Southern Ocean heat uptake and redistribution in theoretical framework and model perturbation experiments

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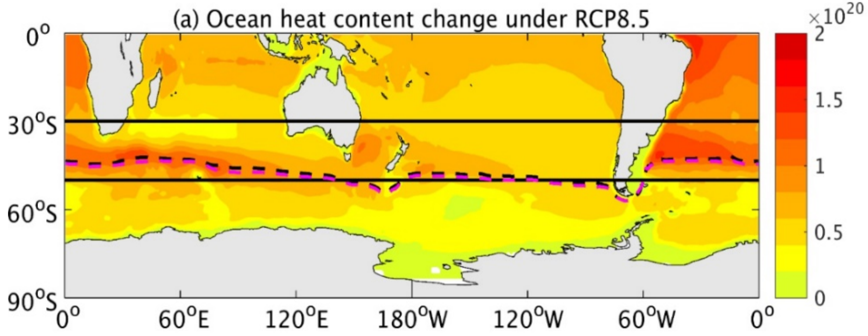
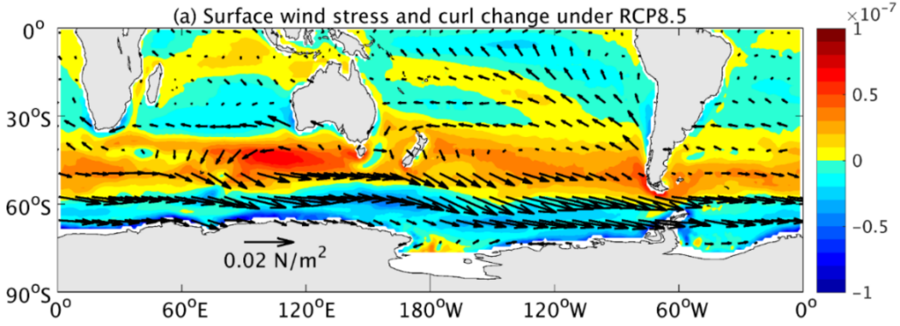
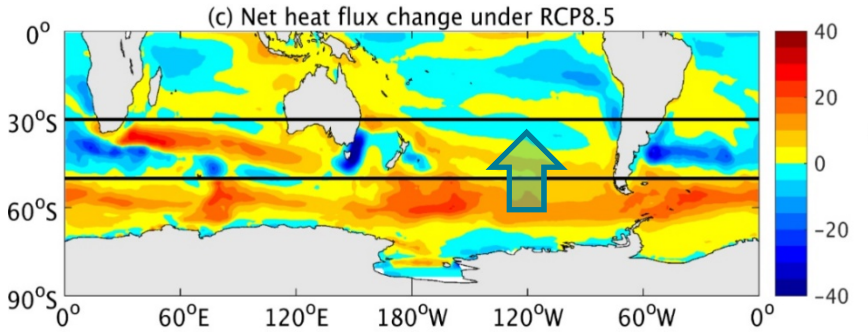
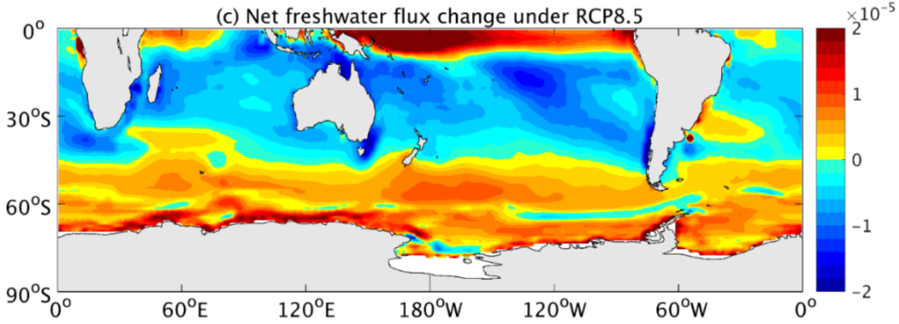
CMIP5 multi-model mean changes under RCP8.5







