Climate effects of overturning on heat content anomalies and atmospheric CO$_2$

1. Heat content anomalies in the North Atlantic
2. Heat transport & overturning cells
3. Effect of overturning changes on atmospheric CO$_2$

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Methodology

1. Estimate interior T & S from available data extrapolate via Hadley model covariance (Smith and Murphy, 2007)

at each point, correlation between observed and modelled SST anomaly correlation patterns

2. Solve for velocity and heat transport via dynamical relaxation to T & S data within MIT model (Lozier et al., 2010). Similar to Mellor et al. (1982) diagnostic.

MOC anomaly (Sv) model estimate

RAPID MOC annual running mean
Thermal anomalies with depth for each gyre

subtropical (0-45N)
Thermal anomalies with depth for each gyre

**subtropical (0-45N)**

**subpolar (45-75N)**
Link between heat content tendency and heat transport convergence

\[ \int_{-D}^{0} \frac{\partial \theta^x}{\partial t} \, dz + \int_{-D}^{0} \frac{\partial}{\partial y} v \theta^x \, dz = \frac{\mathcal{H}}{\rho_0 C_p} \]

equivalent surface heat fluxes (Wm\(^{-2}\))

subtropical (5N-45N)

heat content tendency

convergence in heat transport
Link between heat content tendency and heat transport convergence

$$\int_{-D}^{0} \frac{\partial \theta^x}{\partial t} dz + \int_{-D}^{0} \frac{\partial}{\partial y} v \theta^x dz = \frac{\mathcal{H}}{\rho_0 C_p}$$

equivalent surface heat fluxes (Wm\(^{-2}\))

**subtropical (5N-45N)**

-10

+10

heat content tendency

convergence in heat transport

**subpolar (45N-75N)**

-5

+6

heat content tendency

convergence in heat transport
North Atlantic Ocean depth-integrated heat content anomaly

- **1965-1975**: Heat loss in subtropics and heat gain in high latitudes
- **1975-2000**: Heat gain in subtropics and heat loss in high latitudes
- **2000-2009**: Heat gain in subtropics and high latitude

Williams et al. (2013) J Climate, under review
Aim to link thermal anomalies to volume and heat transport

Overturning in depth coordinates

Overturning in density coordinates
Ocean heat transport usually split into MOC + horizontal

\[
\int_{-D}^{0} v \theta^x \, dz = \int_{-D}^{0} \overline{v^x} \overline{\theta^x} \, dz + \int_{-D}^{0} v' \theta' \, dz
\]

MOC dominates at most latitudes, horizontal becomes important over subpolar
MOC further split into part due to winds (Ekman) in mass-conserving manner

\[
\int_{-D}^{0} \overline{u}^x \overline{\theta}^x \, dz = \left( \int_{-D}^{0} \overline{u}^x \overline{\theta}^x \, dz - \overline{V}_{ek}^x (\overline{\theta}_{ek}^x - \overline{\theta}_{r}^{x,z}) \right) + \overline{V}_{ek}^x (\overline{\theta}_{ek}^x - \overline{\theta}_{r}^{x,z})
\]

MOC

\[\text{MOC-Ekman}\]

Ekman

solve for Ekman return flow via a dynamical adjustment after 1 year

Ekman overturning cell (Sv)

-6 Sv

+6 Sv
Heat transport by Ekman peaks in tropics
by MOC-Ekman peaks at 35N
by horizontal peaks at 55N
Returning to depth-integrated heat content anomaly
Returning to depth-integrated heat content anomaly

Returning to depth-integrated heat content anomaly

Ekman heat transport anomaly (TW)

Consistent with contrasting gyre response
Returning to depth-integrated heat content anomaly

horizontal heat transport anomaly (TW)

Weaker opposing gyre response
subtropical thermal anomaly

heat content anomaly
heat anomaly from convergence in heat transport

Return to thermal anomalies
subtropical heat anomaly and heat convergence

$Q' - \int \nabla \cdot (VQ)' \, dt$

heat content anomaly

heat anomaly from convergence in heat transport

heat anomaly from Ekman heat convergence

heat anomaly from MOC-Ekman heat convergence
subpolar thermal anomaly

heat content anomaly

heat anomaly from convergence in heat transport
Heat content anomaly

Heat anomaly from convergence in heat transport

Heat anomaly from Ekman heat convergence

Heat anomaly from MOC-Ekman heat convergence
what is the link between NAO, heat content and MOC anomalies?
Link to atmospheric modes

