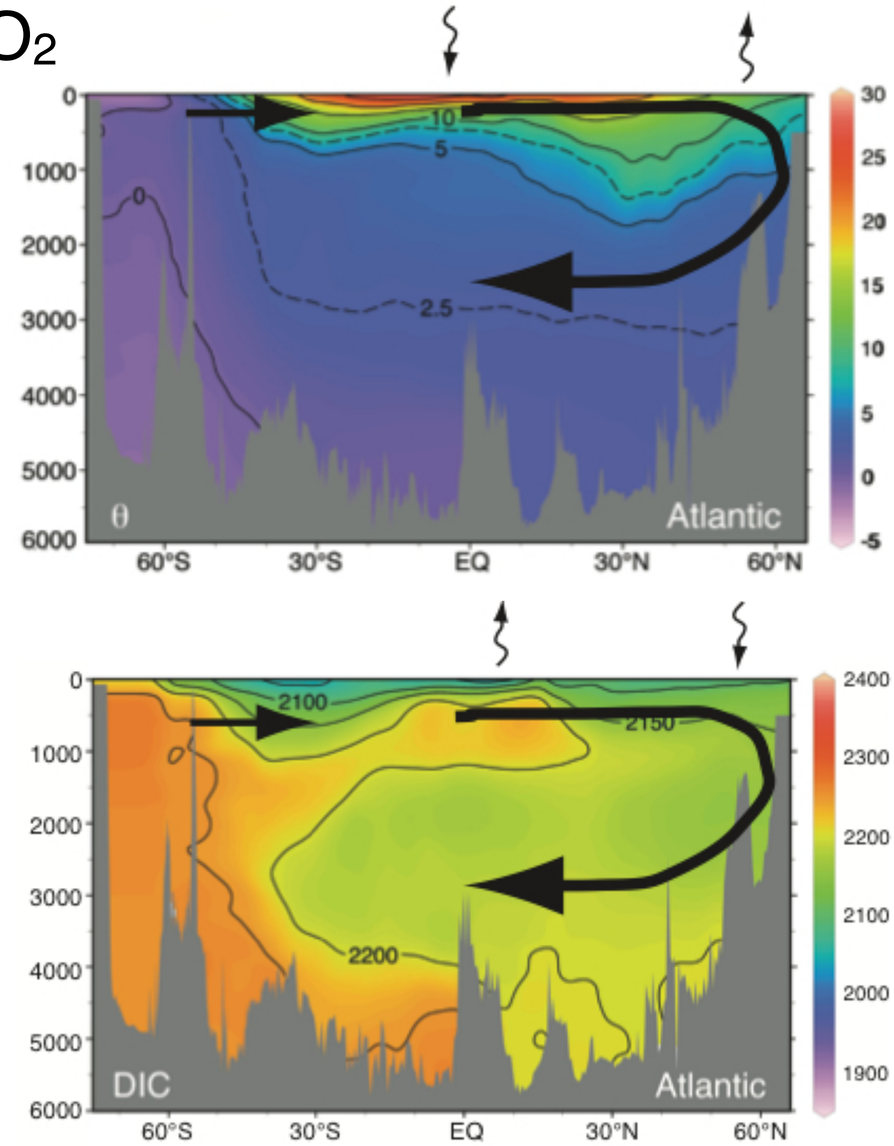
Climate effects of overturning on heat content anomalies and atmospheric CO_2



1. Heat content anomalies in the North Atlantic

2. Heat transport & overturning cells

3. Effect of overturning changes on atmospheric CO_2

Thanks to Vassil Roussenov, Jonathan Lauderdale (Liverpool University)
Susan Lozier (Duke), Doug Smith (Hadley Centre)
Alberto Naveira-Garabato, Kevin Oliver (Southampton), Mick Follows (MIT)

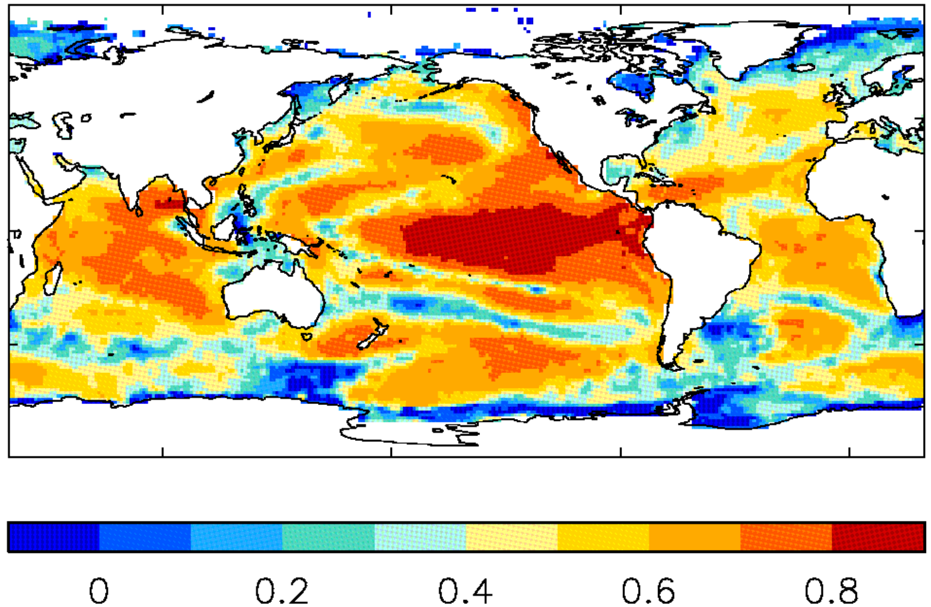
UNIVERSITY OF LIVERPOOL

data/
model

Methodology

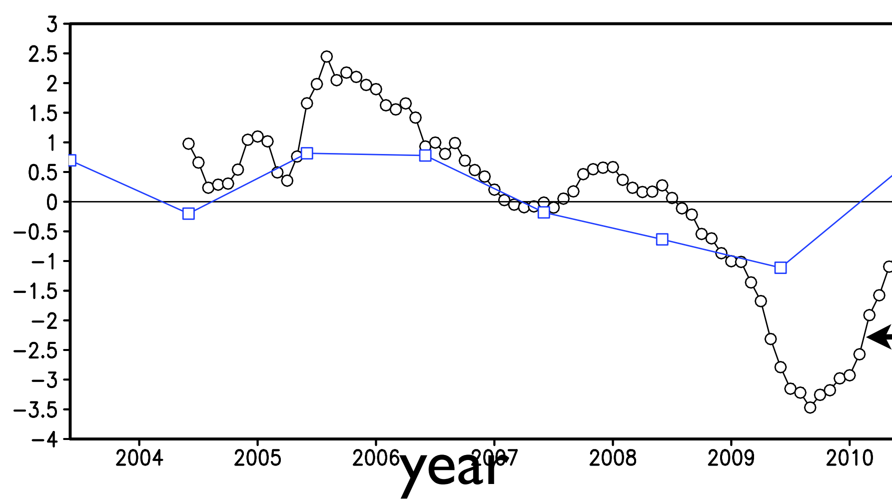
1. Estimate interior T & S from available data
extrapolate via Hadley model covariance (Smith and Murphy, 2007)

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)

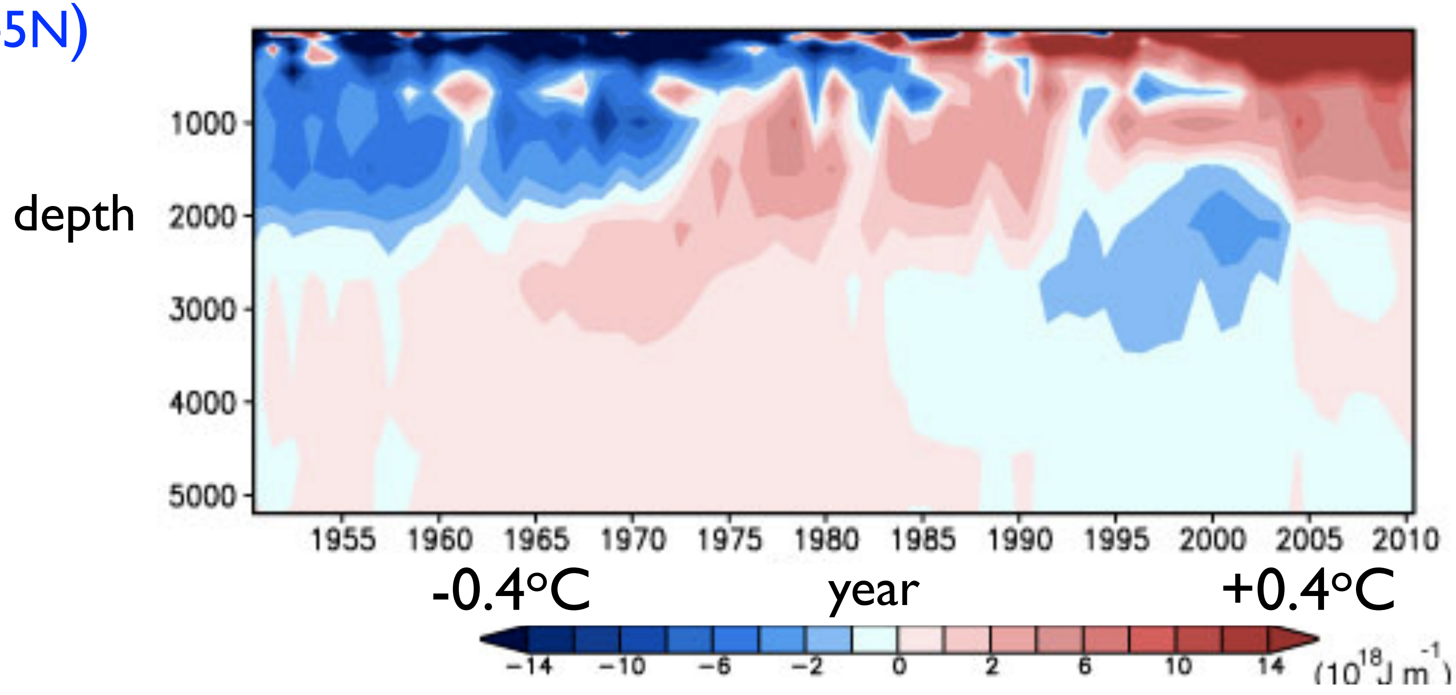


model estimate

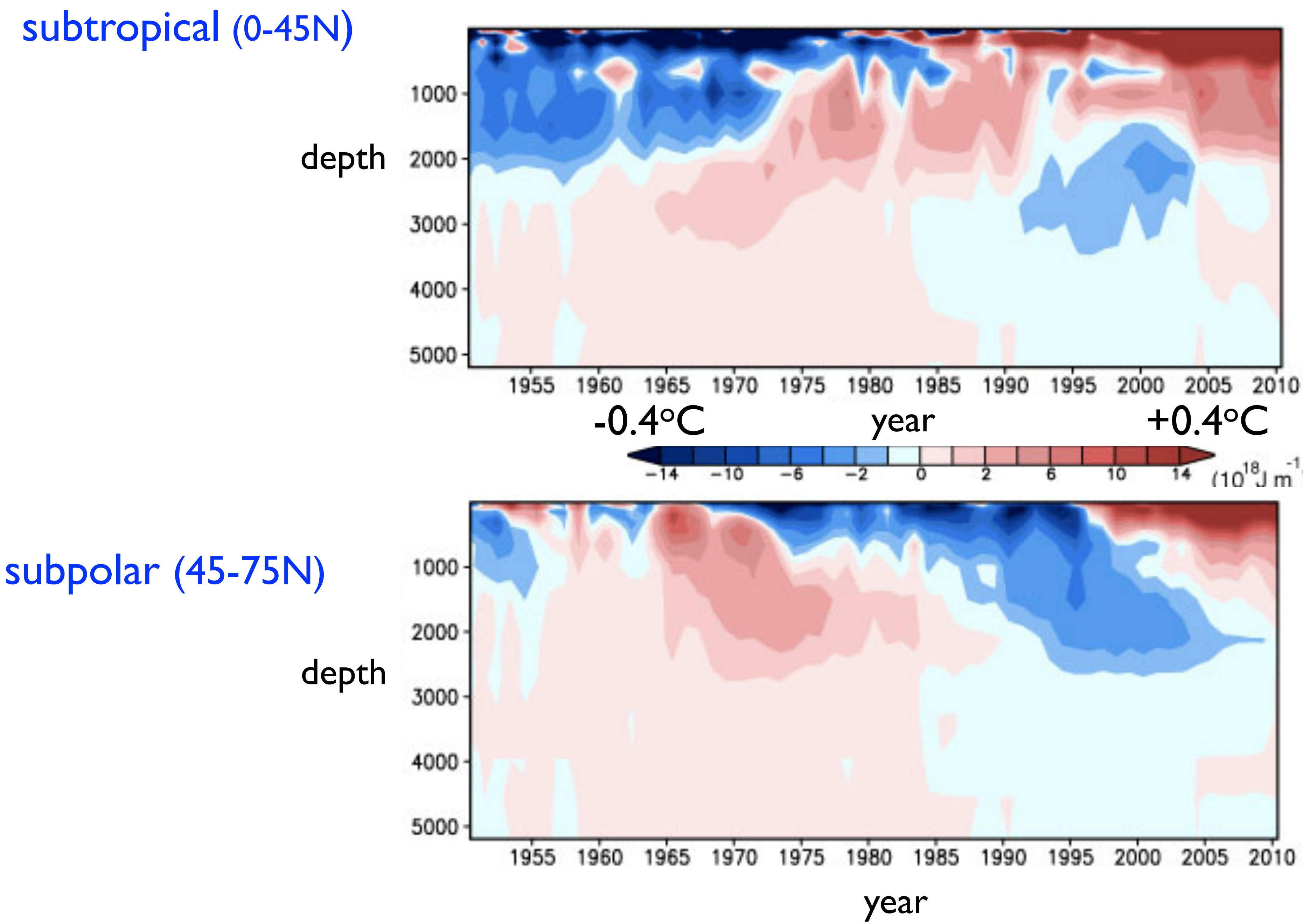
RAPID MOC annual running mean

Thermal anomalies with depth for each gyre

subtropical (0-45N)



