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

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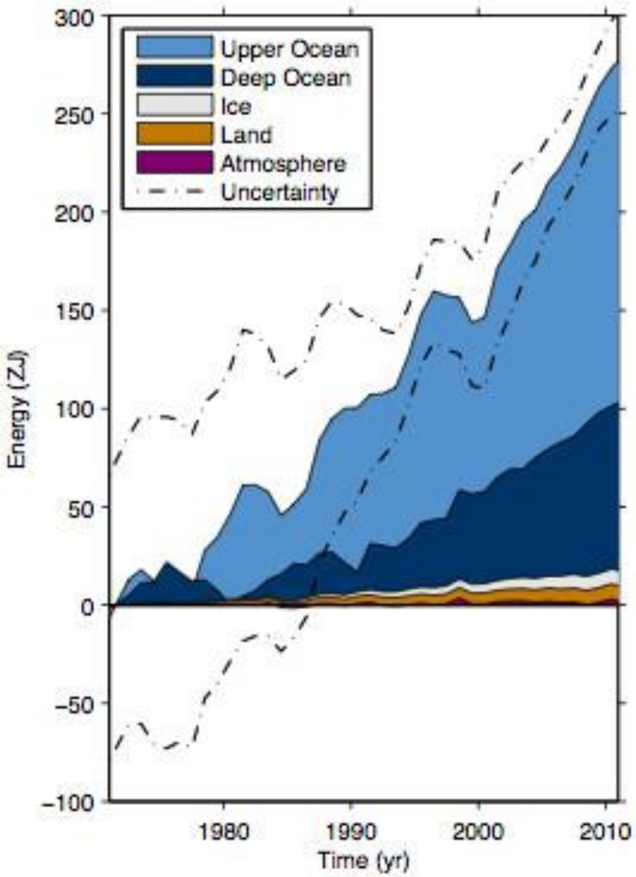
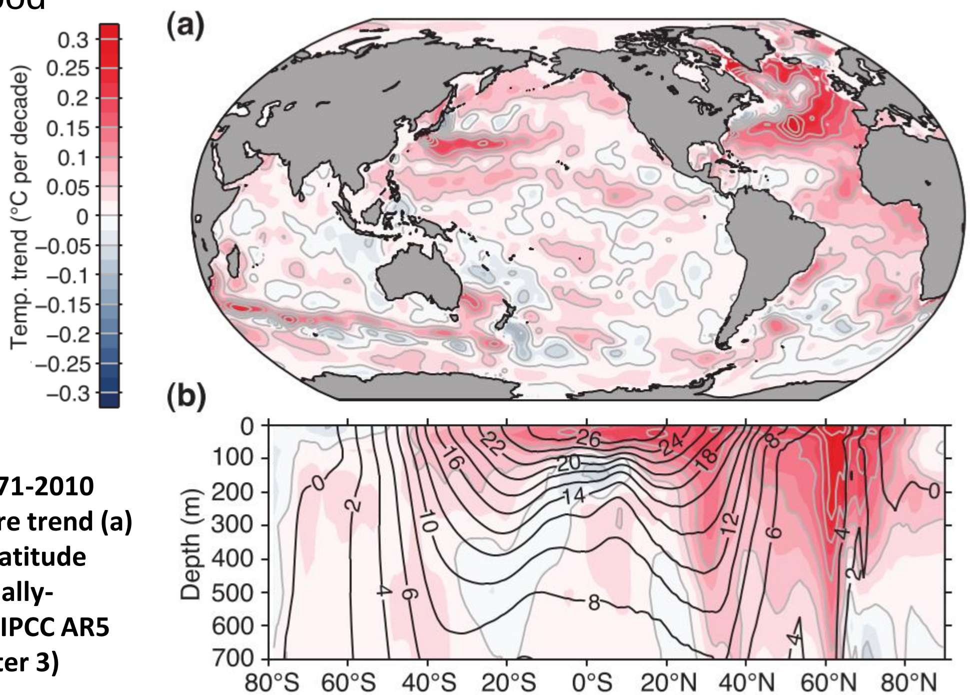
Ocean Heat Uptake and Climate Change

- More than 90% of excess energy is absorbed by the ocean (+30% of anthropogenic carbon)
- Leads to sea level rise via thermosteric expansion (~1/3 of total)
- Adjustment is slow due to time-scale for transport to intermediate/deep ocean
- Uncertainties around spatial structure – processes not fully understood



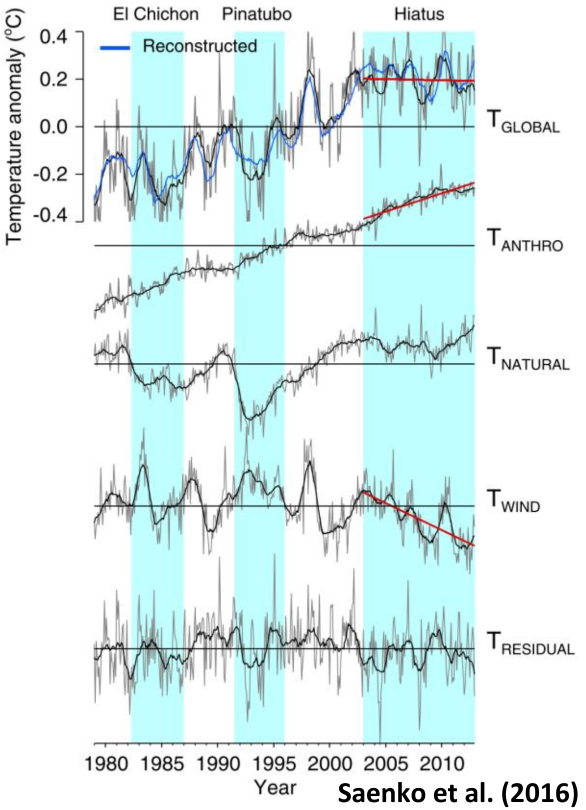
Energy accumulation in different components of the Earth System relative to 1971 (IPCC AR5 WG1 Chapter 3)