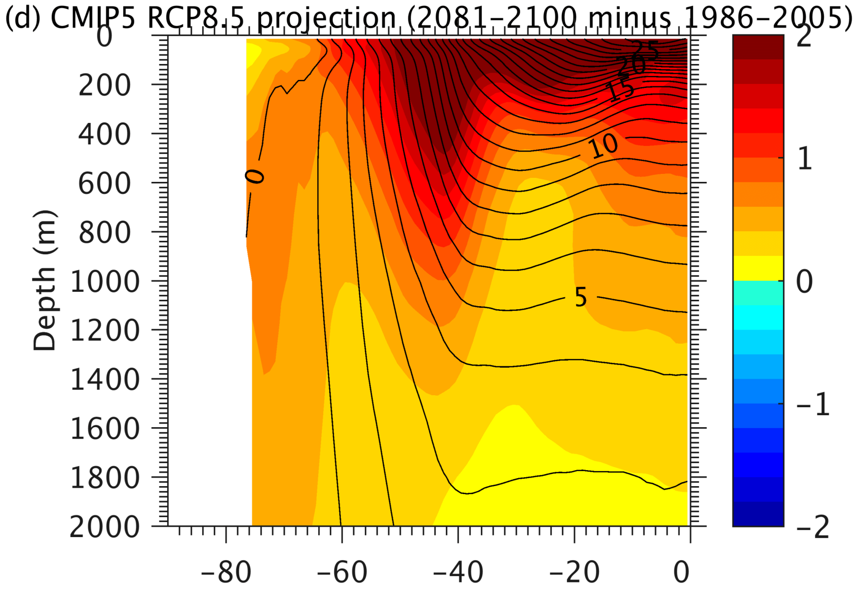
(Positive: freshwater input to ocean)



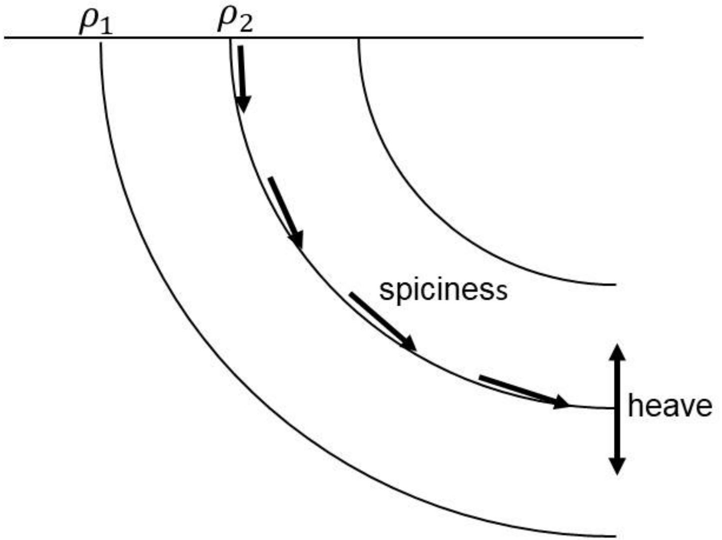
What are the individual roles of momentum, heat, and freshwater fluxes?