Consider stronger winds, eg NAO+

Ekman correlation with NAO

NAO index correlation with Ekman transport

1965-2010, detrended
Link to atmospheric modes

- **Subpolar**: $T' < 0$ (upwelling)
- **Subtropics**: $T' > 0$ (downwelling)

**Upper heat content**

Correlation with NAO

1965-2010, detrended
Link to atmospheric modes

subpolar

T' < 0  ⊙

MOC+

T' > 0  ⊕

MOC-

subtropics

upper MOC

correlation with NAO

NAO index correlation with MOC

1965-2010, detrended

i.e strong imprint on MOC by the winds

weaker MOC

stronger MOC
Link to atmospheric modes

Atmospheric variability excites range of overturning cells,

Strong imprint of the winds on subtropical heat content & MOC

Also delayed response to wind forcing

Now consider carbon cycling
sensitivity to winds
• Southern Ocean westerlies
• northern Trade winds
Stronger westerly winds in Southern Ocean
what is the effect on atmospheric CO$_2$?

Lauderdale et al. (2013) Wind-driven changes in the Southern Ocean Carbon reservoirs .. Climate Dynamics

$2.8^\circ \times 2.8^\circ$, 15 levels, global MIT GCM, 5000 years
wind stress $0.2$ to $0.3$ Nm$^{-2}$
residual circulation $14$ to $26$ Sv

stronger overturning
thicker thermocline
DIC = $C_{\text{sat}}^\uparrow + C_{\text{bio}}^\uparrow + C_{\text{dis}}^\uparrow$

saturated  soft & hard tissue  disequilibrium

Atlantic section
(mmol C m$^{-3}$)
DIC = $C_{\text{sat}}^{\text{sat}} + C_{\text{bio}}^{\text{bio}} + C_{\text{dis}}^{\text{dis}}$

change in $C_{\text{sat}}^{\text{sat}}$

Atlantic section (mmol C m$^{-3}$)

- warmer, thicker thermocline
DIC = $C_{\text{sat}}^{\text{saturated}} + C_{\text{bio}}^{\text{soft \& hard tissue}} + C_{\text{dis}}^{\text{disequilibrium}}$

- warmer, thicker thermocline
- thicker nutricline
\[
\text{DIC} = C_{\text{sat}} + C_{\text{bio}} + C_{\text{dis}}
\]

- warmer, thicker thermocline
- thicker nutricline
- greater upwelling, less equilibration

Atmospheric CO$_2$ rises by +15 ppm
27 experiments: variety of winds, GM values, buoyancy forcing

\[ R^2 = 0.89 \]

atmospheric CO\(_2\) (ppm)

stronger overturning upper cell, greater atmospheric CO\(_2\)

Lauderdale et al. (2013) Climate Dynamics
Overturning perturbations in the North Atlantic

stronger Trade winds in N. Atlantic (by 50%)

strengthen shallow overturning cell ~ 8 Sv, deep cell ~ 2 Sv

change in DIC

0

+10

-10

(mmol C m^{-3})

depth

latitude

80S

0

80N

80°S

40°S

0°

40°N

80°N
DIC = $C_{sat}^{saturated} + C_{bio}^{soft \ & \ hard \ tissue} + C_{dis}^{disequilibrium}$

- greater advection of equatorial waters
- more tropical upwelling
- greater subduction of undersaturated DIC

atmospheric CO$_2$ rises by 7 ppm
Summary

- Thermal anomalies on gyre and sub-gyre scale dominate thermal response in N. Atlantic basin over last 60 years.

- Subtropical changes linked to Ekman heat convergence. See Lozier et al. (2008) Science

- Subpolar changes linked to MOC-Ekman heat convergence
  See Robson et al. (2012) J Clim
  also talks by Alexey Federov & Rym Msadek
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- Overturning changes can alter atmospheric CO$_2$ via subduction, disequilibrium & upwelling

at equilibrium, coarse models suggest stronger overturning increases atmospheric CO$_2$