Thermal anomalies with depth for each gyre



Link between heat content tendency and heat transport convergence

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

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

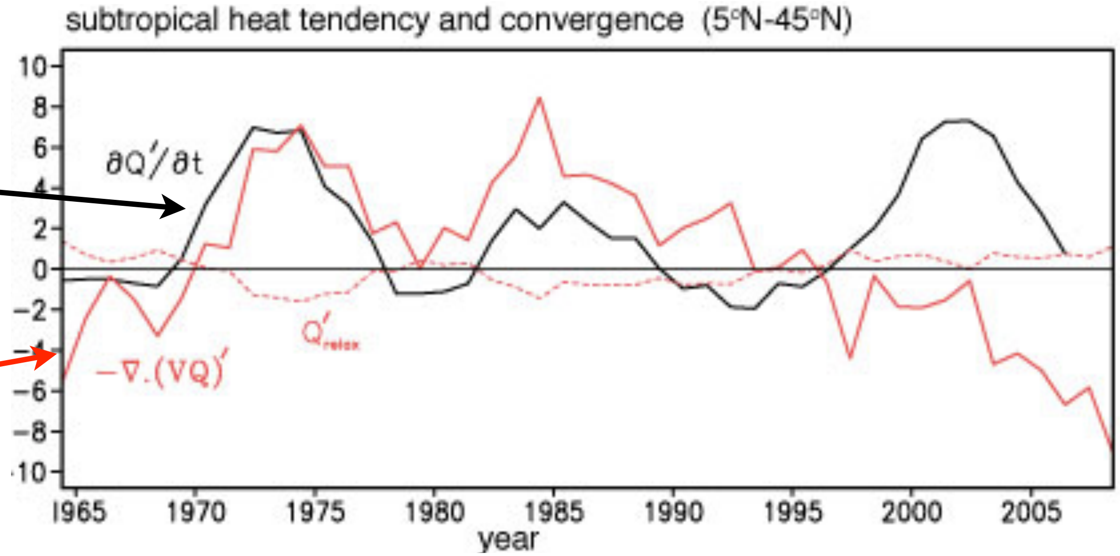
subtropical (5N-45N)

heat content tendency

convergence in heat transport

+10

-10



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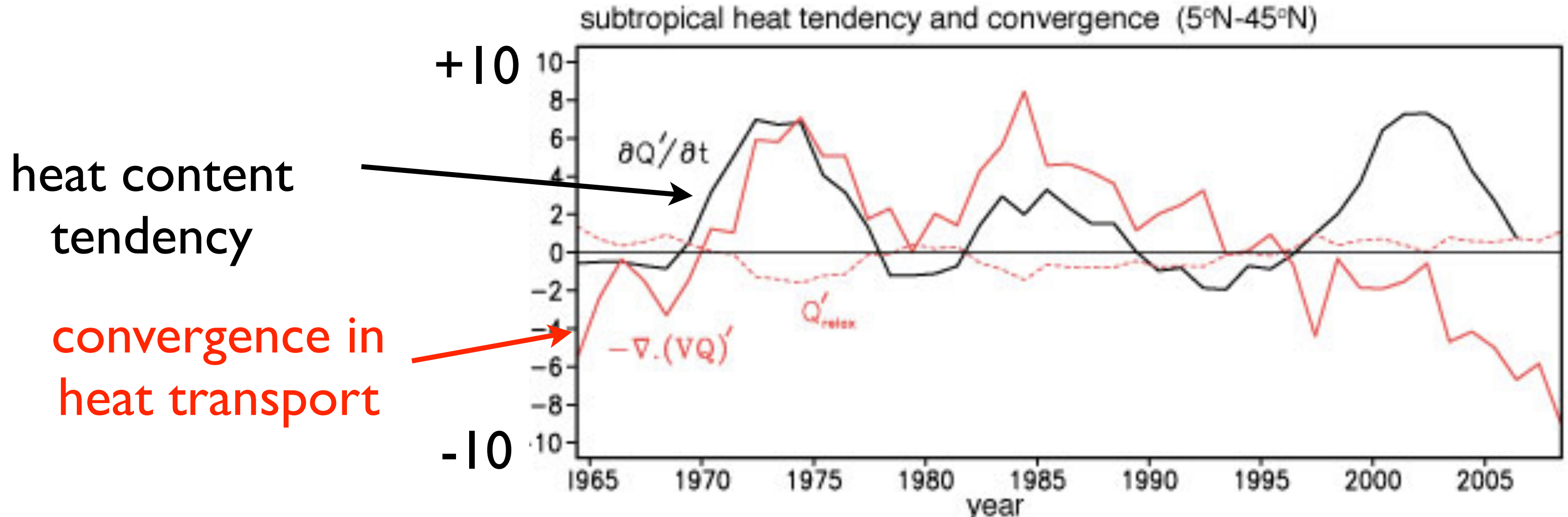
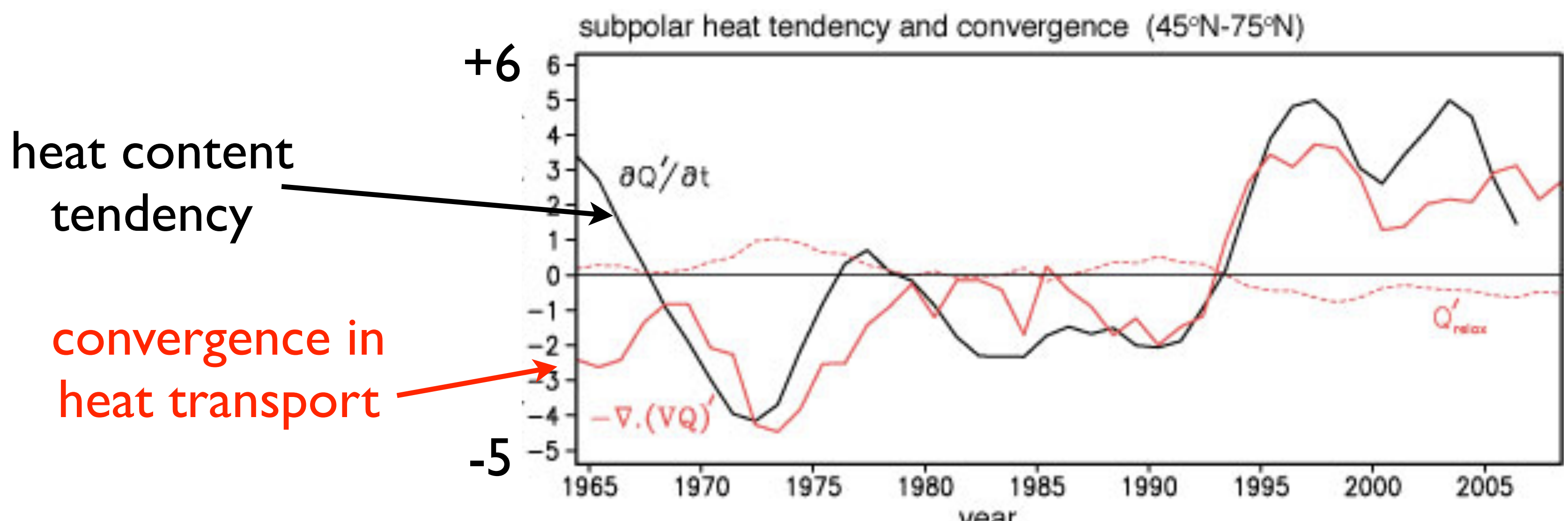
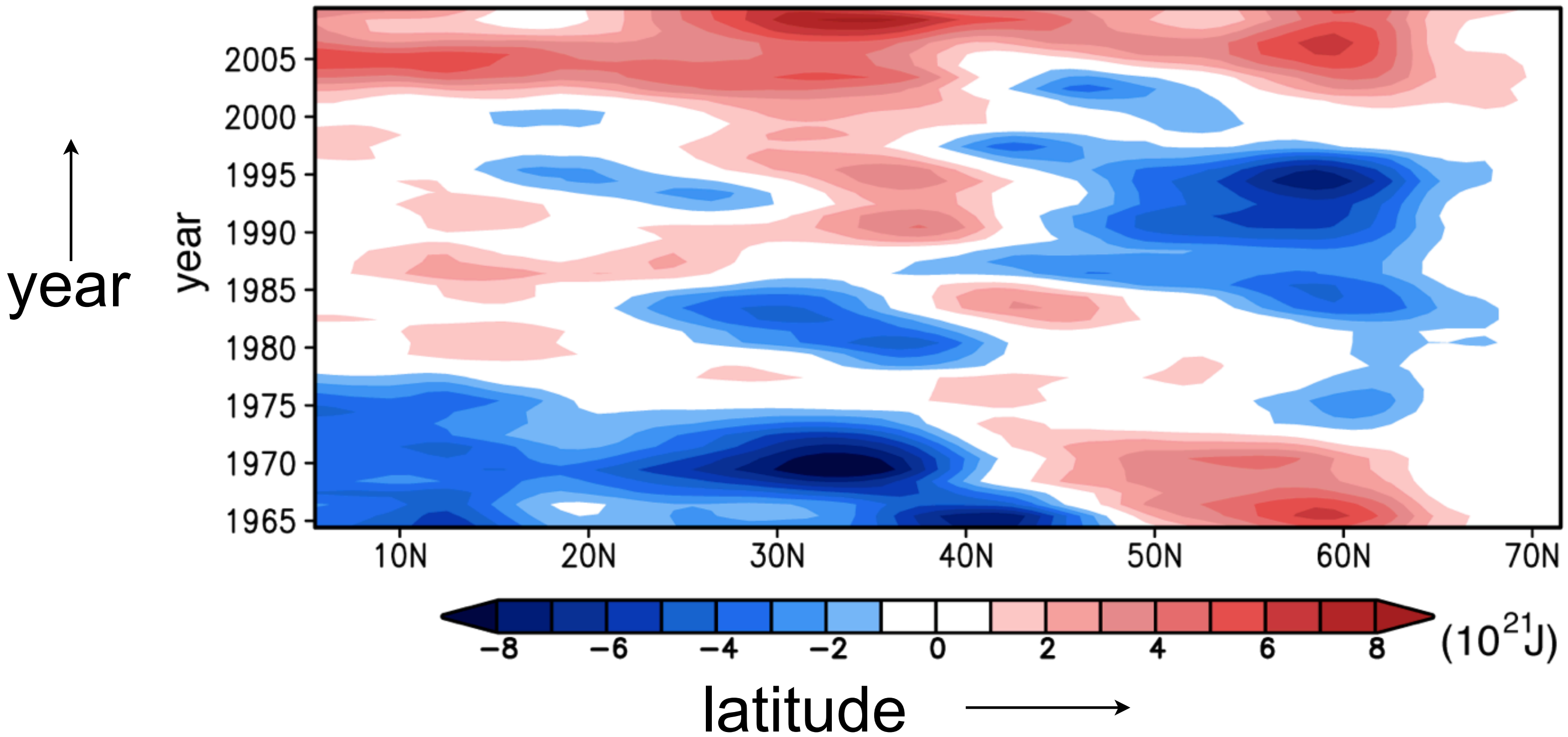


subpolar (45N-75N)



North Atlantic Ocean depth-integrated heat content anomaly



2000-2009 heat gain in subtropics and high latitude

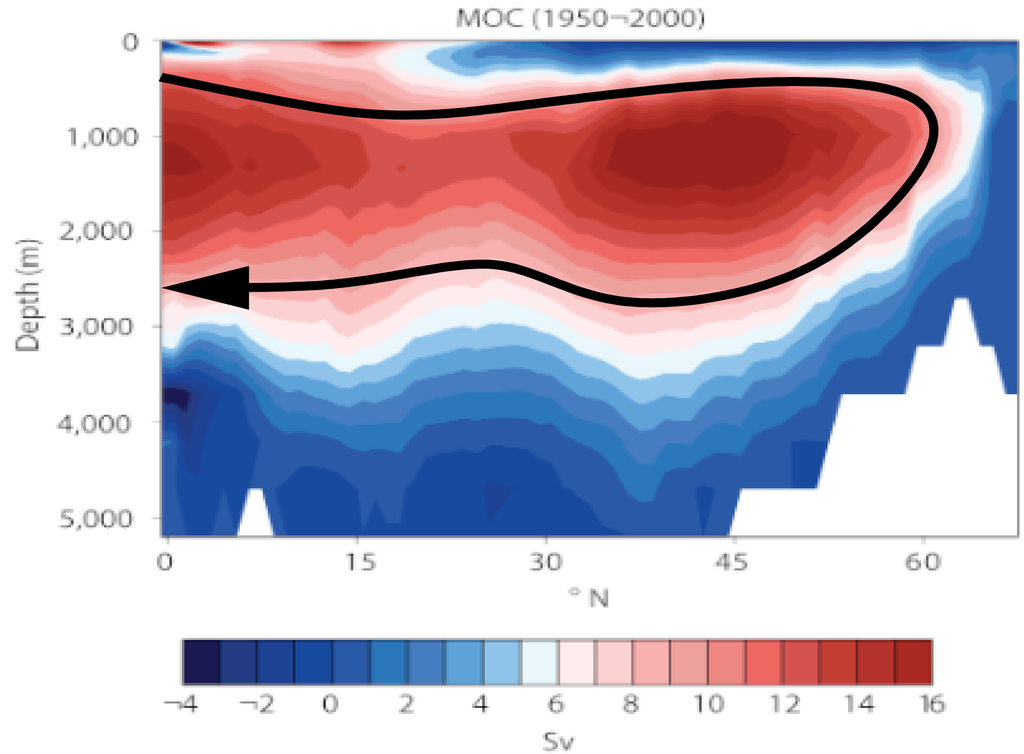
1975-2000 heat gain in subtropics heat loss in high latitudes

1965-1975 heat loss in subtropics heat gain in high latitudes

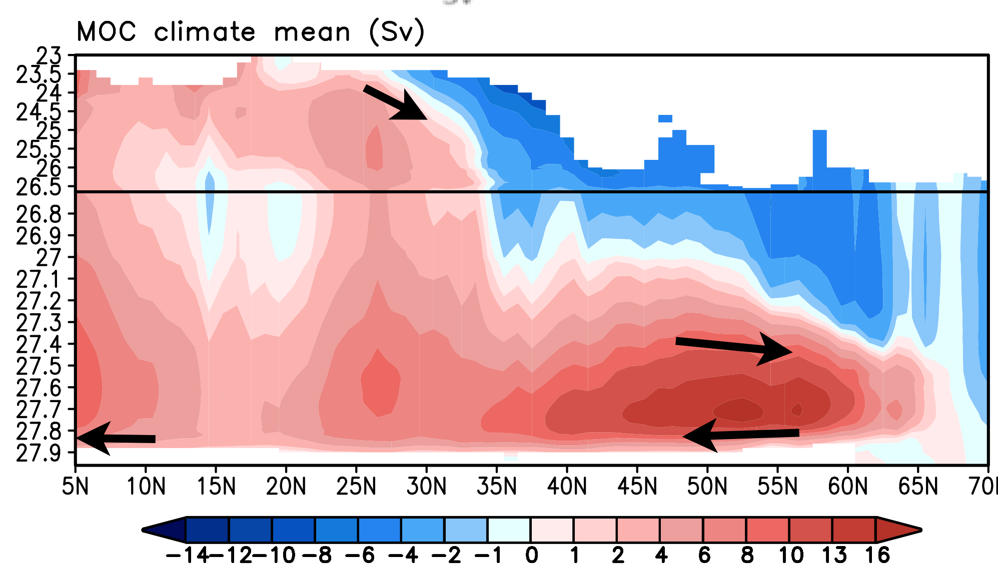
Lozier et al., 2008. Science. for 1980-2000 versus 1950-1970
Williams et al. (2013) J Climate, under review