Spiciness and heave components

Total



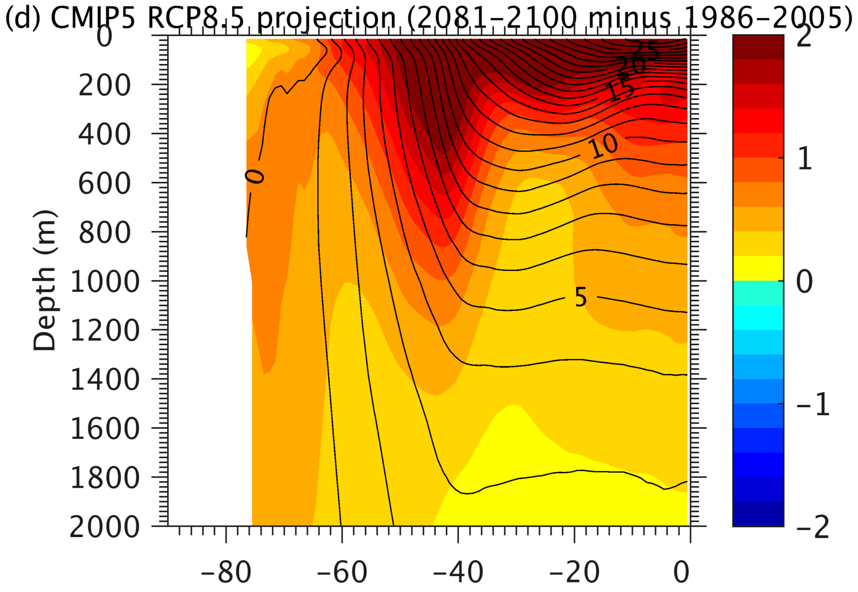
Global zonal mean ocean temperature
Current climatology (contours) & RCP8.5 change (colour)



Spiciness: T&S changes along isopycnals
Heave: changes due to heave of isopycnals

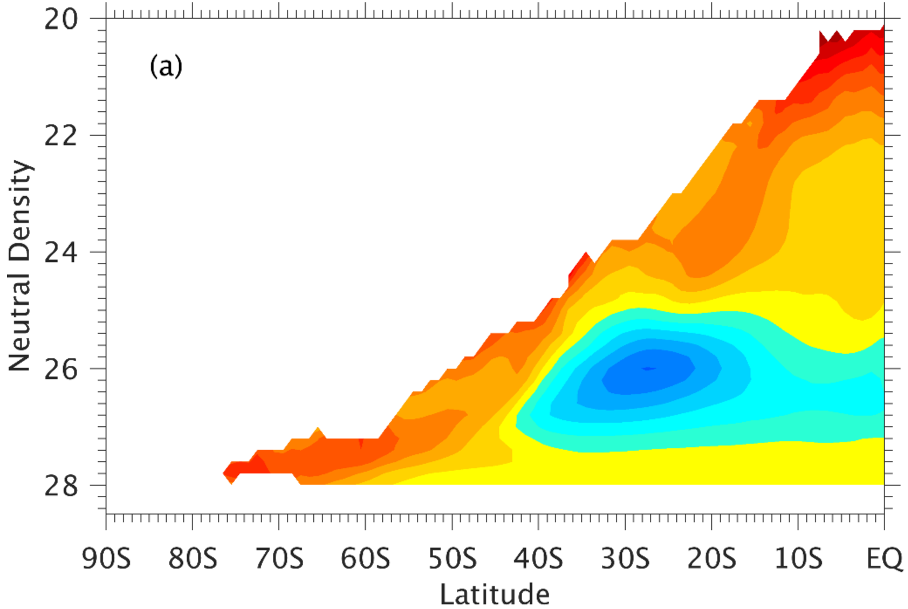
Spiciness and heave components

Total



Global zonal mean ocean temperature
Current climatology (contours) & RCP8.5 change (colour)