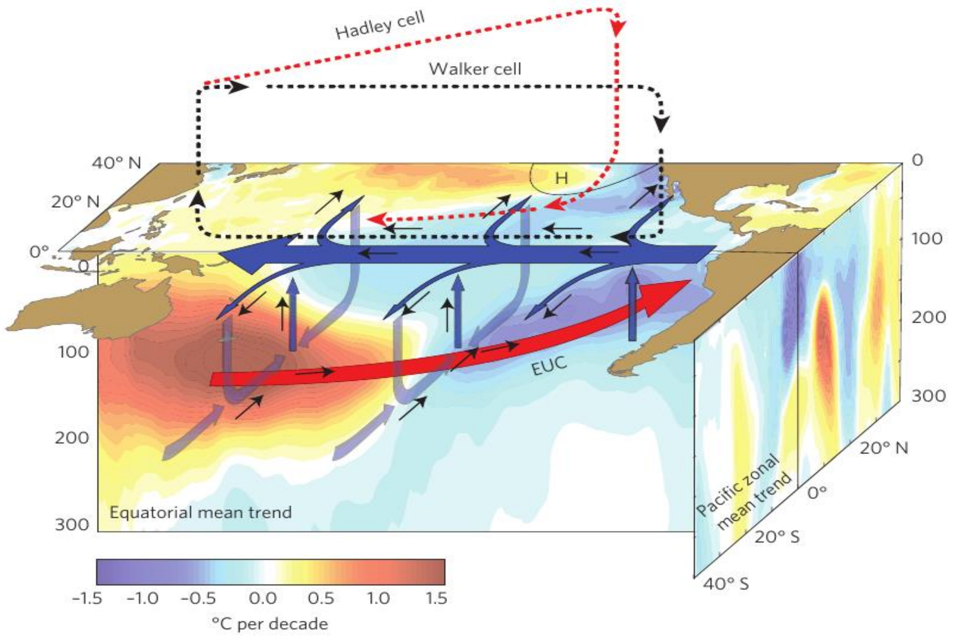
0-700m 1971-2010 temperature trend (a) longitude-latitude and (b) zonally-averaged (IPCC AR5 WG1 Chapter 3)

Natural variability

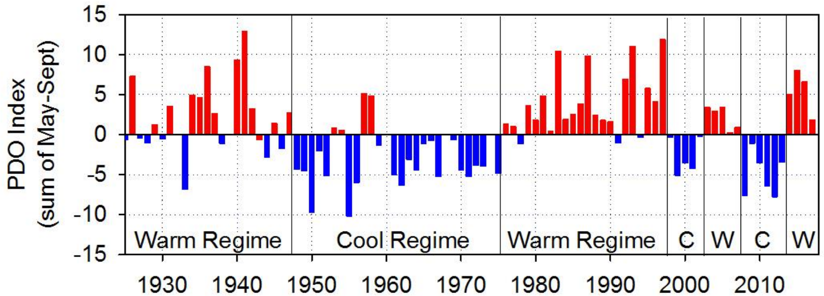
- Climate change is modulated by natural cycles (multi-decadal, decadal, interannual, seasonal).
- How are these modes going to change in the future? What will be the regional impacts?
- Would like to be able to predict these changes – which requires a through process understanding and good representation in *conceptual and numerical models*



Saenko et al. (2016) Climate Dynamics



England et al. (2014) Nature Climate Change



NOAA

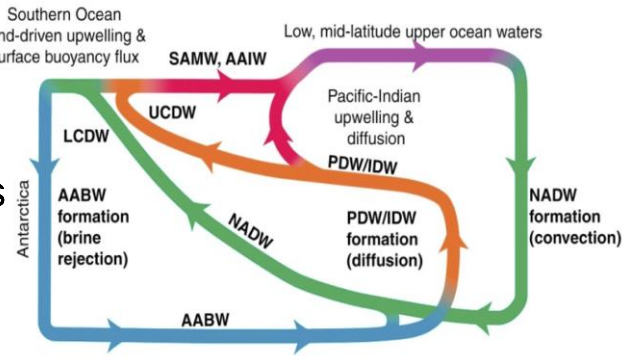
Ocean Heat Transport

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

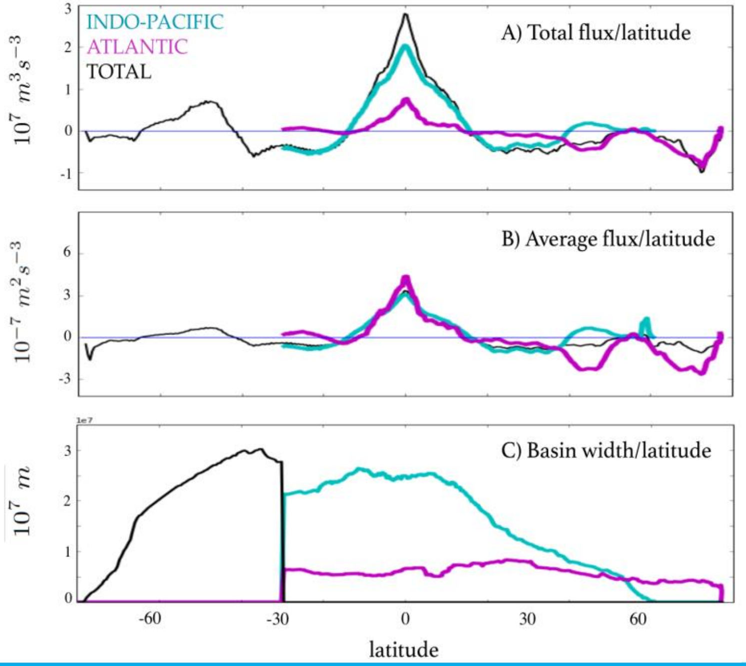
- Recent studies highlight importance of tropical Indo-Pacific

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

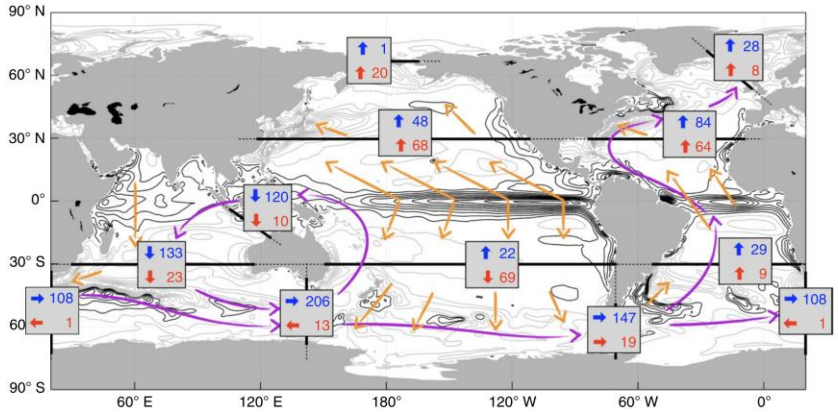
Talley (2011)



Surface buoyancy fluxes in CESM (Newsom and Thompson 2018)