Aim to link thermal anomalies to volume and heat transport

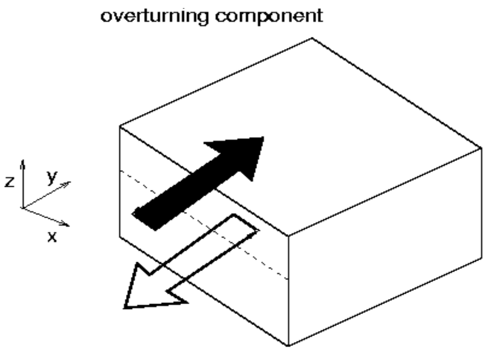
Overturning in depth coordinates

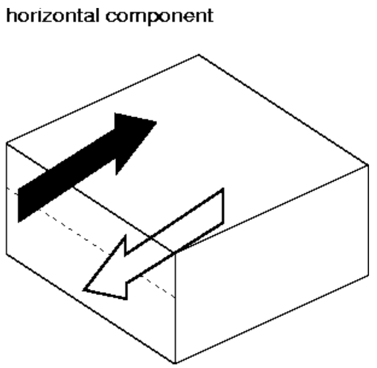


Overturning in density coordinates

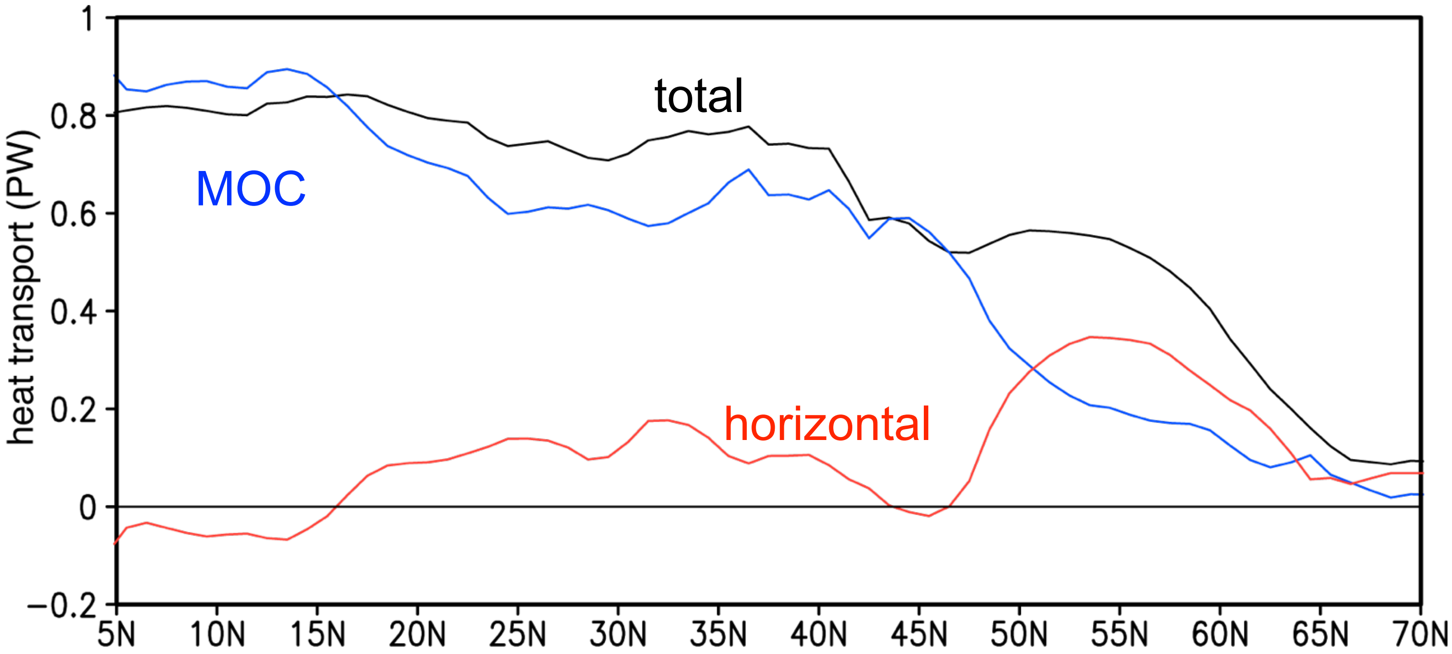


Ocean heat transport usually split into MOC + horizontal





$$\int_{-D}^{0} \overline{v\,\theta}^{x} dz = \underbrace{\int_{-D}^{0} \overline{v}^{x}\overline{\theta}^{x} dz}_{\text{MOC}} + \underbrace{\int_{-D}^{0} \overline{v'\,\theta'}^{x} dz}_{\text{horizontal}}$$



MOC dominates at most latitudes

horizontal becomes important over subpolar

MOC further split into part due to winds (Ekman) in mass-conserving manner

$$\underbrace{\int_{-D}^{0} \overline{v}^{x}\, \overline{\theta}^{x} dz}_{\text{MOC}} = \underbrace{\left(\int_{-D}^{0} \overline{v}^{x}\overline{\theta}^{x} dz - \overline{V}^{x}_{ek}(\overline{\theta}^{x}_{ek} - \overline{\theta}^{x,z}_{r})\right)}_{\text{MOC-Ekman}} + \underbrace{\overline{V}^{x}_{ek}(\overline{\theta}^{x}_{ek} - \overline{\theta}^{x,z}_{r})}_{\text{Ekman}}$$

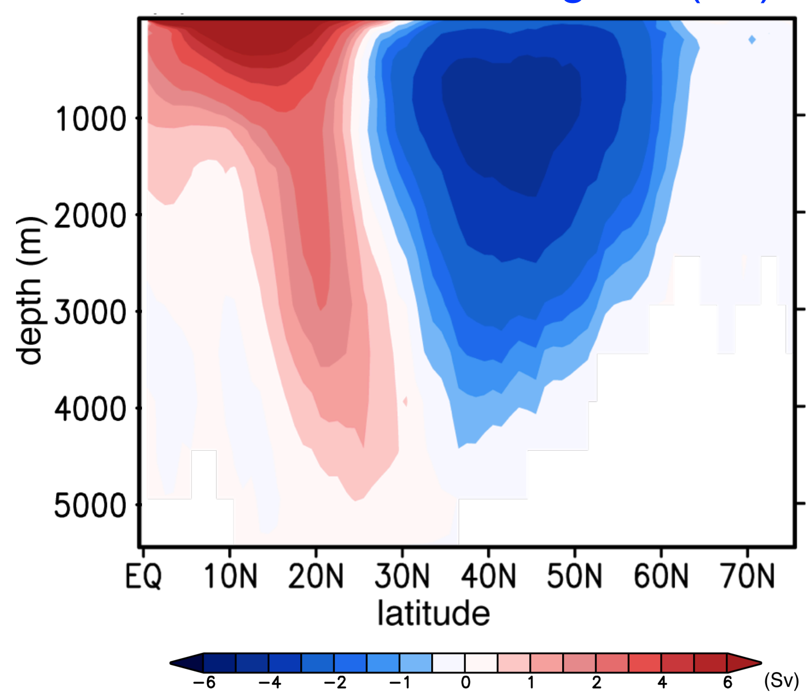
MOC

MOC-Ekman

Ekman

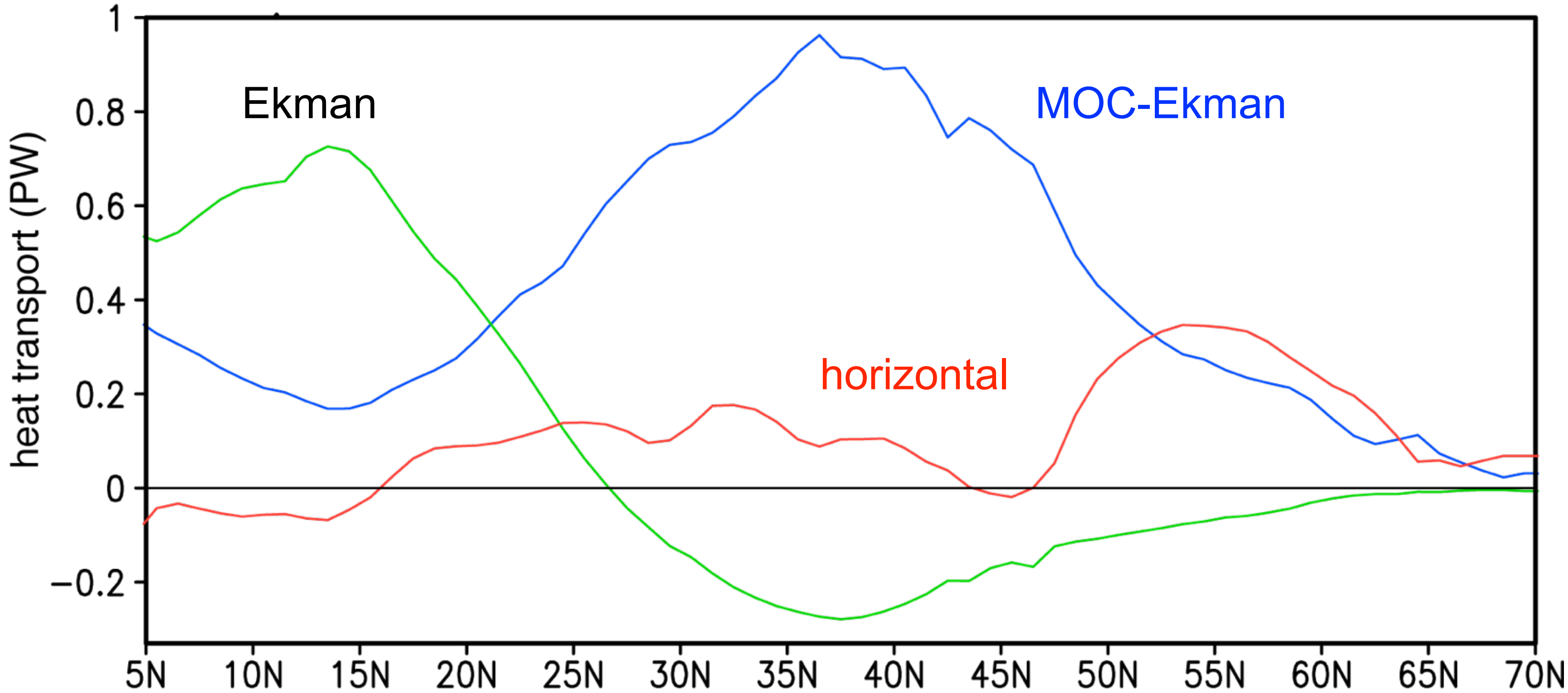
solve for Ekman return flow via a dynamical adjustment after 1 year

Ekman overturning cell (Sv)



-6 Sv

+6 Sv

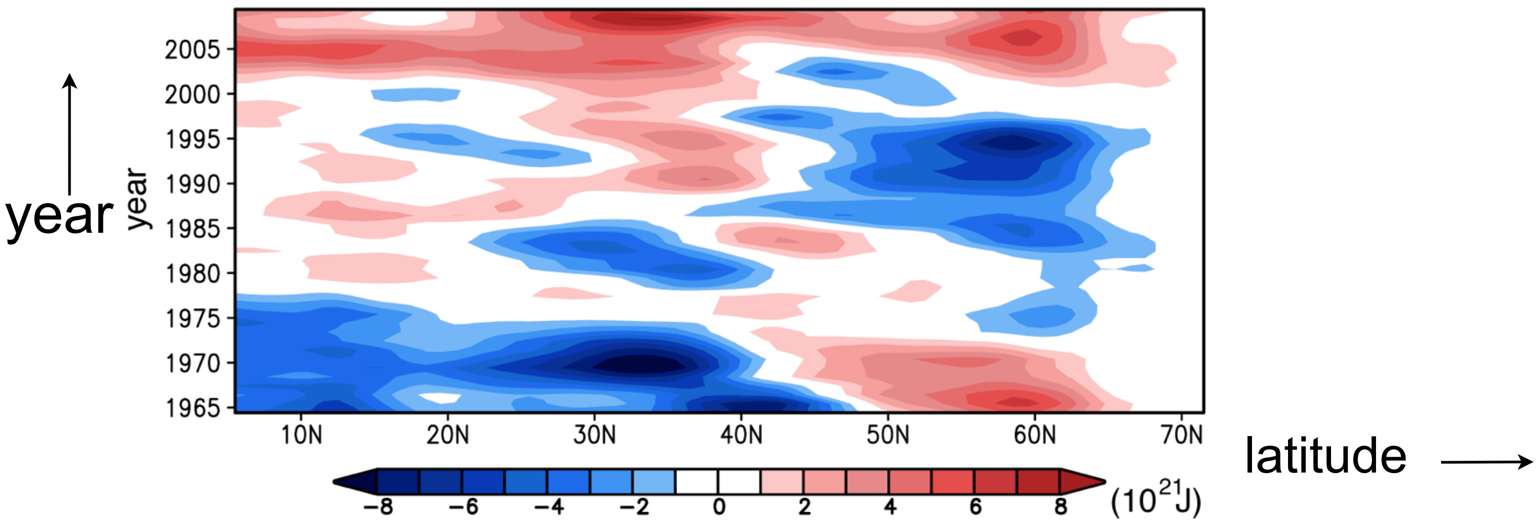


Heat transport by Ekman peaks in tropics

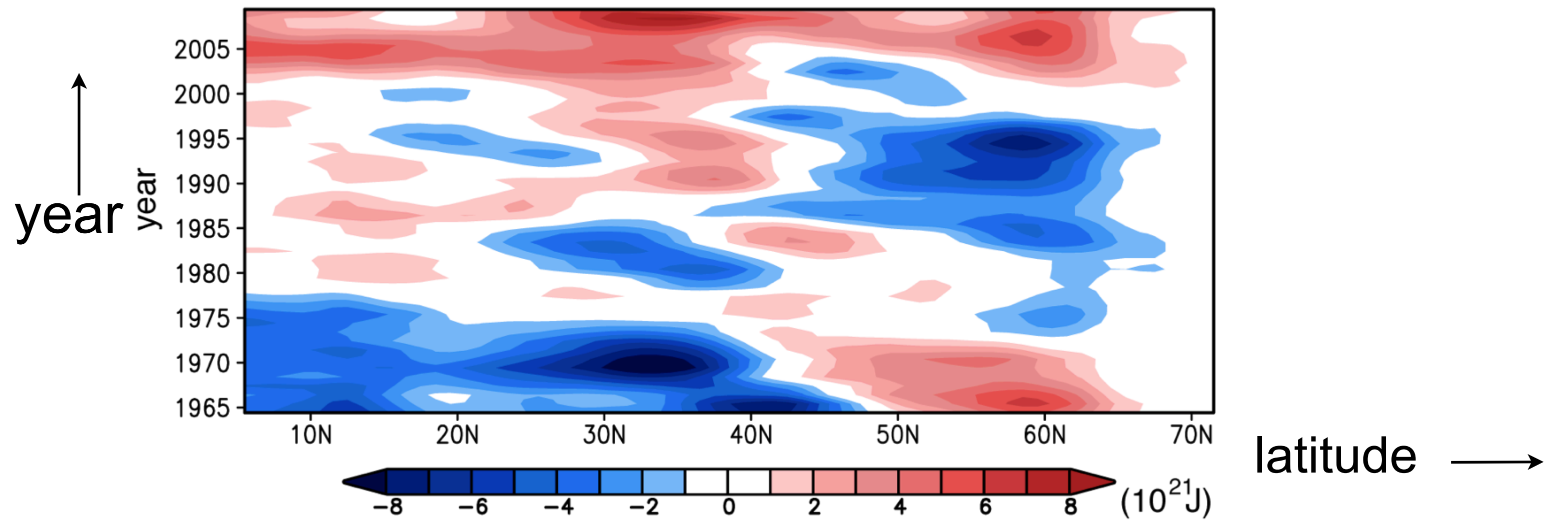
by MOC-Ekman peaks at 35N

by horizontal peaks at 55N

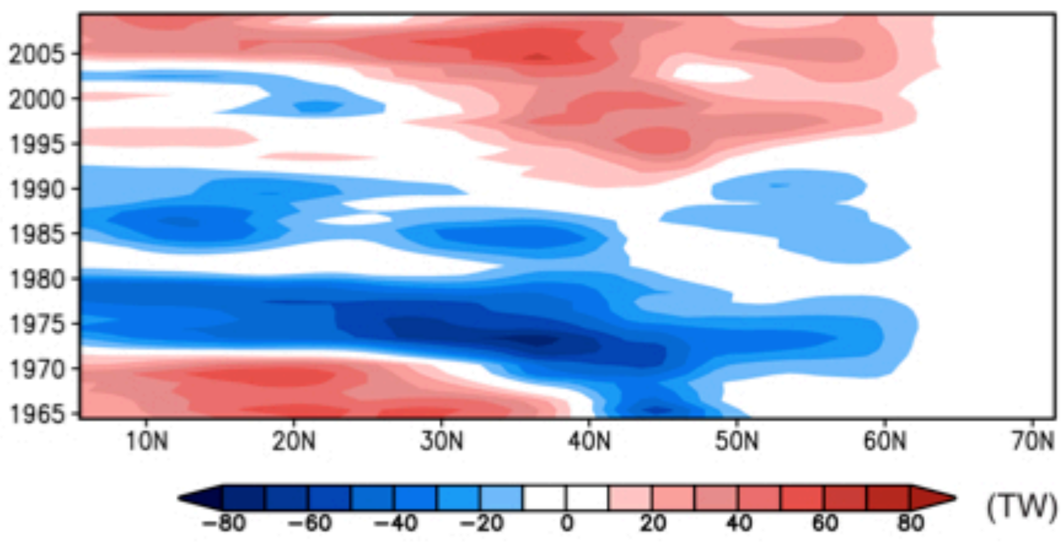
Returning to depth-integrated heat content anomaly