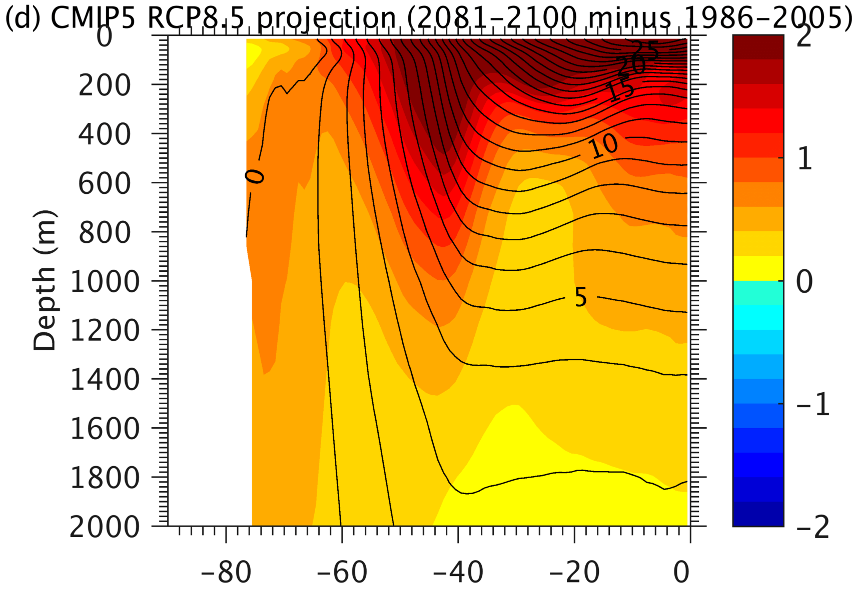
Spiciness



Coordinate transformation: Zonal mean spiciness changes on density surfaces

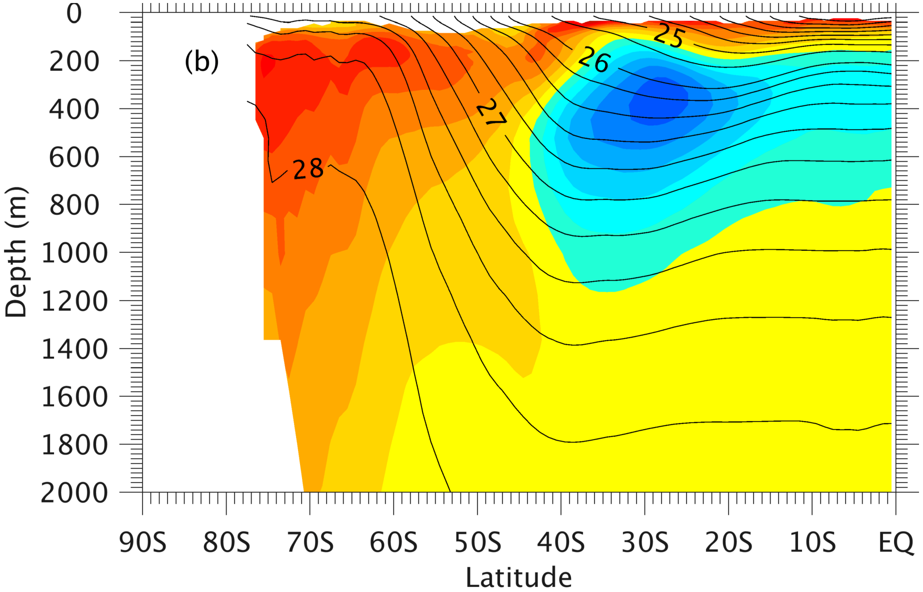
Spiciness and heave components

Total



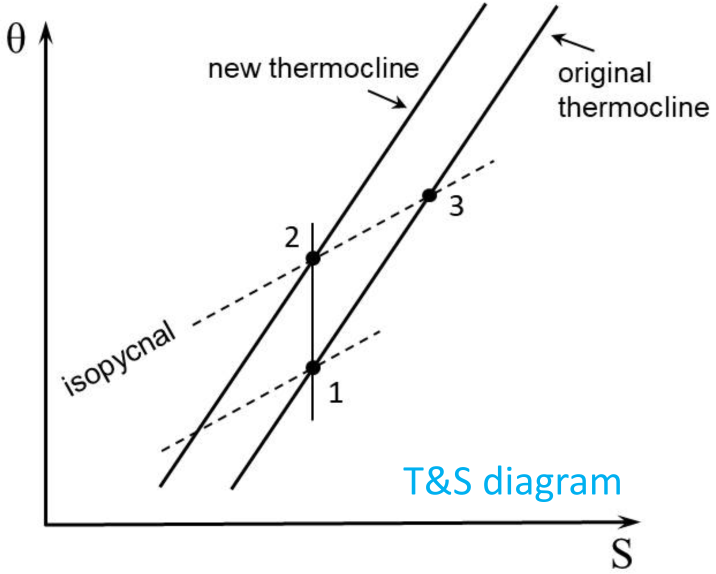
Global zonal mean ocean temperature
Current climatology (contours) & RCP8.5 change (colour)