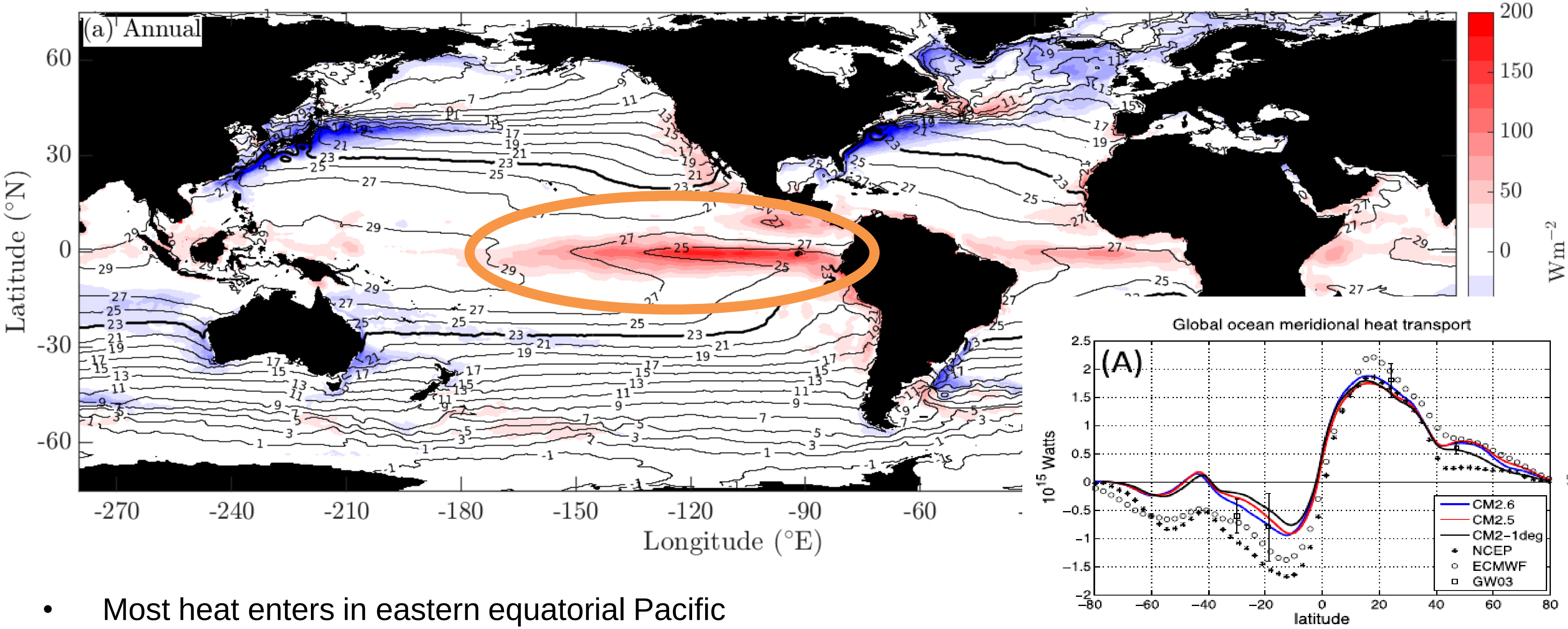


Vertically-integrated divergent heat transport (Forget and Ferriera 2019)



Diathermal Heat Transport

¼-degree MOM5 Net Surface Heat Flux



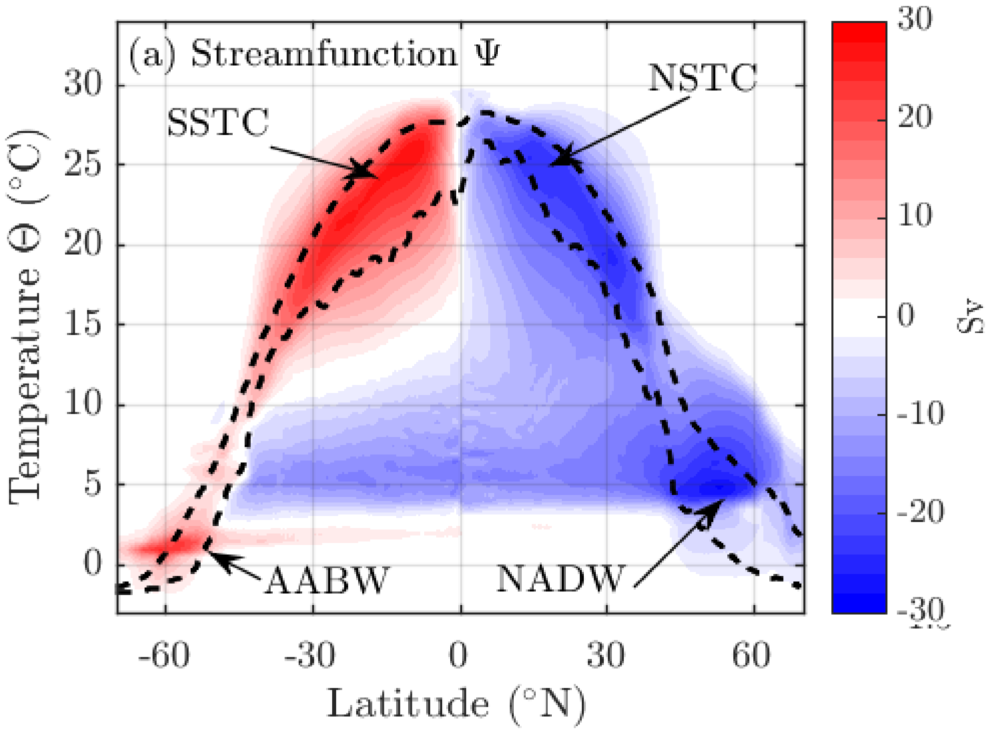
Griffies et al. (2015)

- 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)

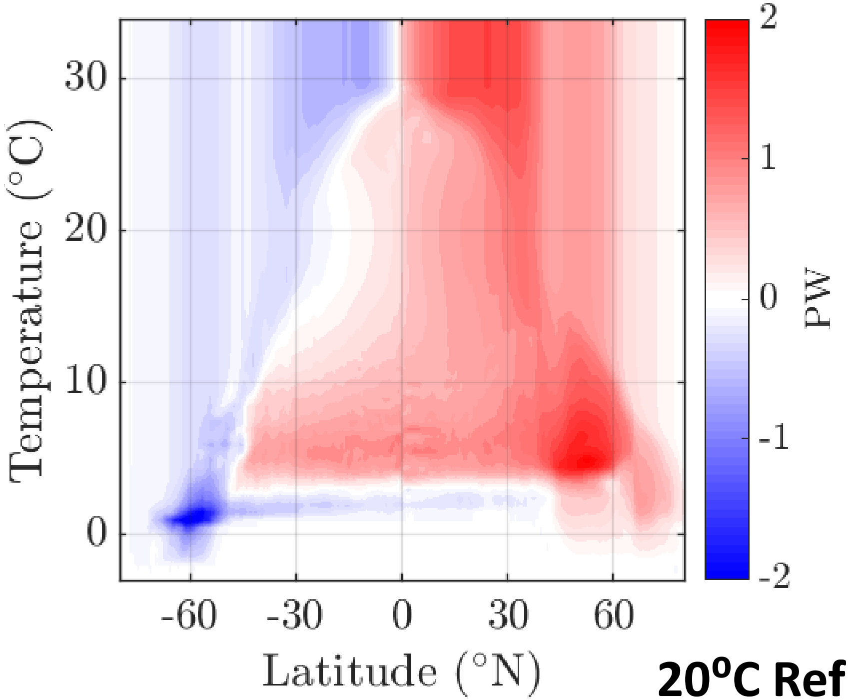
Meridional heat transport is linked to heat transport in temperature space (mixing, surface forcing)