Returning to depth-integrated heat content anomaly



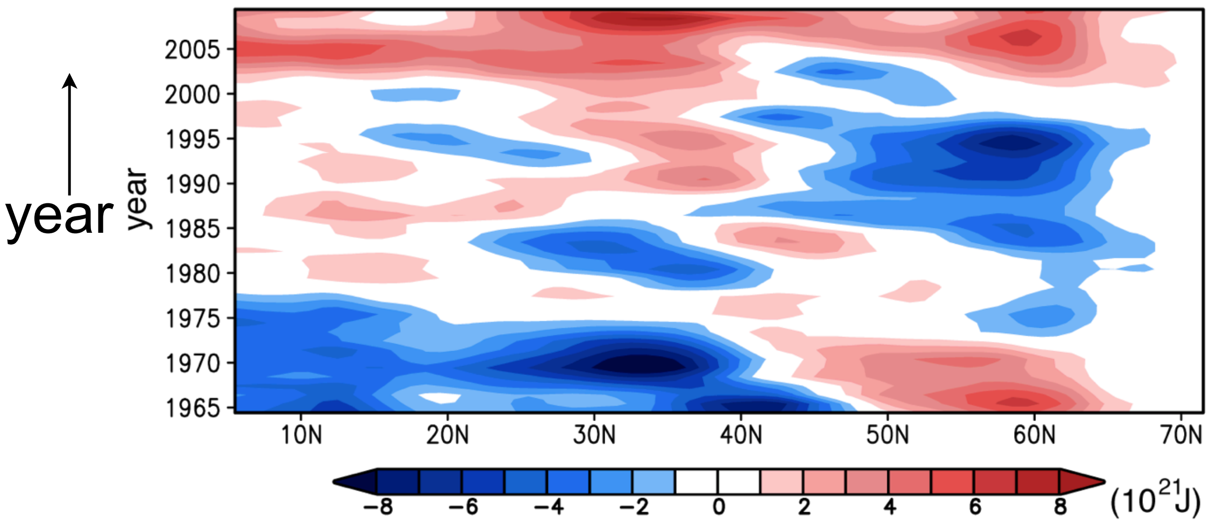
MOC-Ekman heat transport anomaly (TW)



Basin-scale response and sometimes gyre contrasts

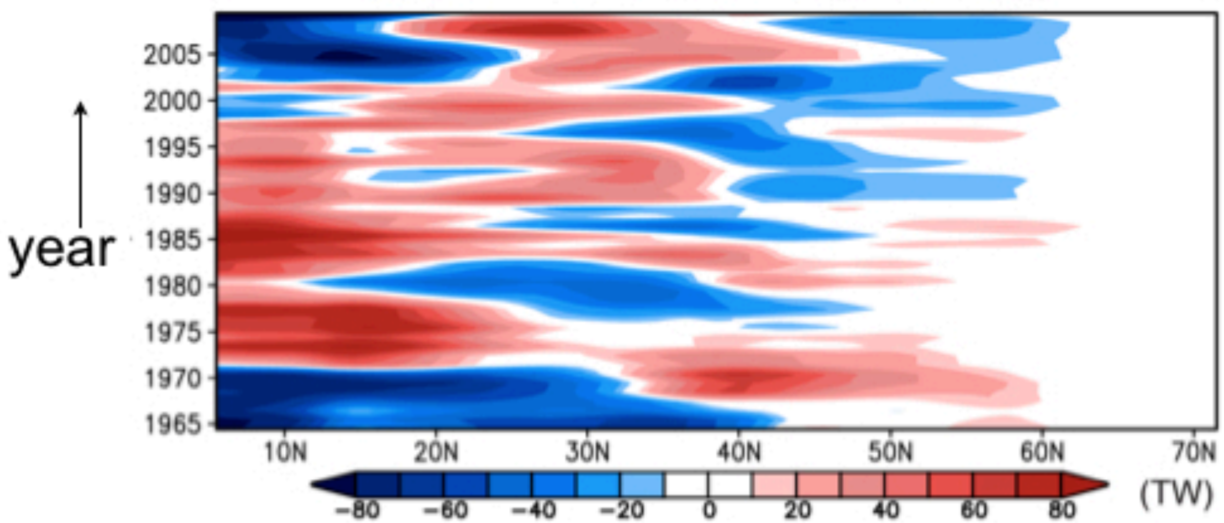
See Lozier et al. (2011) Nature Geoscience for similar overturning changes for 1980-2000 and 1950-1970

Returning to depth-integrated heat content anomaly



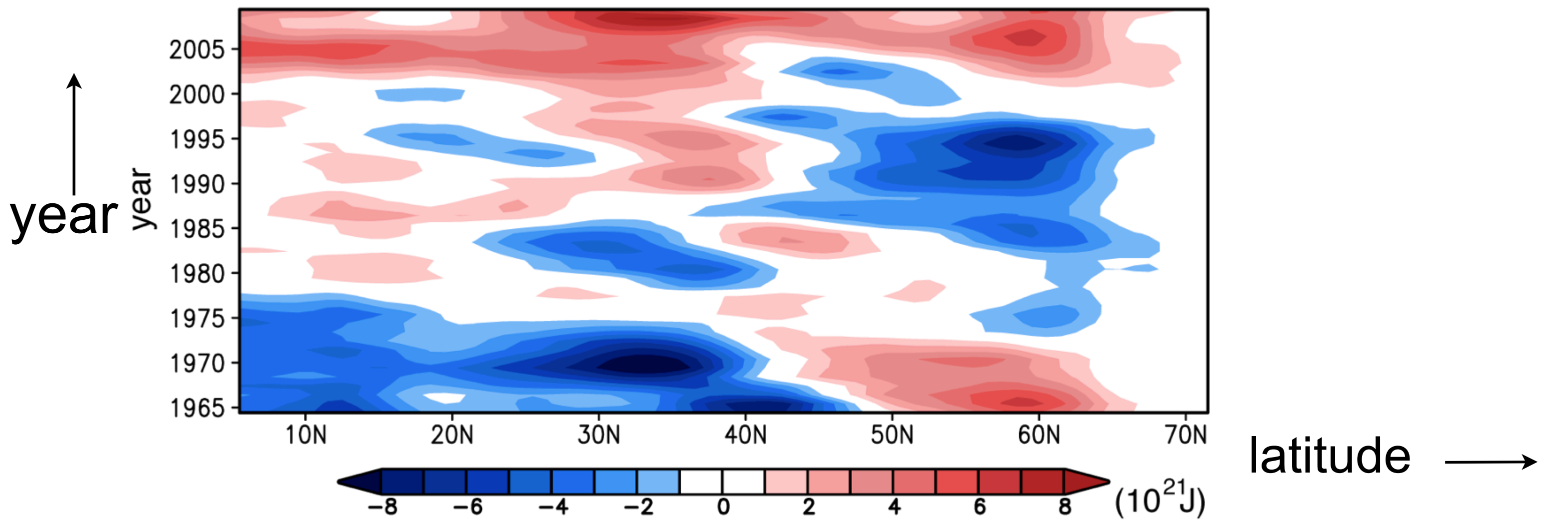
latitude →

Ekman heat transport anomaly (TW)

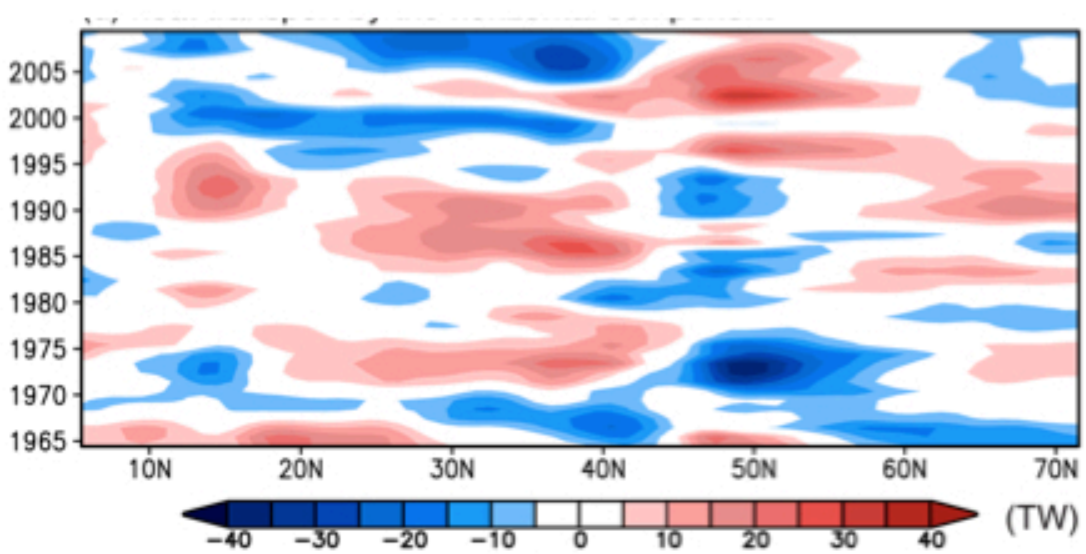


Consistent with *contrasting* gyre response

Returning to depth-integrated heat content anomaly



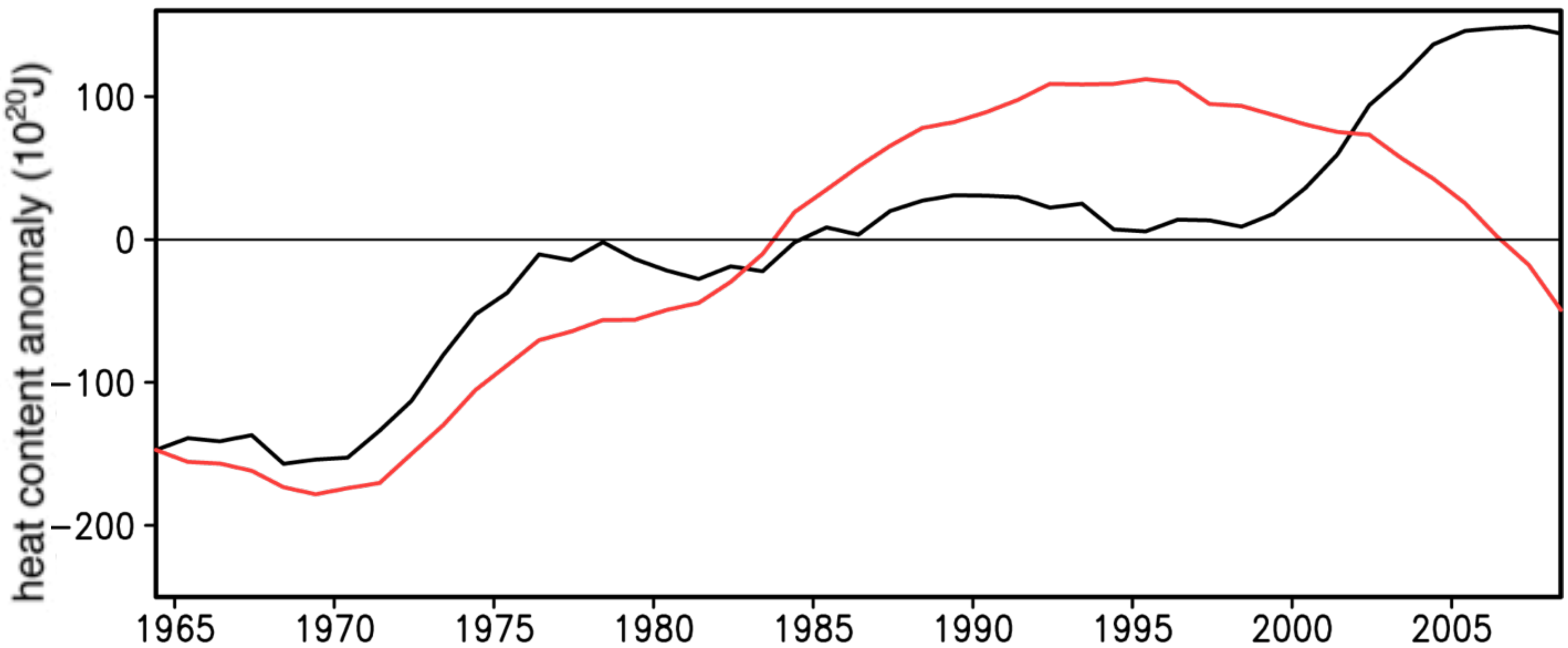
horizontal heat transport anomaly (TW)



