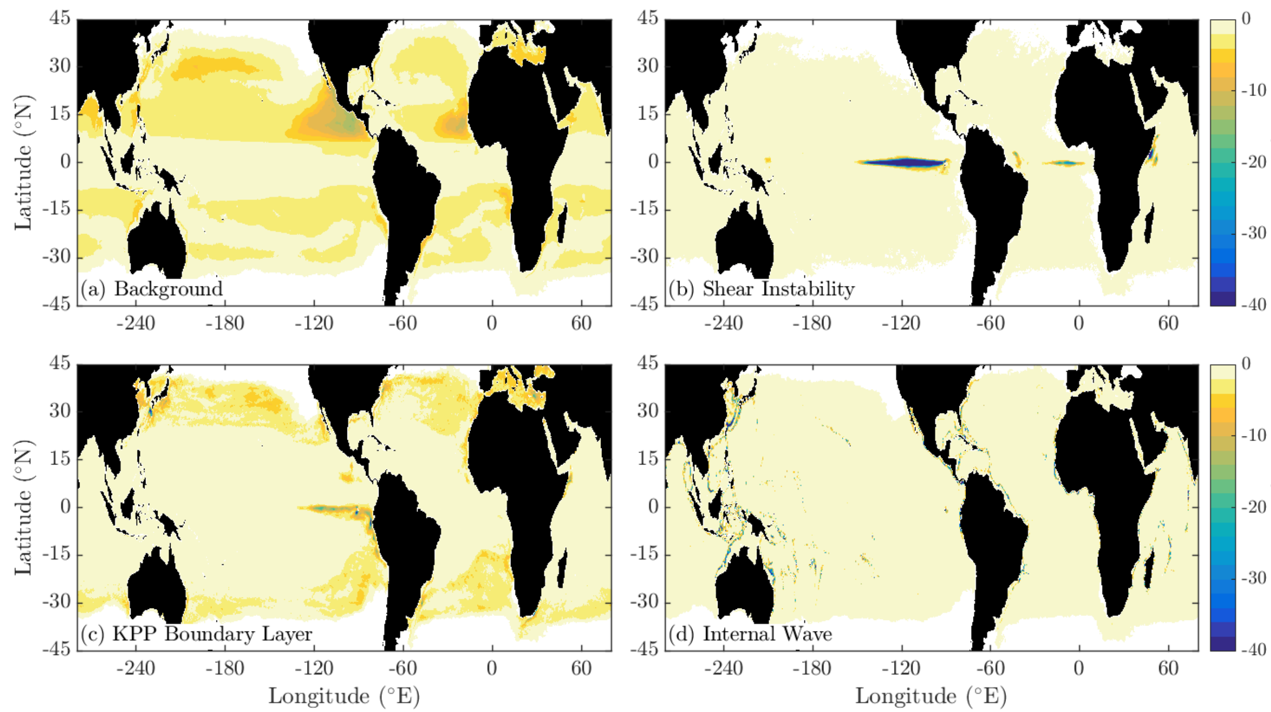
Spatial Structure

Holmes, Zika and England, JPO 2019

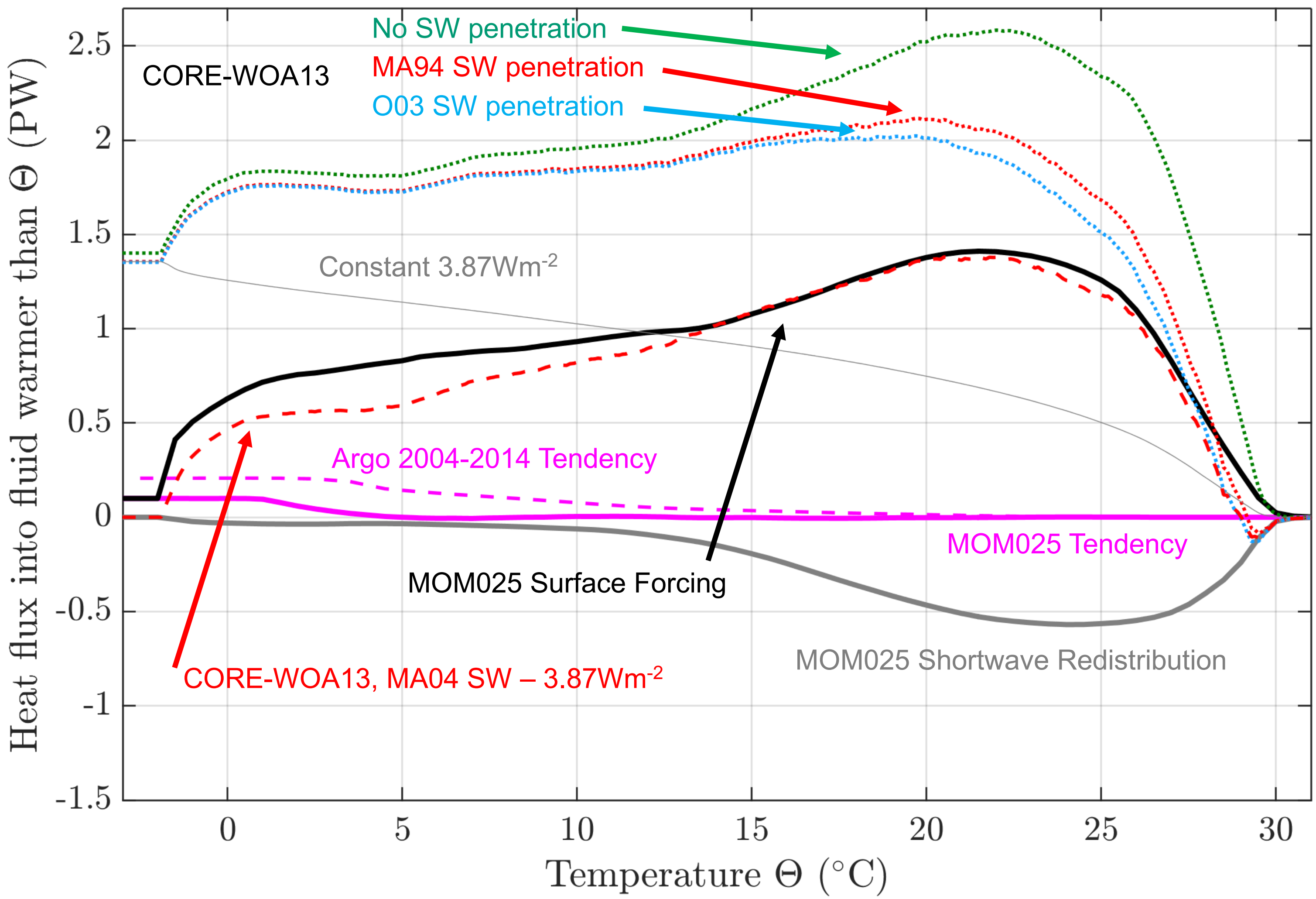


Heat Flux through the 21.5C isotherm due to vertical mixing

Vertical mixing split by *Process*:



Diathermal heat budget – comparison with obs.



Calculation performed by Sjoerd Groeskamp using WOA13 climatological SSTs, CORE surface heat fluxes (which have a global $3.87Wm^{-2}$ imbalance) and various SW penetration schemes (MA94, O03).