Heat/mass transport in the latitude-temperature plane

Temperature-space MOC



Meridional heat transport



20°C 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

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

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

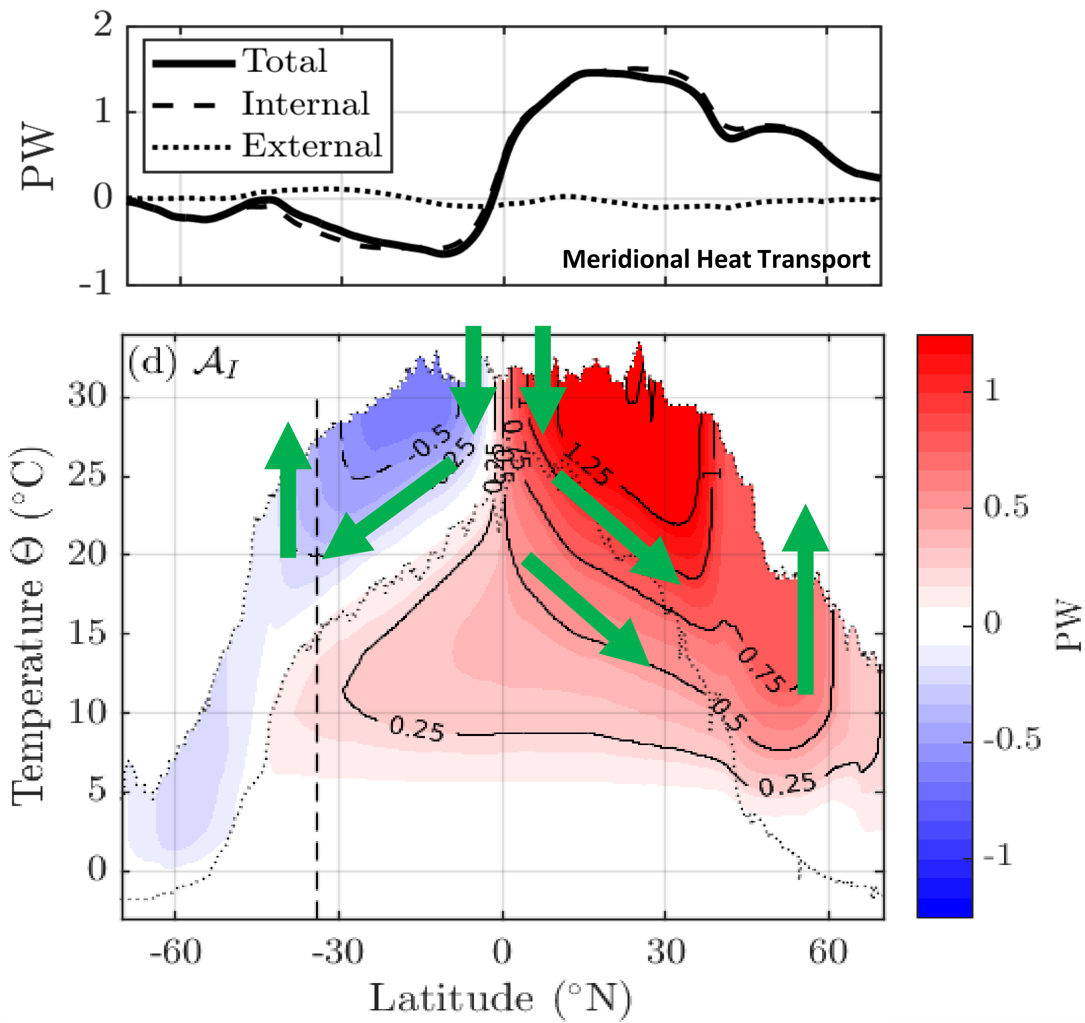
Heat function ($\mathcal{A}_I$, Ferrari and Ferriera 2011) -> heat transport pathways independent of reference temperature

Heat enters at equatorial latitudes and warm temperatures

Moves down-gradient toward cooler temperatures and poleward

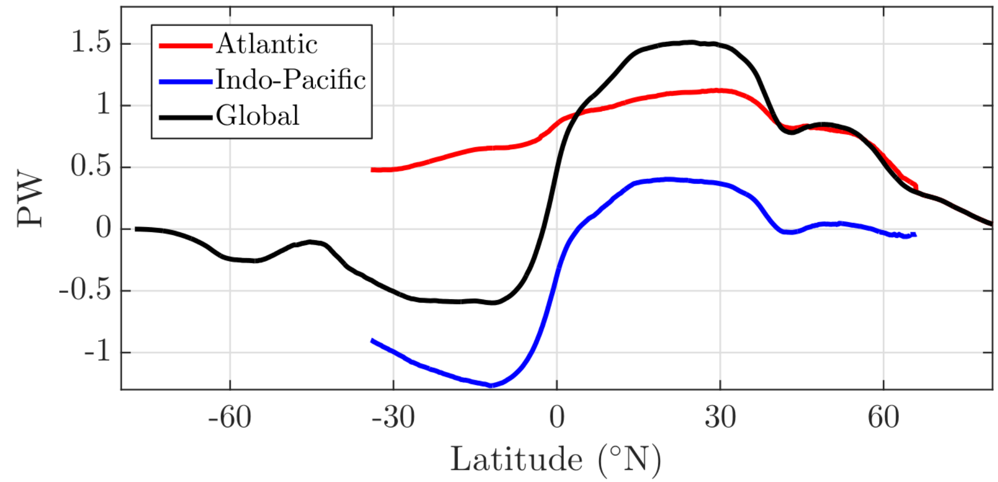
Eventually reaching high-latitudes where it is lost back to the atmosphere