Weaker *opposing* gyre response

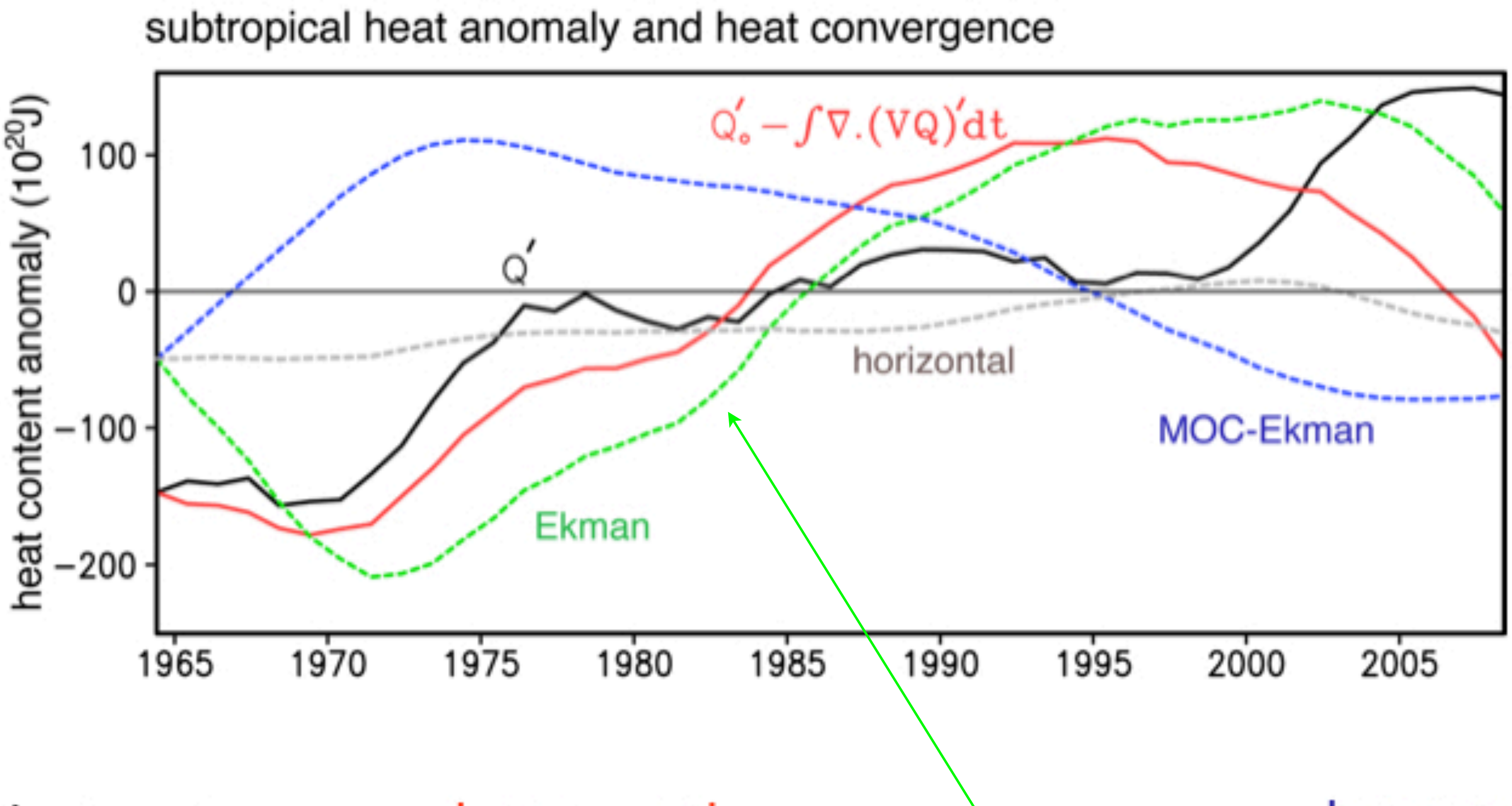
Return to thermal anomalies

subtropical thermal anomaly



heat content anomaly

heat anomaly from convergence in heat transport



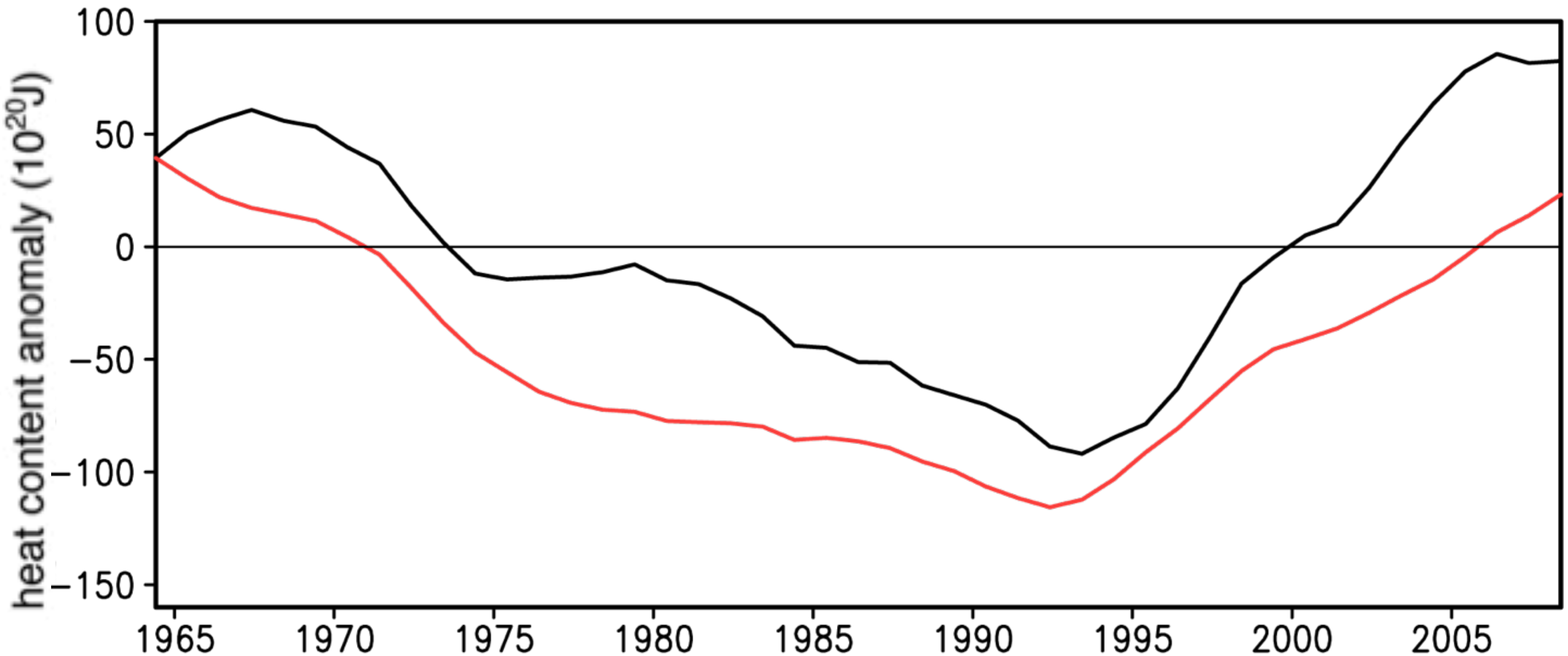
heat content anomaly

heat anomaly from convergence in heat transport

heat anomaly from Ekman heat convergence

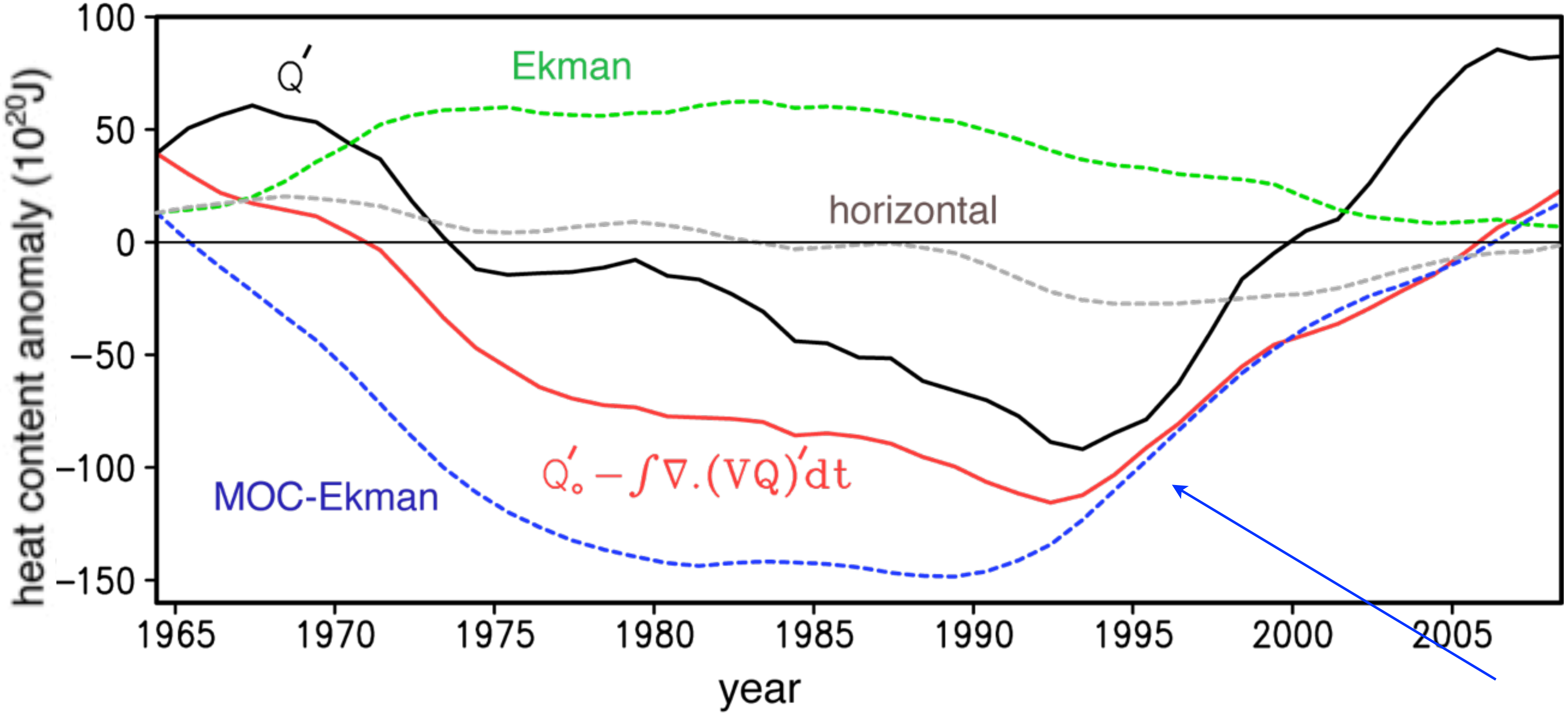
heat anomaly from MOC-Ekman heat convergence

subpolar thermal anomaly



heat content anomaly

heat anomaly from convergence in heat transport



heat content anomaly

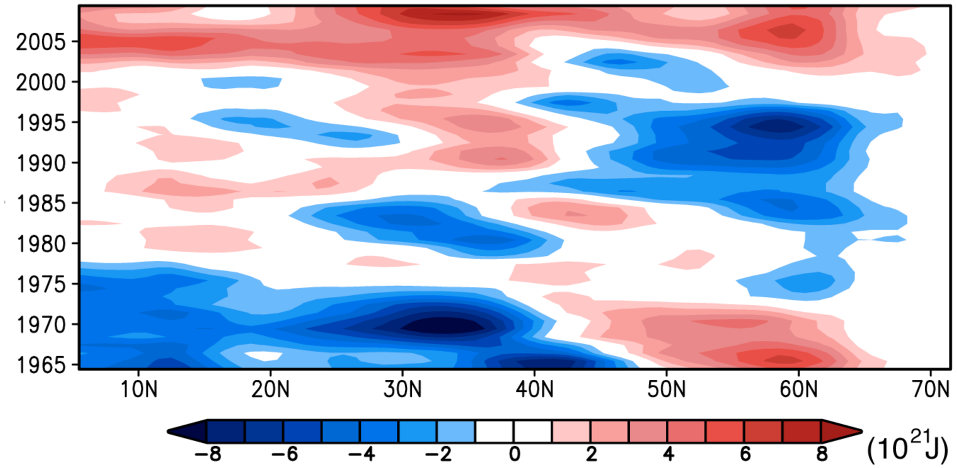
heat anomaly from convergence in heat transport

heat anomaly from Ekman heat convergence

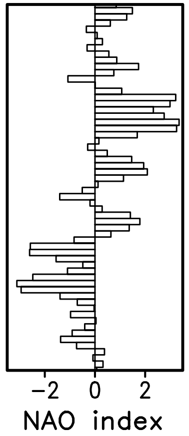
heat anomaly from MOC-Ekman heat convergence

Link to atmospheric modes

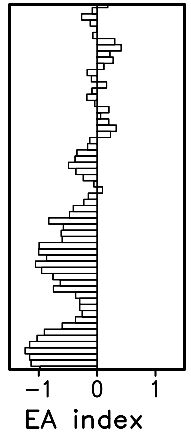
heat content anomaly



NAO

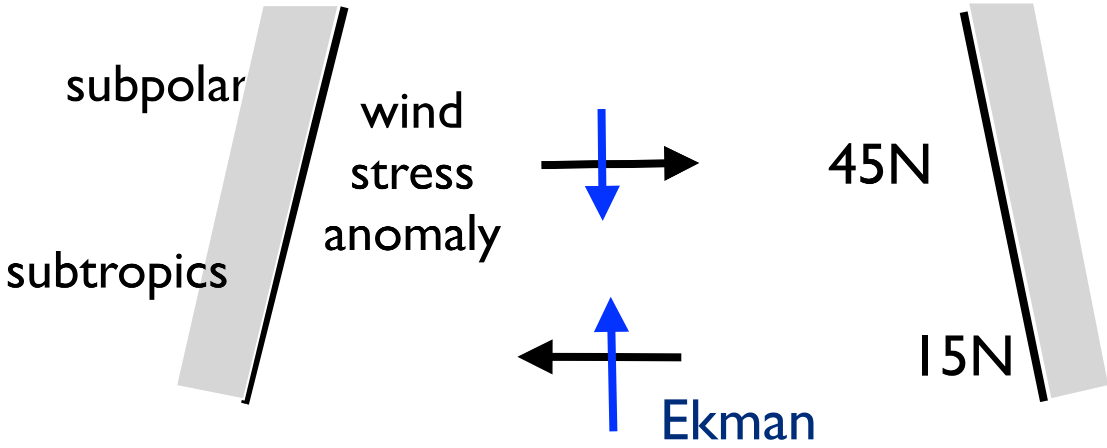


EA

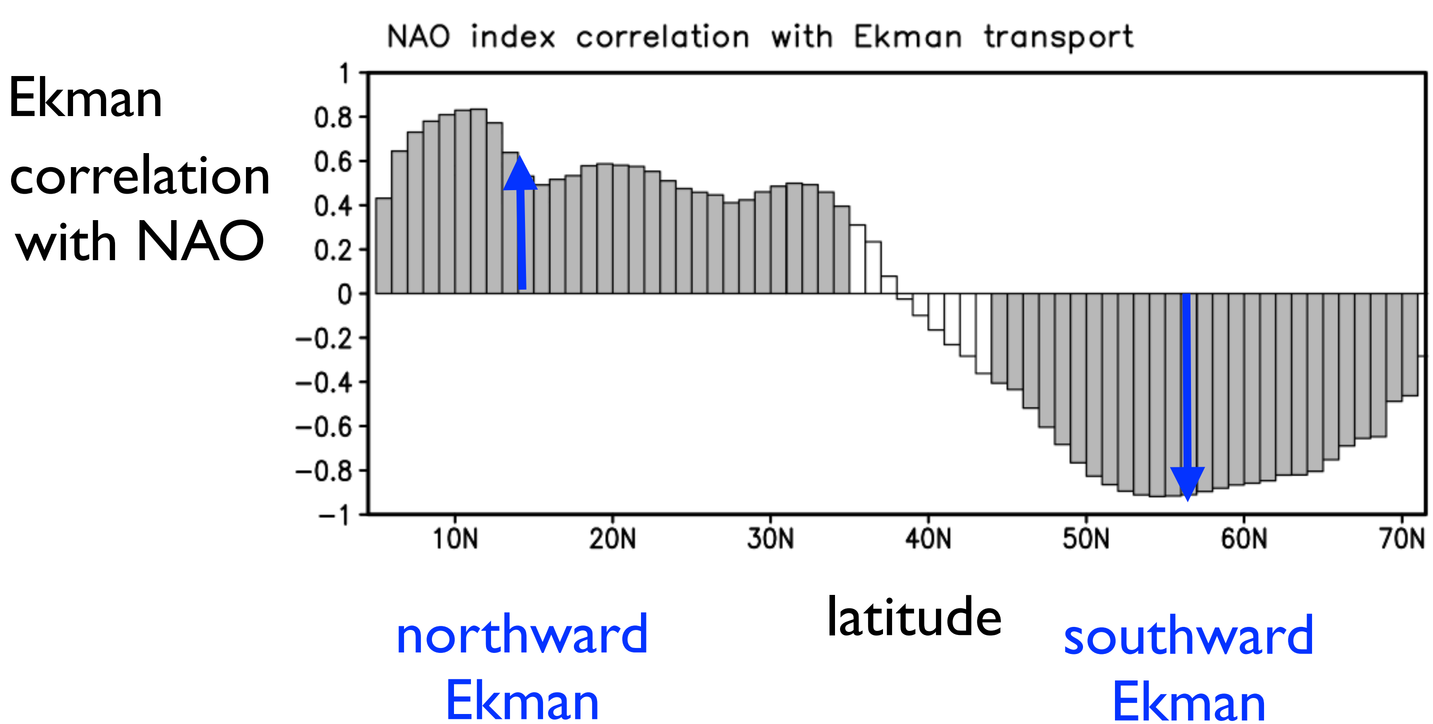


what is the link between NAO,
heat content and MOC anomalies?

