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 thorough process understanding and good representation in conceptual and numerical models.
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

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

Surface buoyancy fluxes in CESM (Newsom and Thompson 2018)
Diathermal Heat Transport

Most heat enters in eastern equatorial Pacific

Equatorial heating + mid-latitude cooling => Poleward heat transport (~2PW)

Heating at SSTs warmer than ~23°C, cooling at SSTs colder than ~23°C => Heat transport from warm to cold temperatures (~1.6PW)

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

Griffies et al. (2015)
Heat/mass transport in the latitude-temperature plane

Temperature-space MOC

- **Streamfunction** \( \Psi \)
- **SSTC**
- **NSTC**
- **AABW**
- **NADW**

Meridional heat transport

- **20°C Ref**
- **0°C Ref - 273.15°C Ref**

Mass/volume transport below \( \Theta \):

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

Heat transport below \( \Theta \):

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

Answer depends on reference temperature
The heat function

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

$$= \rho_0 C_p \Theta \Psi - \rho_0 C_p \int_{-\infty}^{\Theta} \Psi d\Theta'$$

Heat function ($A_I$, 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

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

0.4-0.5PW
A process-budget for the heat function

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

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

- \mathcal{F} = \text{Forcing}
- \mathcal{M} = \text{Mixing}
- \mathcal{A} = \text{Transport}
- \mathcal{G} = \text{Diathermal Advection}

Internal heat content budget:

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

\[
\mathcal{H} = \rho C_p \nabla \bar{\Theta} = \rho C_p \nabla \Theta + \rho C_p \nabla (\bar{\Theta} - \Theta)
\]

\[
\mathcal{H}_I = \rho C_p \int_{\Theta}^{\infty} \nabla d\Theta'
\]

Analog with Palmer and Haines (2009)
Diathermal transports: Mixing and Surface forcing

\[ \frac{\partial \mathcal{H}_I}{\partial t} = -\mathcal{F} - \mathcal{M} - A_I \]

Hieronymus et al. 2014, Holmes et al. (2019)
Diathermal transports: Mixing and Surface forcing

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

Closed budget for internal heat content:

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

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 50°N is supplied from Indo-Pacific at temperatures above 15°C, 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*

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

More info:
Holmes et al. (2019) minor revisions at GRL
An application to the global warming hiatus

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