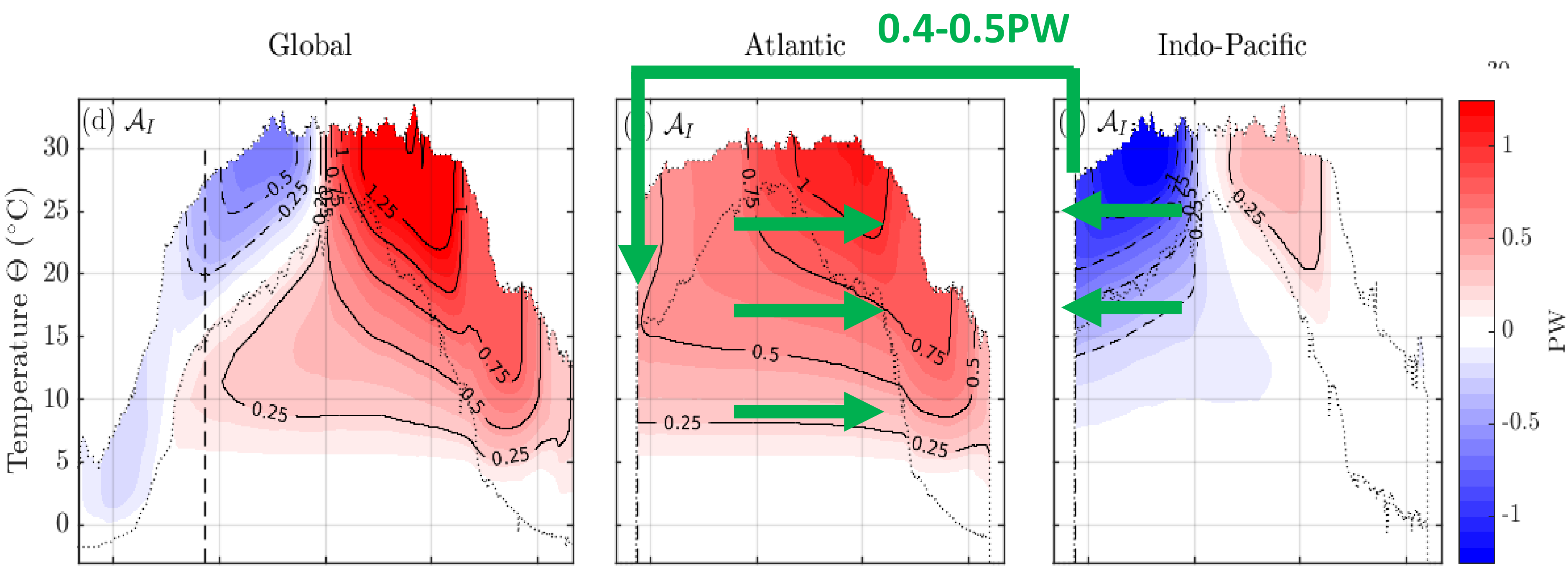
Boccaletti et al. (2005), Czaja and Marshall (2006), Greatbatch and Zhai (2007), Zika et al. (2013)



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

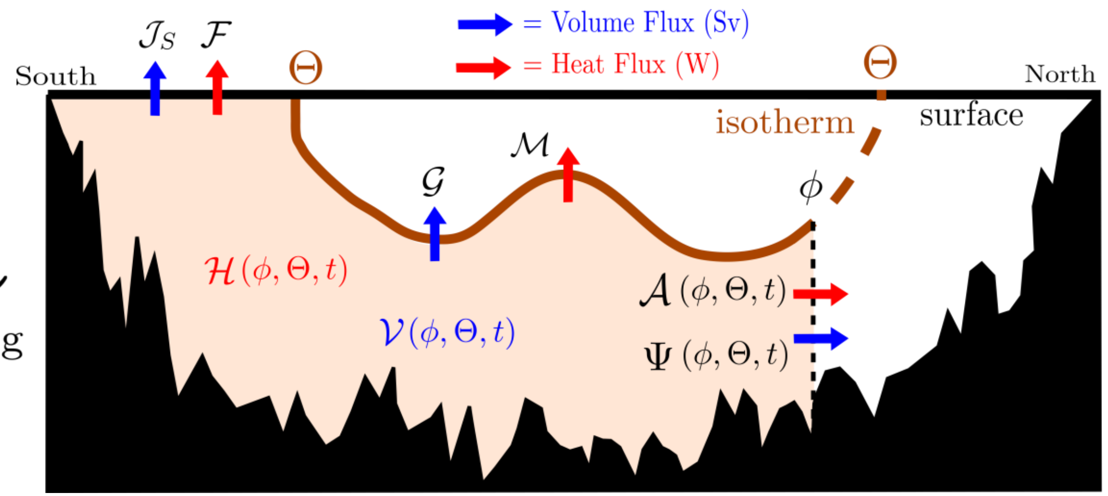




A process-budget for the heat function

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:

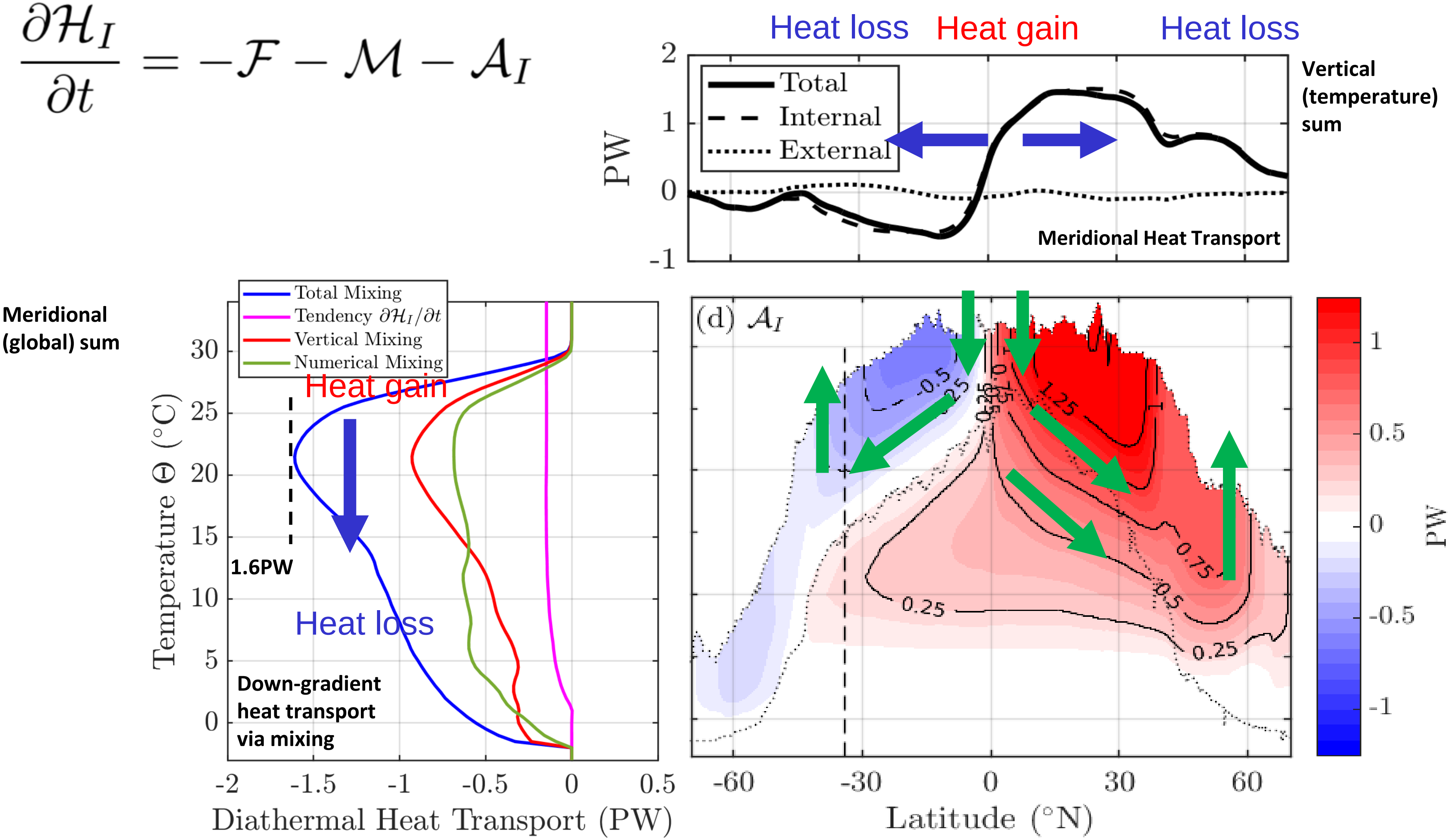
- Independent of reference temperature
- Does not include transformation $\mathcal{G}$
- Smoother/more robust (integrated)