Link to atmospheric modes

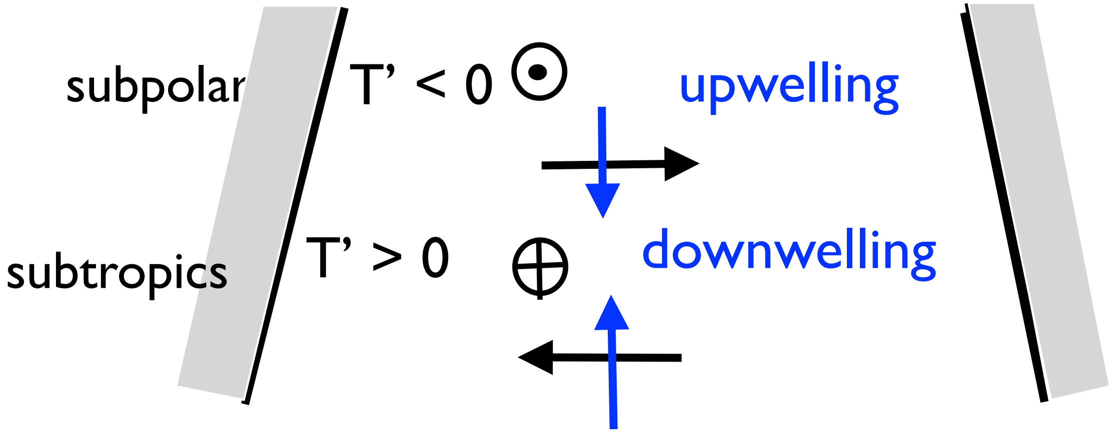


Consider stronger winds, eg NAO+



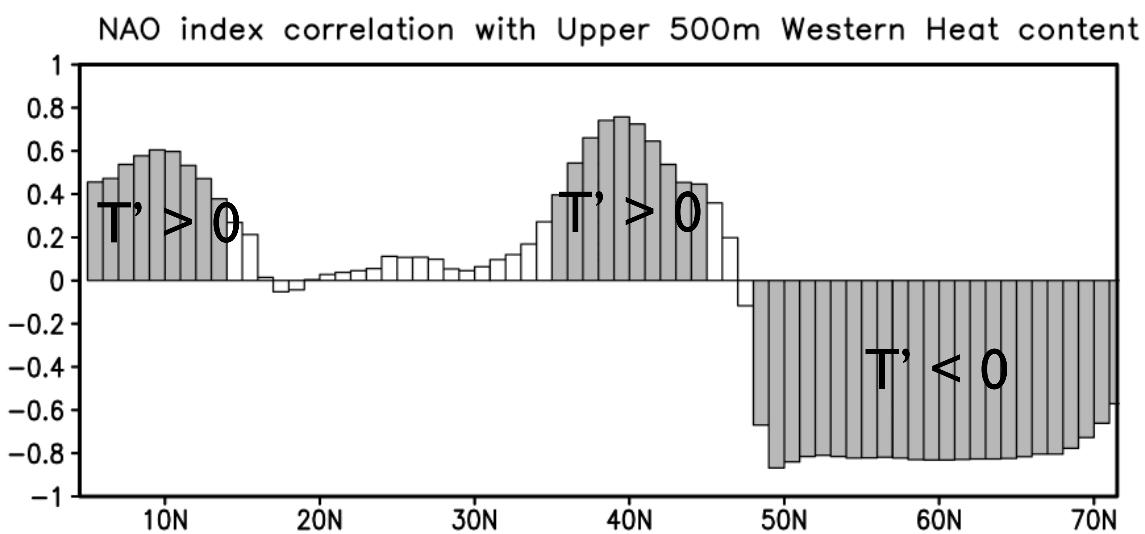
1965-2010, detrended

Link to atmospheric modes



upper heat content

correlation with NAO



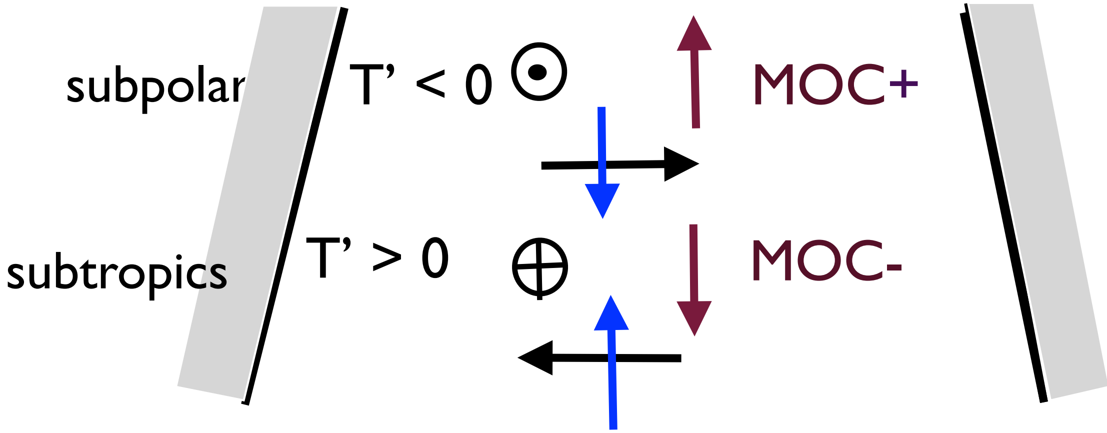
1965-2010, detrended

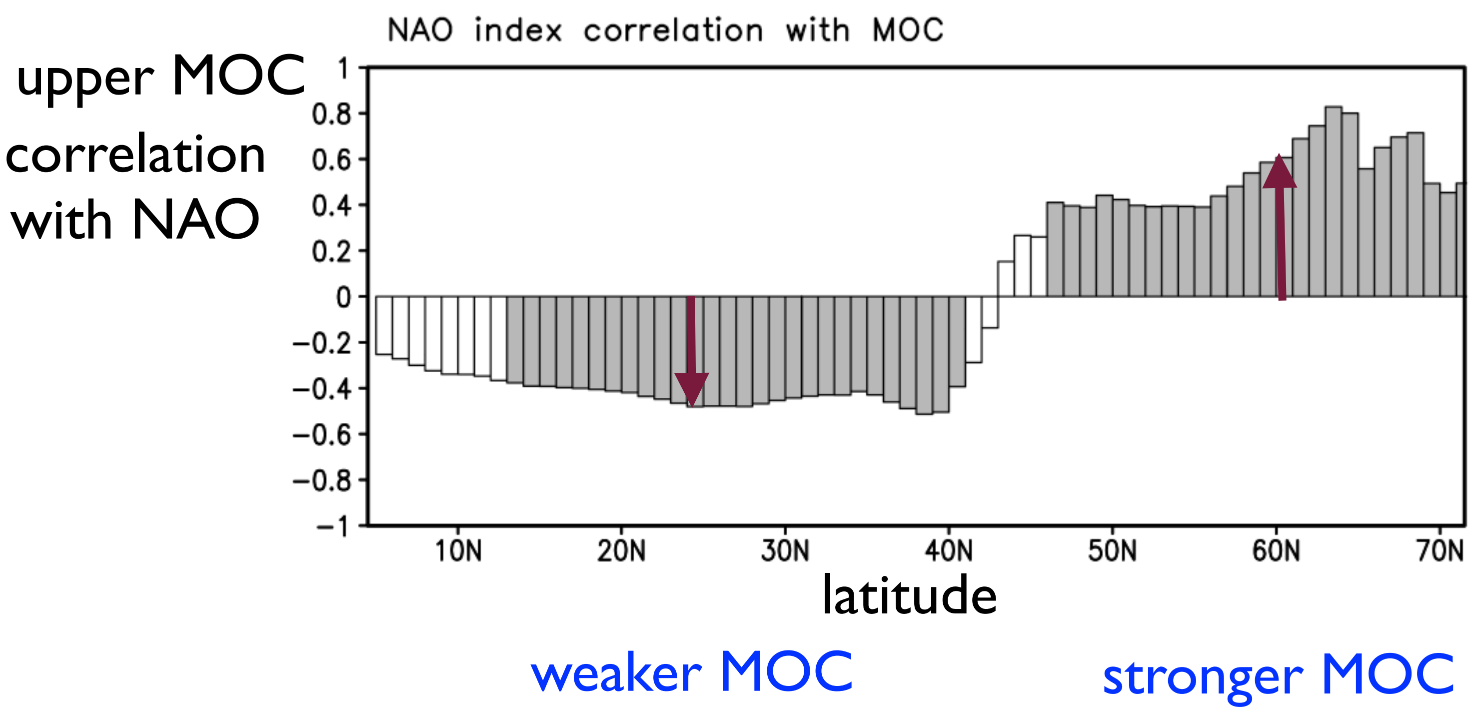
latitude

thicker thermocline

thinner thermocline

Link to atmospheric modes

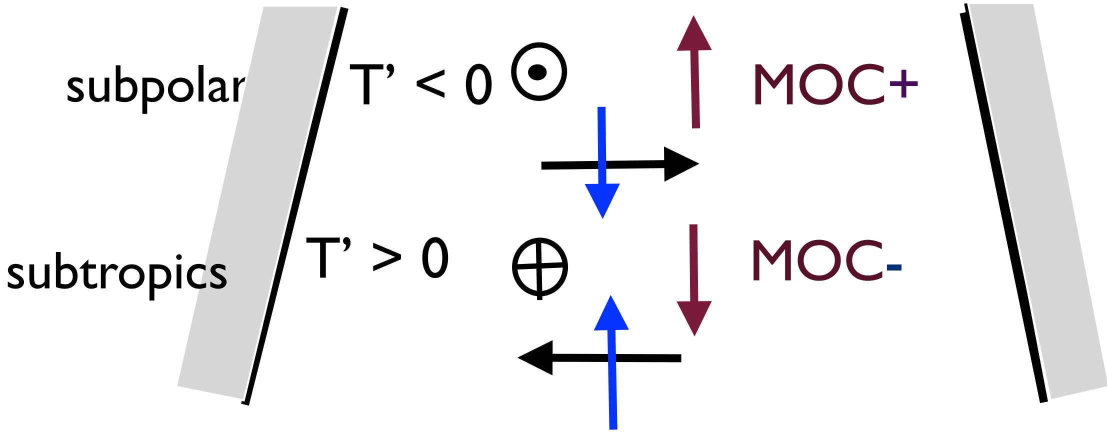




1965-2010, detrended

i.e strong imprint on MOC by the winds

Link to atmospheric modes

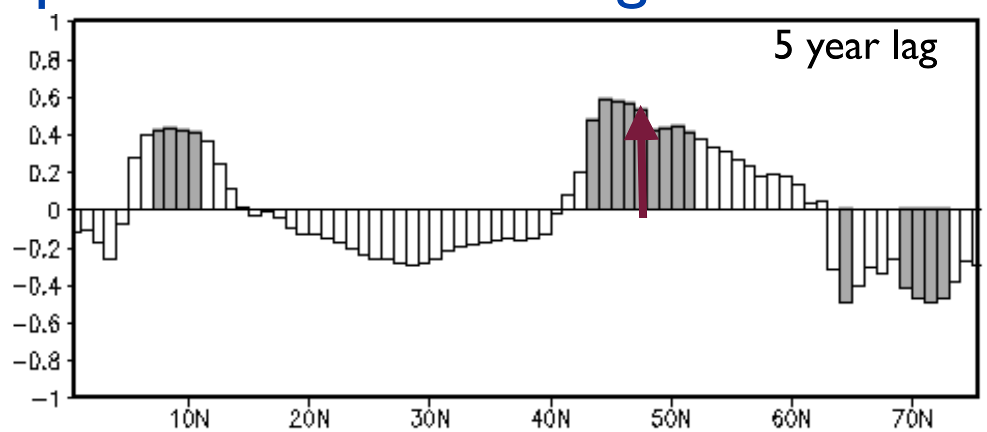


Atmospheric variability excites range of overturning cells,

Strong imprint of the winds on subtropical heat content & MOC

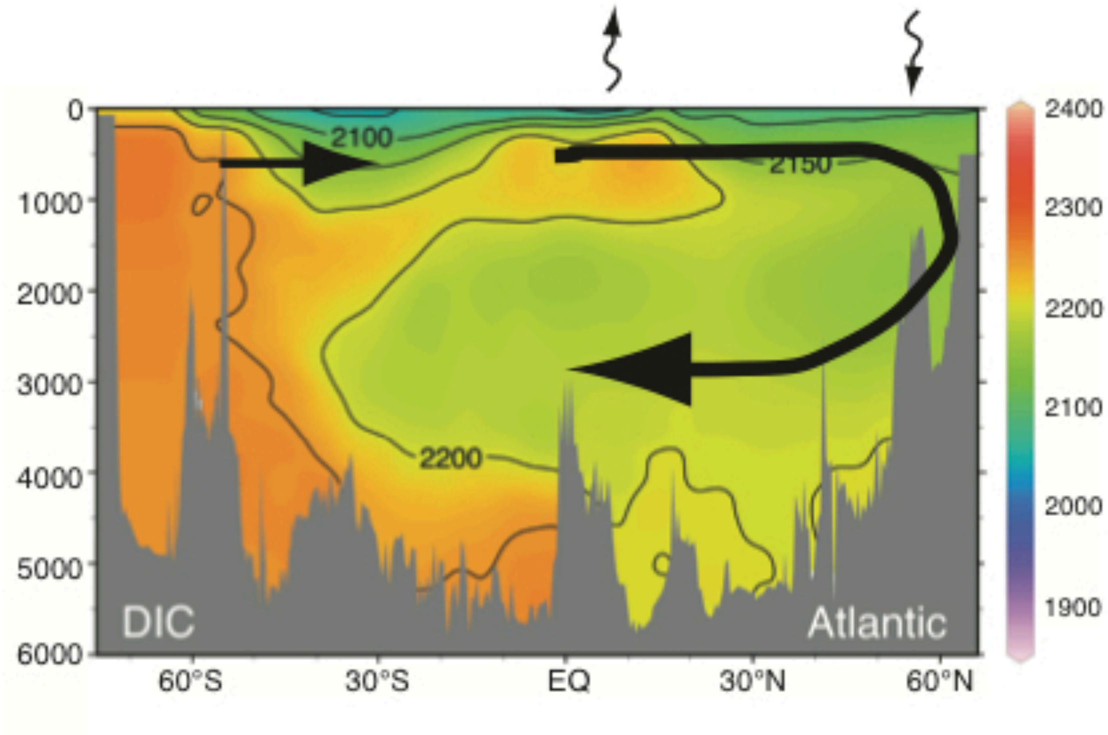
Also delayed response to wind forcing

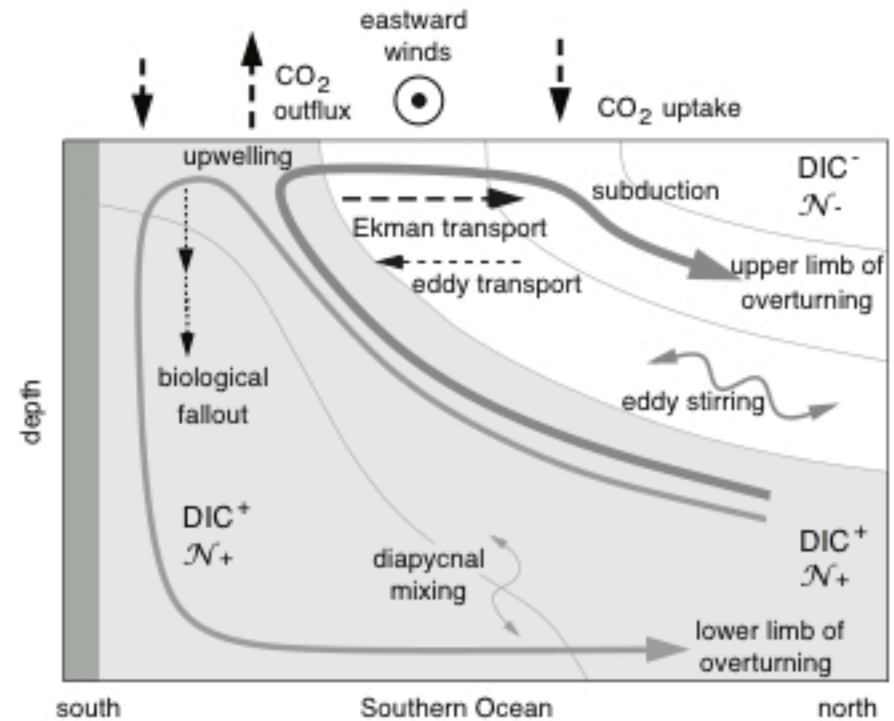
MOC heat transport correlation with NAO



Now consider carbon cycling

3. Atmospheric carbon dioxide





sensitivity to winds

- Southern Ocean westerlies
- northern Trade winds

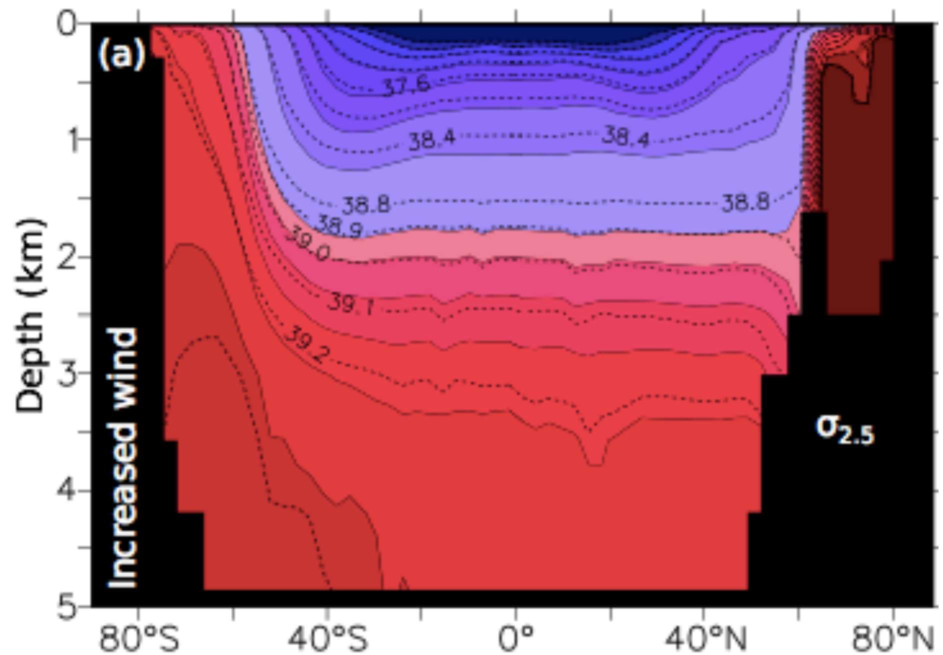
