Interbasin redistribution of heat and nutrients due to AMOC changes

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Interbasin heat redistribution following a weakening of AMOC
Anti-phasing temperature between hemispheres and bi-polar seesaw

**Anti-phasing temperature changes between Greenland and Antarctica**

Normalized signal

-500 -250 0 250 500 750

WAIS (2015)

**Heat Reservoir**

$T_S(t)$

$-T_N(t)$

S Atlantic  N Atlantic

Trenberth and Caron (2001)

Stocker and Johnson (2003)
Climate response to AMOC changes not confined to the Atlantic and Southern Ocean

Compensating heat transport responses between the Atlantic and Indo-Pacific at southern boundary following a collapsed AMOC.
Compensating heat transport due to transient inter-basin overturning compensation

\[ H'_{\text{SO}} = H'_{\text{ATL}} + H'_{\text{IP}} \]

Overturning circulation anomaly associated with AMOC weakening
Heat transport anomaly due to AMOC weakening
Surface heat uptake anomaly

Sun et al. (2020); Sun (2022)
Transient inter-basin overturning compensation between Atlantic and Indo-Pacific

Overturning circulation streamfunction in CESM1 (RCP 8.5)

Different from the steady state balance, the Indo-Pacific develops an overturning circulation anomaly that opposes the Atlantic changes, balanced by an adiabatic deepening of isopycnals (not PMOC or interbasin overturning seesaw as discussed in Saenko et al., 2004).

Sun et al. (2020)
Overturning circulation in reduced gravity model

Reduced gravity model (Lat x Lon x 1.5)

Control: NADW formation balanced by Southern Ocean overturning

$$T_{\text{NADW}} \approx T_{\text{SO}}$$

Perturbation: reduced NADW formation leads to a deepening of the interface

$$T_{\text{SO}} = -\frac{\tau}{\rho f_s} + K_{\text{GM}} s \rightarrow -K_{\text{GM}} \frac{\bar{h}}{L_y}$$
Overturning circulation in reduced gravity model

**Reduced gravity model** (Lat x Lon x 1.5)

- **Control**: NADW formation balanced by Southern Ocean overturning
  \[ T_{\text{NADW}} \approx T_{\text{SO}} \]

- **Perturbation**: reduced NADW formation leads to a deepening of the interface

- \[ T_{\text{SO}} = \frac{-\tau}{\rho f_s} + K_{\text{GM}} s - K_{\text{GM}} \frac{\bar{h}}{L_y} \]

- Wind

- Eddy

- Abyss

- Depth

- Latitude

- \( T_{\text{SO}} \)

- \( T_{\text{NADW}} \)

- \( h \)

- \( \kappa \frac{h}{w_{\text{diap}}} \)
Overturning responses to reduced NADW formation

Interface depth anomaly propagate as Kelvin/Rossby waves

[Diagram showing the propagation of interface depth anomalies in the Atlantic and Indo-Pacific basins]

Sun et al. (2020)
Compensating overturning responses between Atlantic and Indo-Pacific

MITgcm ocean-only simulation at 1deg resolution

(a) Volume transport anomaly by upper 1km

- AMOC
- Indo-Pacific
- Atlantic
- Global

Transport at 30°S (Sv)

Years

Sun et al. (2022)
Compensating heat transport responses between Atlantic and Indo-Pacific

MITgcm ocean-only simulation at 1deg resolution

Heat transport anomaly

- Atlantic
- Global
- Indo-Pacific

Sun et al. (2022)
Indo-Pacific subsurface warming due to inter-basin heat exchanges

- Centennial subsurface warming due to inter-basin overturning (compare with vertical diffusion)
- This is an important heat source for future Indo-Pacific warming on centennial timescales
An update to bi-polar seesaw: a thermal inter-basin seesaw

Using paleoclimatic data is the construction of absolute timescales for records which are geographically distant from each other. However, timescales need not be absolute; the ice core synchronizations have demonstrated that common timescales, constructed based on varying global properties, are equally suitable.