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

Budget diagnosed online in 0.5ºC temperature bins

Diathermal transports: Mixing and Surface forcing

$$\frac{\partial \mathcal{H}_I}{\partial t} = -\mathcal{F} - \mathcal{M} - \mathcal{A}_I$$



Hieronymus et al 2014, Holmes et al (2019)

Diathermal transports: Mixing and Surface forcing

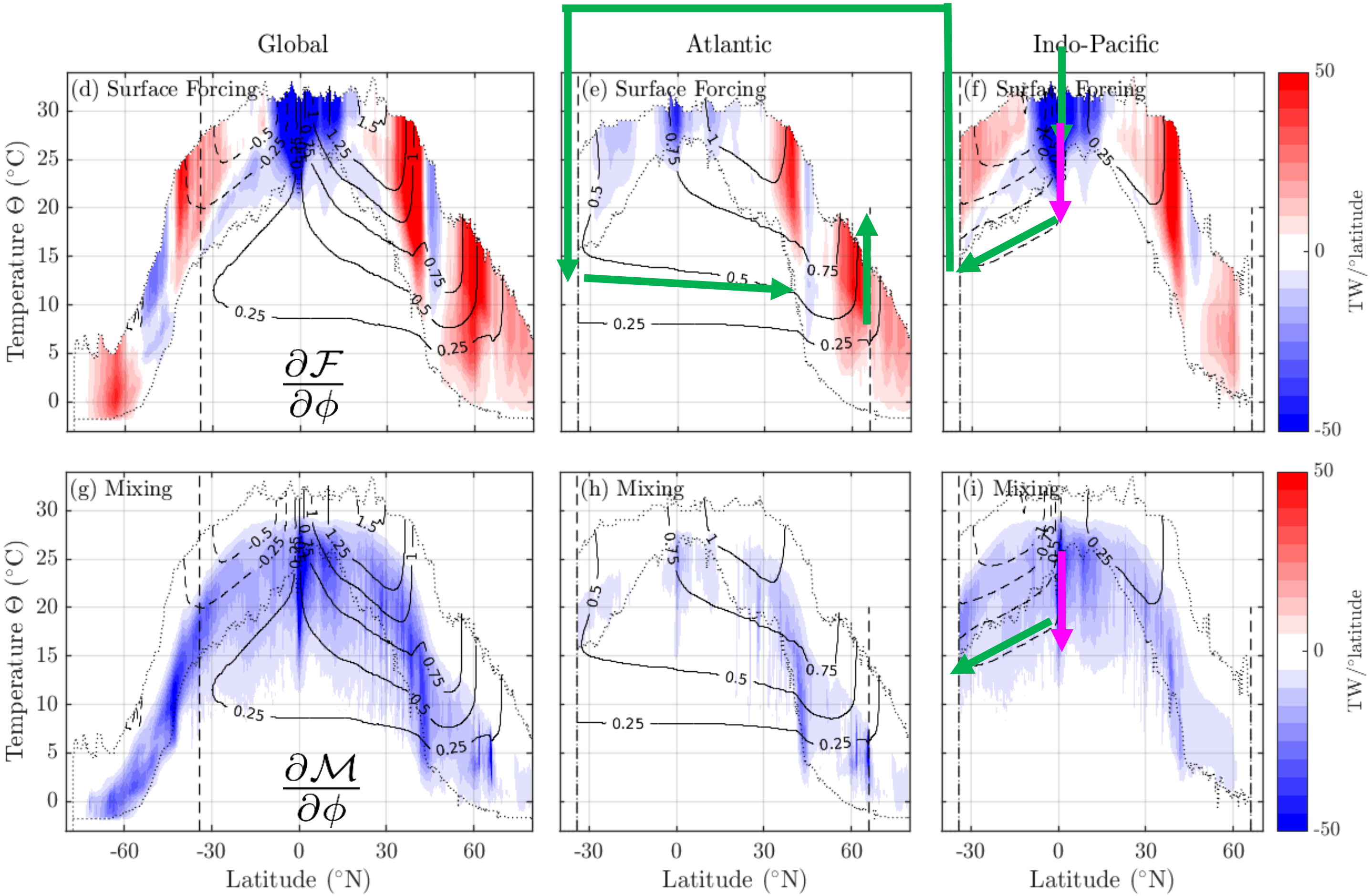
Closed budget for internal heat content: $$\frac{\partial \mathcal{H}_I}{\partial t} = -\mathcal{F} - \mathcal{M} - \mathcal{A}_I$$

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

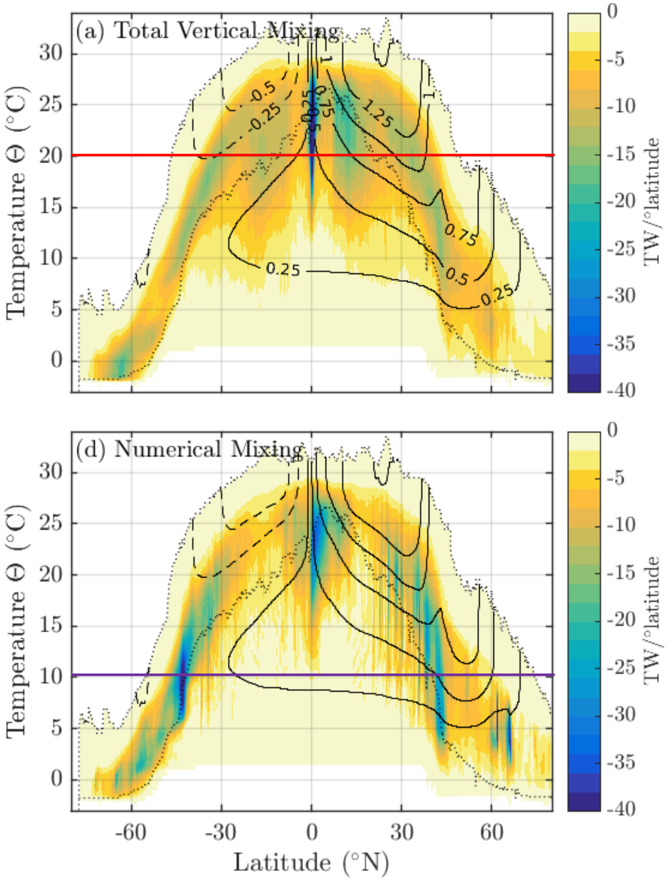
Mixing moves heat toward colder temperatures. Largely in Indo-Pacific