Spiciness



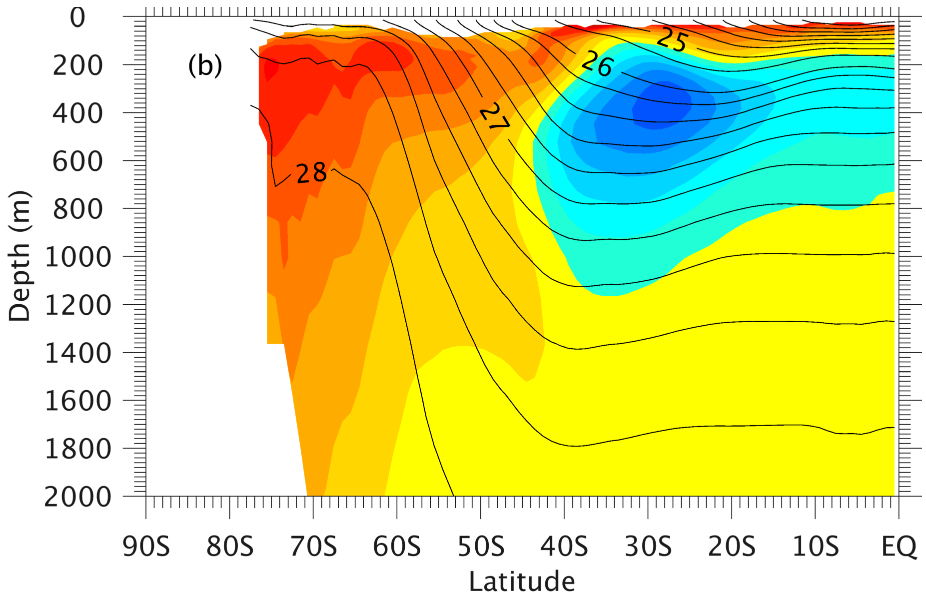
Zonal mean spiciness changes at depth levels
(Density surface contours)
Cooling and freshening within SAMW

Spiciness and heave components



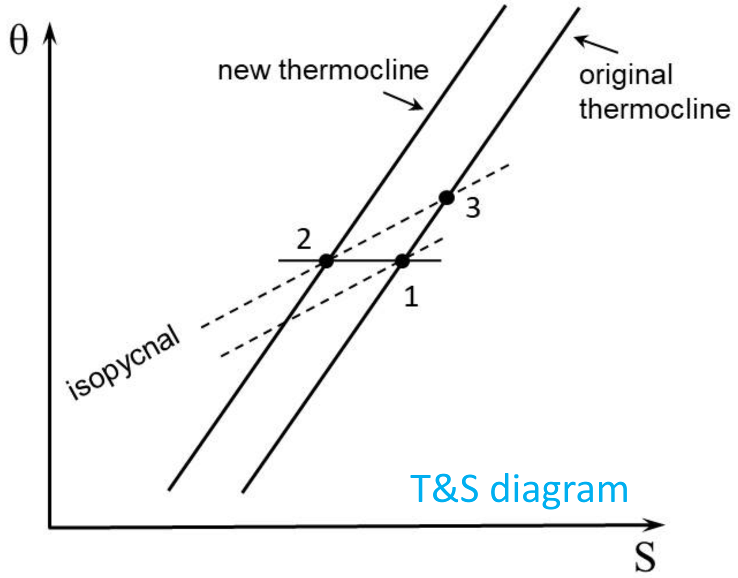
Pure warming process (from 1 to 2)
Induced spiciness change (from 3 to 2)
(Bindoff and McDougall 1994)