Stronger westerly winds in Southern Ocean what is the effect on atmospheric CO_2?

zonal average section

2.8°x2.8°, 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

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

$$DIC = C^{sat} + C^{bio} + C^{dis}$$

saturated — soft & hard tissue — disequilibrium

Atlantic section

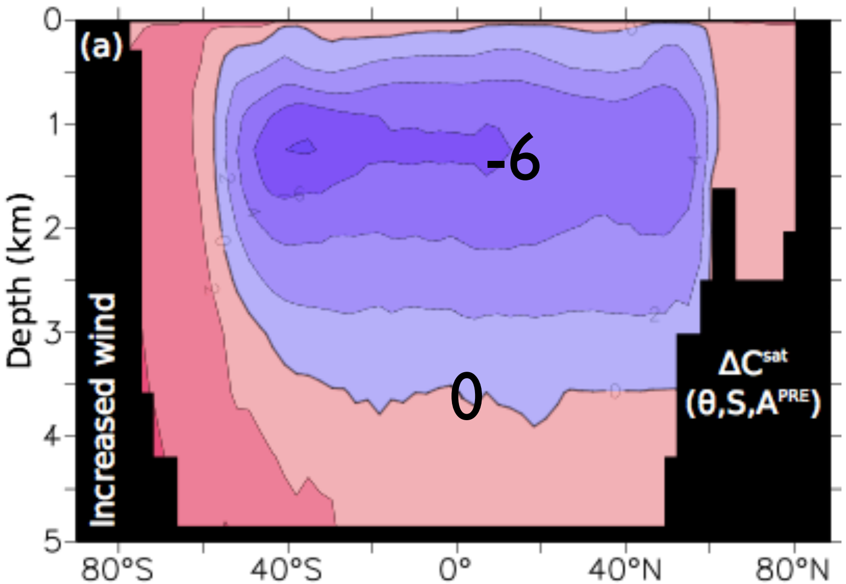
(mmol C m^{-3})

$$\mathrm{DIC} = C^{sat} + C^{bio} + C^{dis}$$

saturated — soft & hard tissue — disequilibrium

change in C^{sat}

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

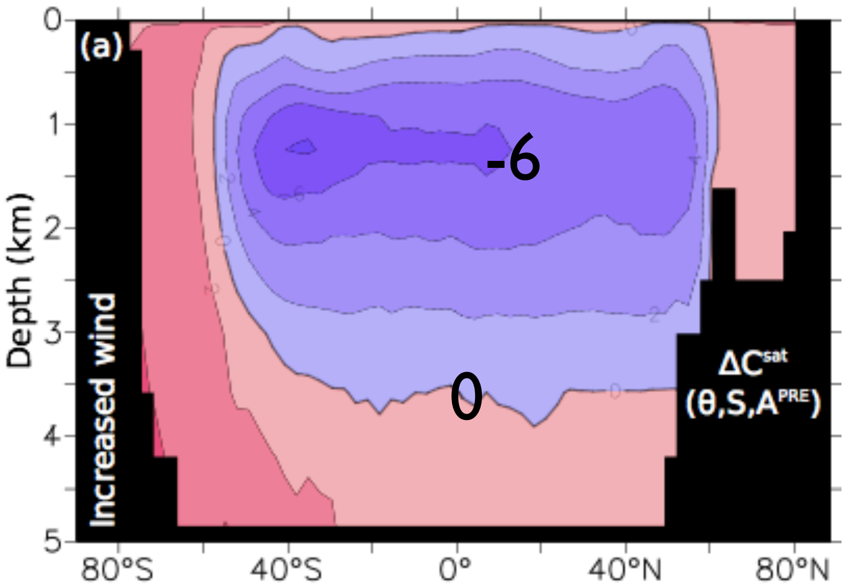


- warmer, thicker thermocline

$$DIC = C^{sat} + C^{bio} + C^{dis}$$

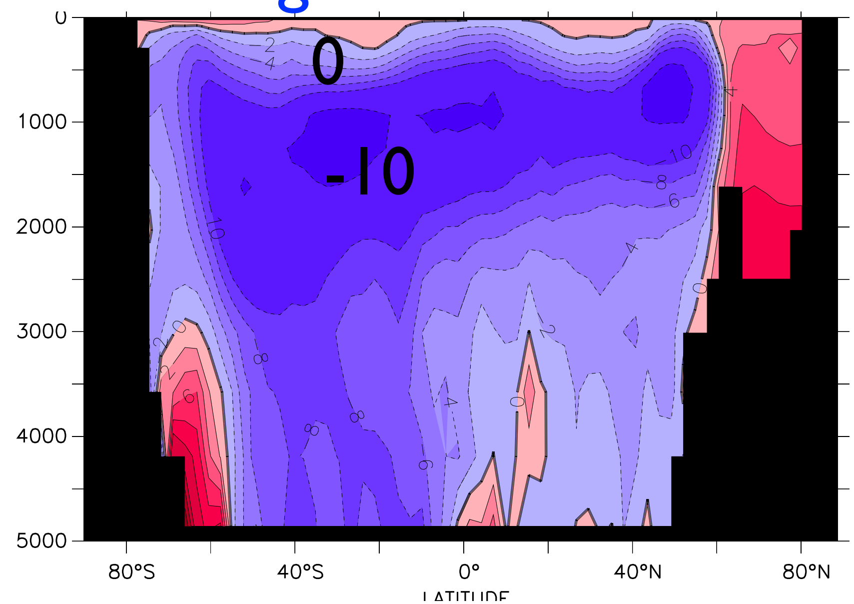
saturated — soft & hard tissue — disequilibrium

change in C^{sat}



change in C^{bio}

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



- warmer, thicker thermocline
- thicker nutricline

$$\mathrm{DIC} = C^{sat} + C^{bio} + C^{dis}$$

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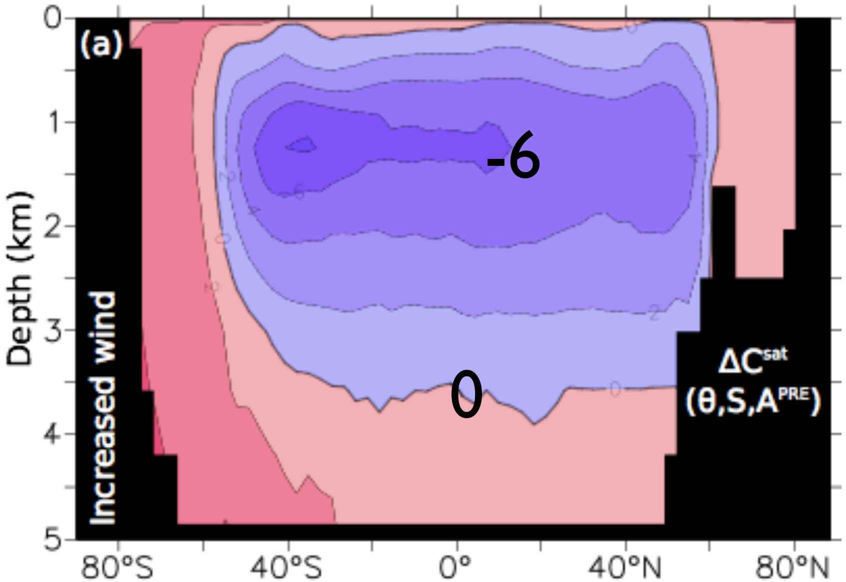
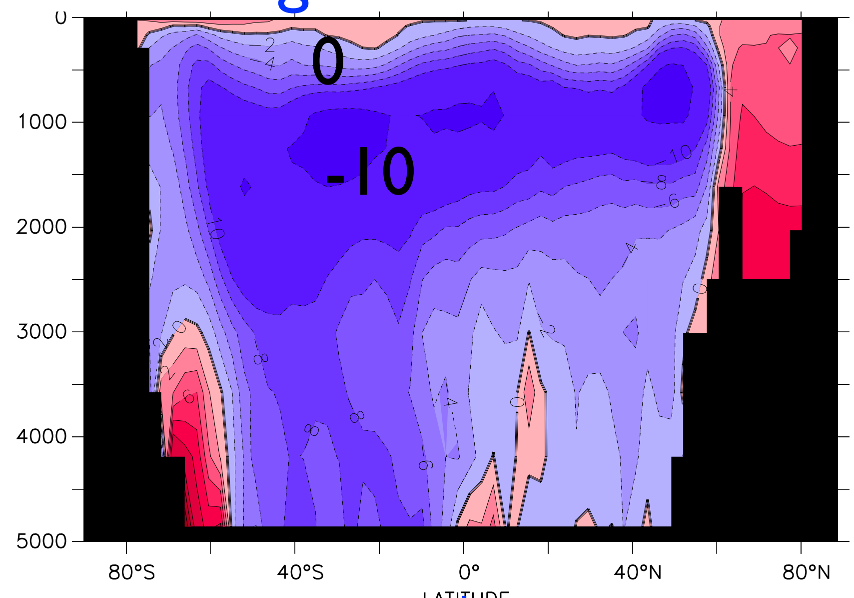
Atlantic section (mmol C m^{-3})