Supplies heat at cool temperatures to the South Atlantic

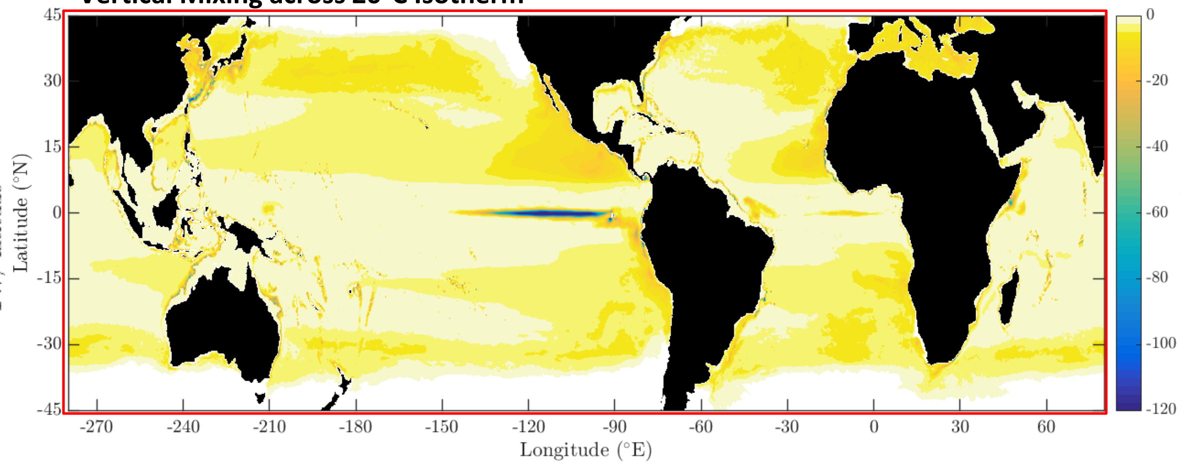
Northward transport through Atlantic to North Atlantic heat loss



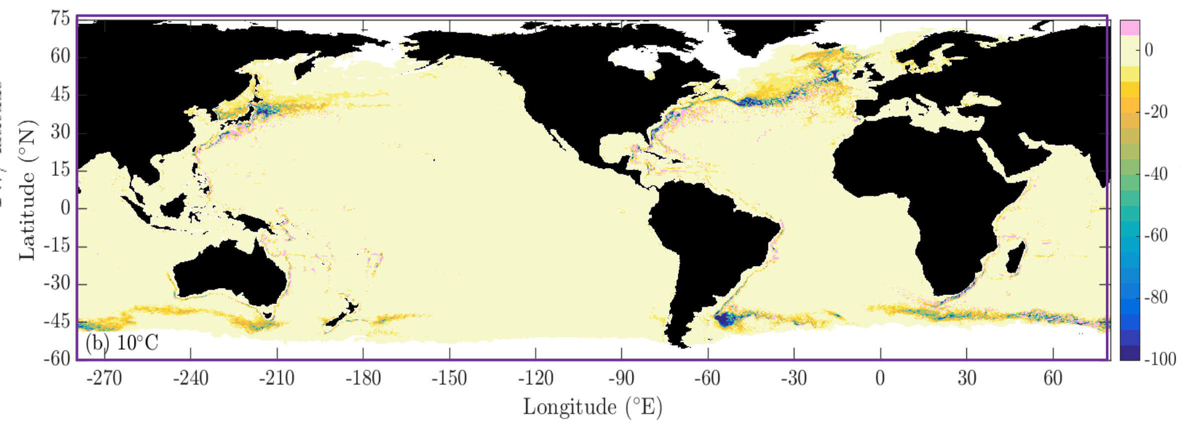
Mixing spatial structure



Vertical Mixing across 20^{o}C Isotherm



Numerical Mixing across 10^{o}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 unambiguous view of diathermal heat flows

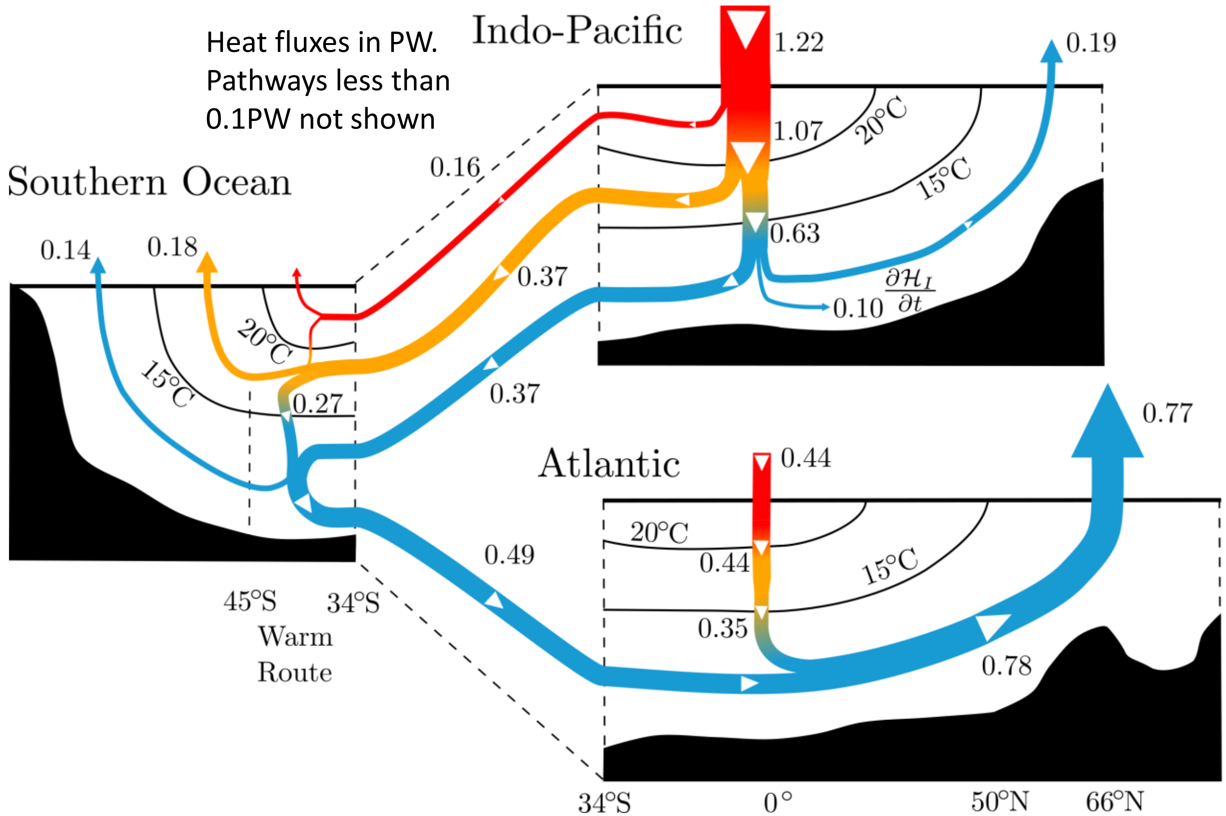
60% of the 0.78PW of Atlantic MHT across 50ºN is supplied from Indo-Pacific at temperatures above 15ºC, ultimately from cold tongue heating