The original bipolar seesaw (Figure 2, right) implied that changes in the north and south occur at the same time. This requires very fast signal transmission in the ocean. Heating large water bodies requires time due to thermal inertia. A faster response is afforded by wave propagation and the associated vertical displacement of isopycnals. Ocean models show that density anomalies are propagated meridionally by coastal Kelvin waves along the western and eastern basin boundaries. From there, the interior then adjusts in response to westward propagating Rossby waves [Kawase, 1987].

S u c h w a v e - m e d i a t e d a d j u s t m e n t p r o c e s s e s are fast and occur on timescales of months to a few decades [Goodman, 2001]. In the Southern Ocean, the response is slower because of the absence of lateral boundaries which support waves. There, a thermal response is more appropriate. Circulation models suggest that the typical adjustment time of the modern Southern Ocean is on the order of 300 to 500 years [England, 1995]. There exist evidence from various paleoceanographic proxy data [François et al., 1997; Sikes et al., 2000; Goldstein et al., 2001; van Beek et al., 2002] and modeling [Winguth et al., 2000; Meissner et al., 2003] that the ventilation in the Southern Ocean was reduced during the last ice age due to increased stratification, and therefore, adjustment times are expected to be longer.

This naturally leads to the following hypothesis: Does the addition of a heat reservoir to the original bipolar seesaw significantly improve the correlation between the isotopic records from Antarctica and Greenland, and if so, what typical timescale of the heat reservoir would be predicted by the correlation analysis? On the basis of Figure 2, we formulate an energy balance of the modified ''thermal bipolar seesaw'', for which it is assumed that the change in heat storage of a ''southern heat reservoir'' is proportional to the temperature difference between the reservoir and the southern end of the seesaw,

$$\frac{dT_S}{dt} = \frac{1}{\tau} \left( \frac{TN(t)}{C_0} \right) \frac{TS(t)}{C_1}$$

(1)

The temperature anomaly of the heat reservoir is denoted by $TS$, $t$ is the characteristic timescale of the heat reservoir, and $TN$ denotes the time-dependent temperature anomaly of the northern end of the bipolar seesaw ($\frac{TN(t)}{C_0}$ is the corresponding temperature anomaly of the southern end communicating with the heat reservoir). Using Laplace transform, one can solve for $TS$,

$$TS(t) = \frac{1}{C_0} \left( \frac{TN(t)}{C_0} \right) e^{-\frac{t}{\tau}} + TS_0$$

(2)

The reservoir temperature is therefore a convolution of the northern temperature using the timescale $\tau$. There exist evidence from various paleoceanographic proxy data [François et al., 1997; Sikes et al., 2000; Goldstein et al., 2001; van Beek et al., 2002] and modeling [Winguth et al., 2000; Meissner et al., 2003] that the ventilation in the Southern Ocean was reduced during the last ice age due to increased stratification, and therefore, adjustment times are expected to be longer.

Figure 1. Latitude-depth plots in the Atlantic of the temperature difference between a state of collapsed and one of an active meridional overturning circulation (off minus on). Temperature differences exhibit a bipolar pattern with cold anomalies in the North Atlantic and warm anomalies south of about 10–20°N. (a) Results from the Bern 2d model [Stocker et al., 1992b], (b) and from a three-dimensional coupled model [Schiller et al., 1997]. (Figure 1b supplied by U. Mikolajewicz).

Figure 2. Schematic of the thermal bipolar seesaw model. The original bipolar seesaw is coupled to a heat reservoir possibly representing the Southern Ocean or another slowly responding component of the climate system. The double arrow indicates that in the simple model the heat exchange with the reservoir is parameterized diffusively.

Stocker and Johnson (2003)

Sun et al. (2022)
Nutrient redistribution by the inter-basin overturning responses following AMOC weakening

Following a weakened AMOC,

**Atlantic**: decrease in nutrients supply by the northward AAIW transport

**Indo-Pacific**: Isopycnal deepening decreases upper ocean nutrient concentration

- Due to different vertical nutrients gradient between Atlantic and Indo-Pacific, this inter-basin overturning response could also drive a net nutrient transport into the **Southern Ocean**.
The transient inter-basin overturning responses to AMOC changes plays a key role in redistributing heat and nutrients.