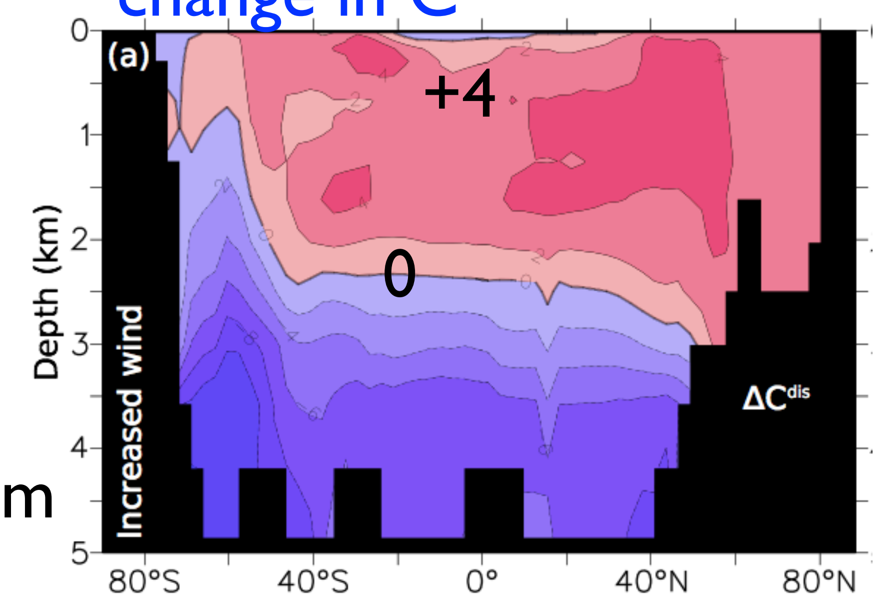
change in C^{sat}



change in C^{bio}



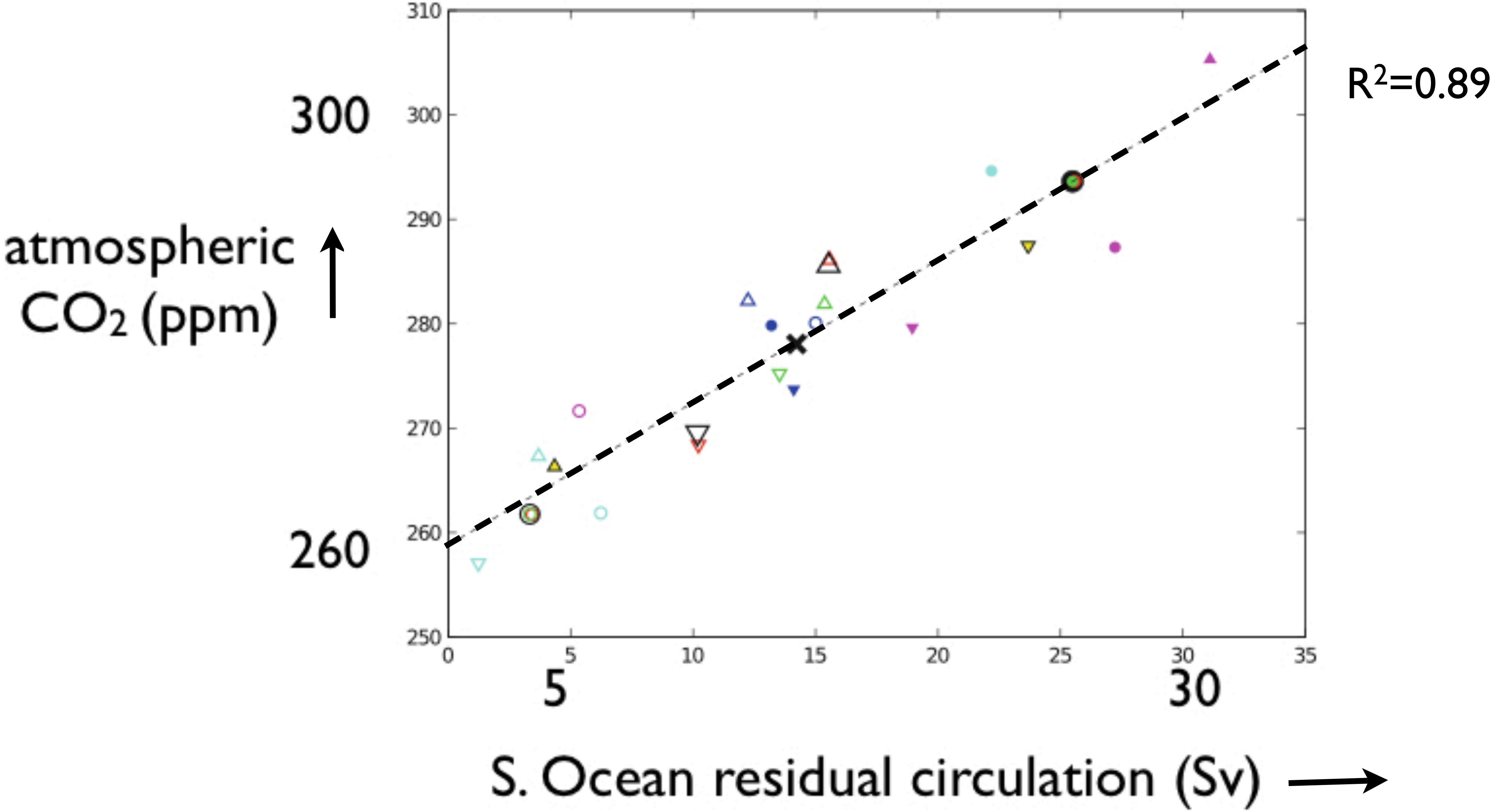
change in C^{dis}



- 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



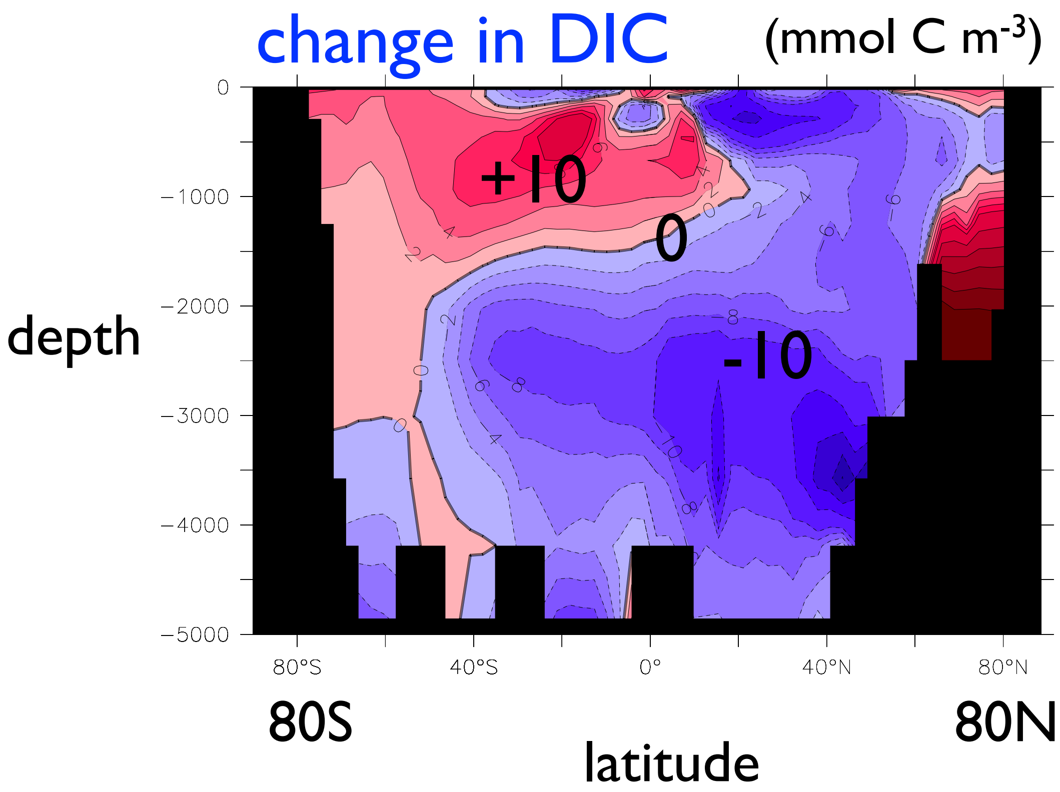
stronger overturning upper cell, greater atmospheric CO_2

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



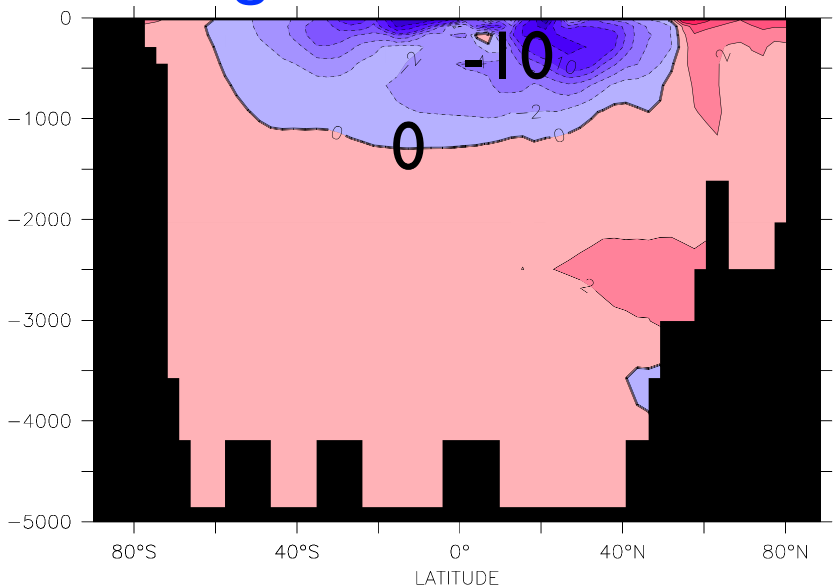
$$DIC = C^{sat} + C^{bio} + C^{dis}$$

saturated | soft & hard tissue | disequilibrium

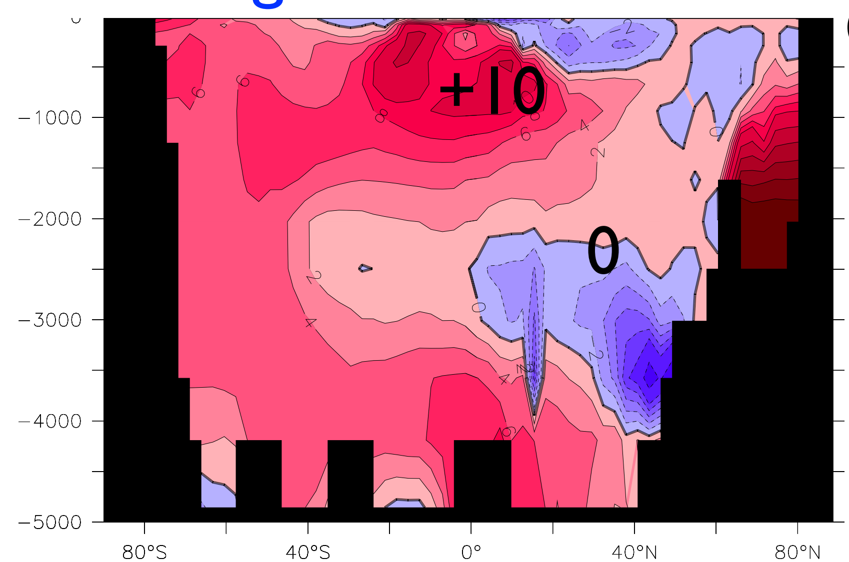
Atlantic section

(mmol C m^{-3})

change in C^{sat}

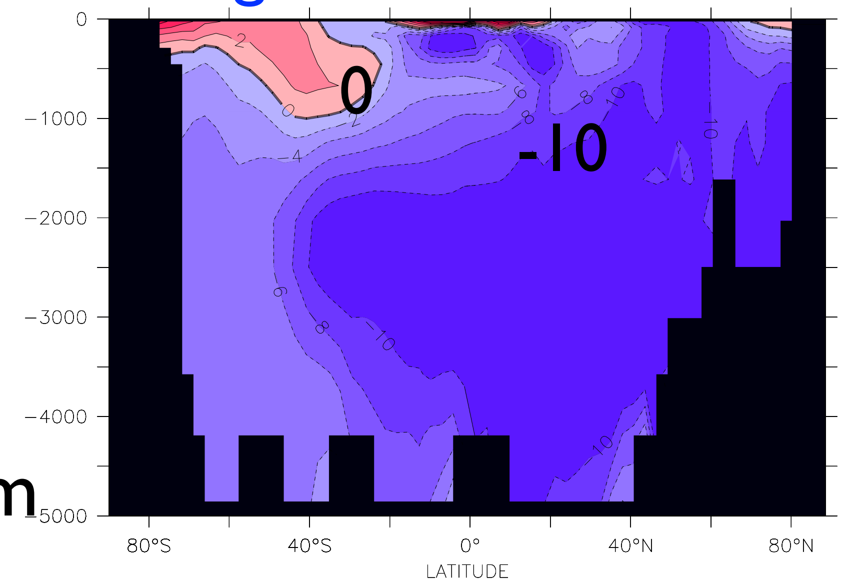


change in C^{bio}



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

change in C^{dis}



atmospheric CO_2 rises by 7 ppm

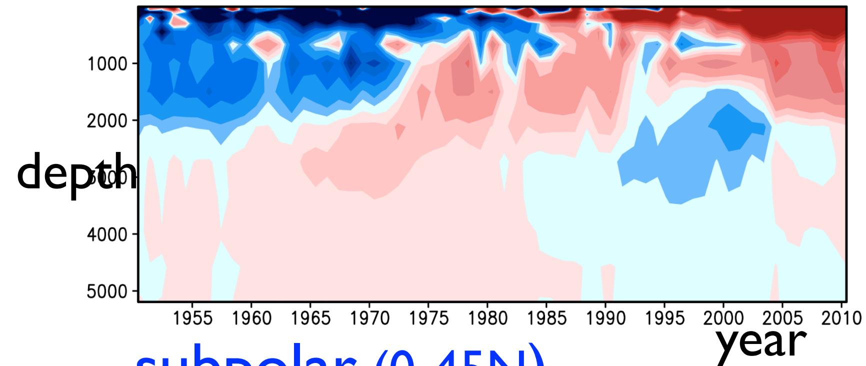
Summary

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

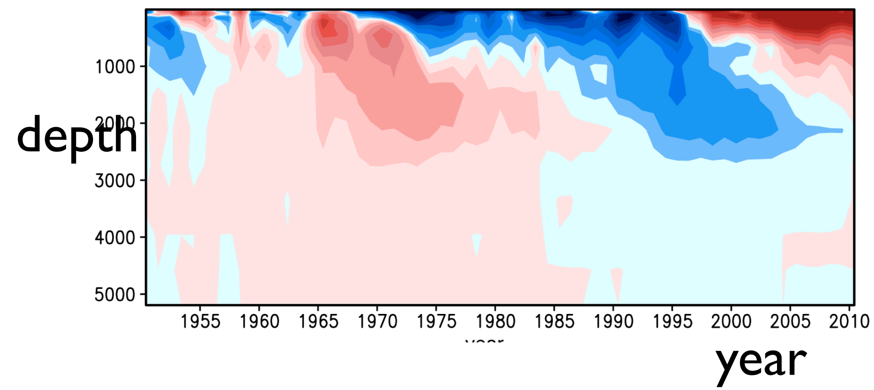
• Subtropical changes linked to Ekman heat convergence. See Lozier et al. (2008) Science

• Subpolar changes linked to MOC-Ekman heat convergence
See Robson et al. (2012) J Clim
also talks by Alexey Federov & Rym Msadek

subtropical (0-45N)



subpolar (0-45N)



Summary

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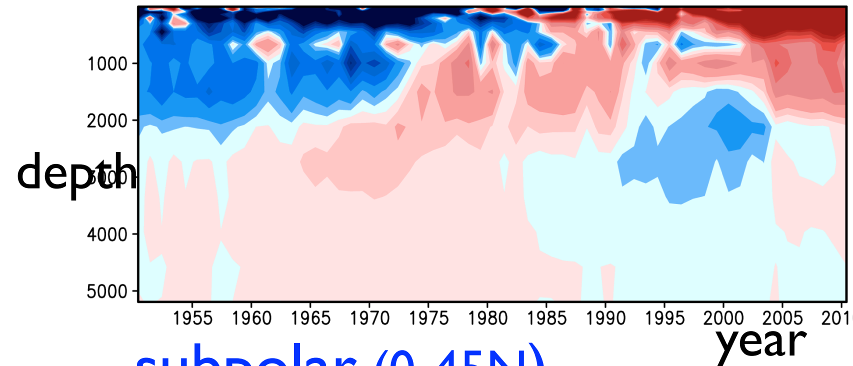
See Robson et al. (2012) J Clim
also talks by Alexey Federov & Rym Msadek

- Overturning changes can alter atmospheric CO_2 via subduction, disequilibrium & upwelling

at equilibrium, coarse models suggest stronger overturning *increases* atmospheric CO_2

subtropical (0-45N)



subpolar (0-45N)