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

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

Single model study => interest in applying similar diagnostics to other models

Heat fluxes in PW.
Pathways less than
0.1PW not shown



Potential for isolating less-reversible component of ocean heat uptake over natural cycles and for model evaluation

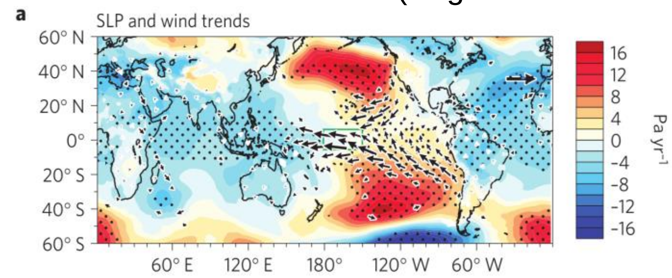
More info:

Holmes, Zika and England (2019) J. Phys. Oceanogr.

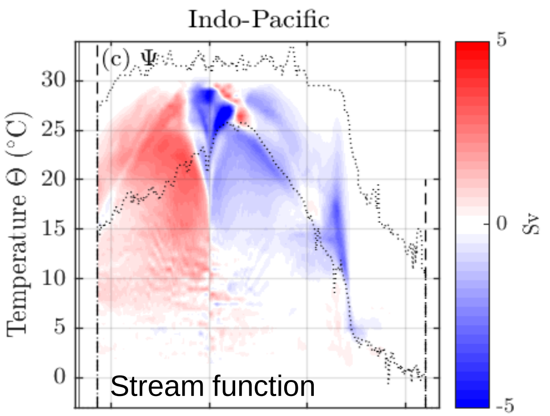
Holmes et al. (2019) minor revisions at GRL

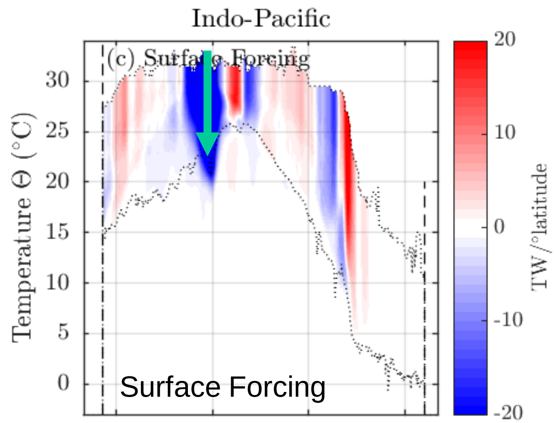
An application to the global warming hiatus

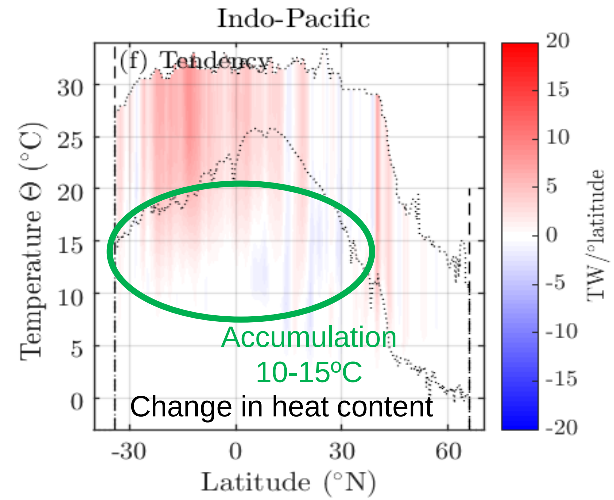
Pacific wind trends 1992-2011 (England et al. 2014)

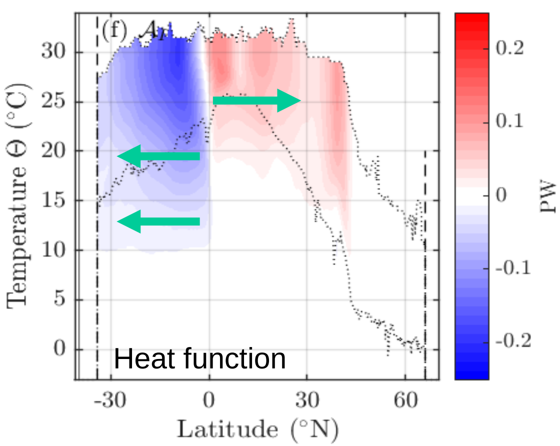


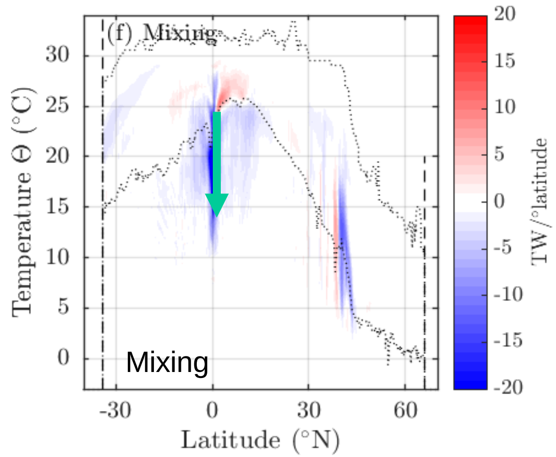
Anomalies years 10-20

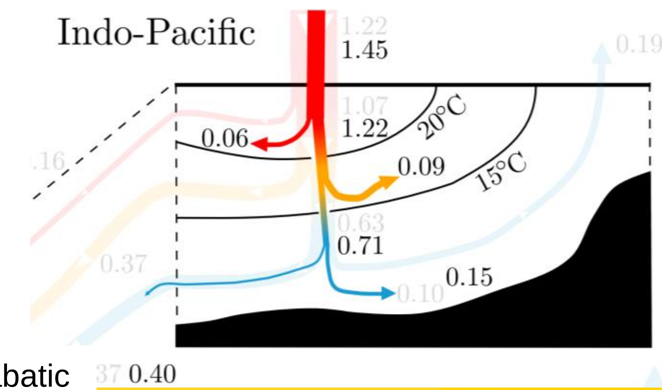












Accelerated trade winds = accelerated subtropical *residual* overturning that drives heat poleward

Increased surface heat uptake penetrates to colder temperatures through enhanced upwelling *and mixing*

0.2PW accumulating in Indo-Pacific – diabatic transfer to colder temperature classes suggests long reemergence time scale