Spiciness



Zonal mean spiciness changes at depth levels
(Density surface contours)
Cooling and freshening within SAMW

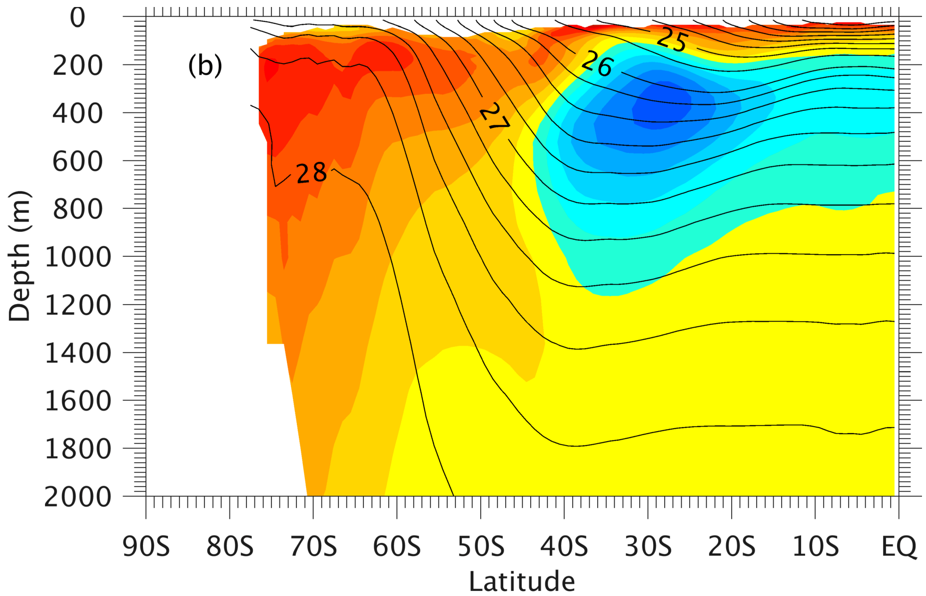
Spiciness and heave components



T&S diagram

Pure freshening process (from 1 to 2)
Induced spiciness change (from 3 to 2)
(Bindoff and McDougall 1994)

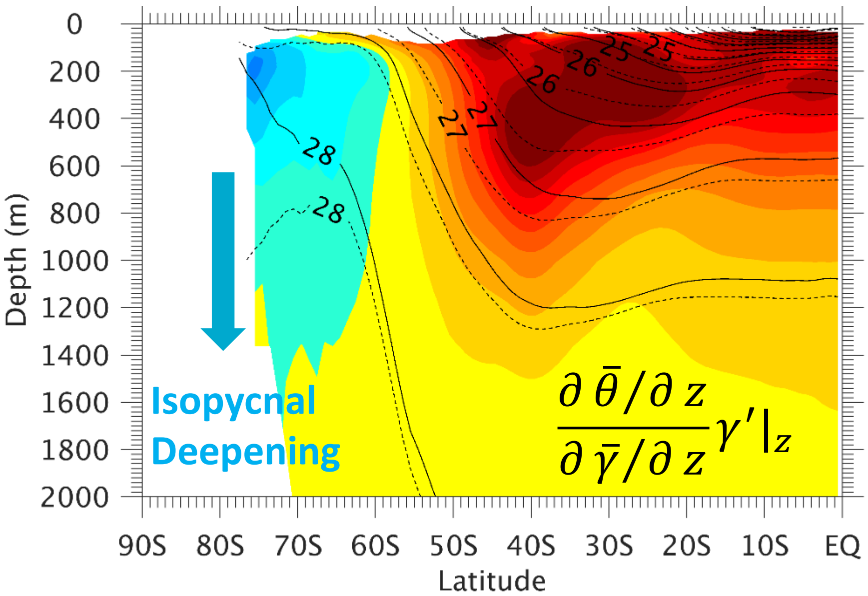
Spiciness



Zonal mean spiciness changes at depth levels
(Density surface contours)
Cooling and freshening within SAMW

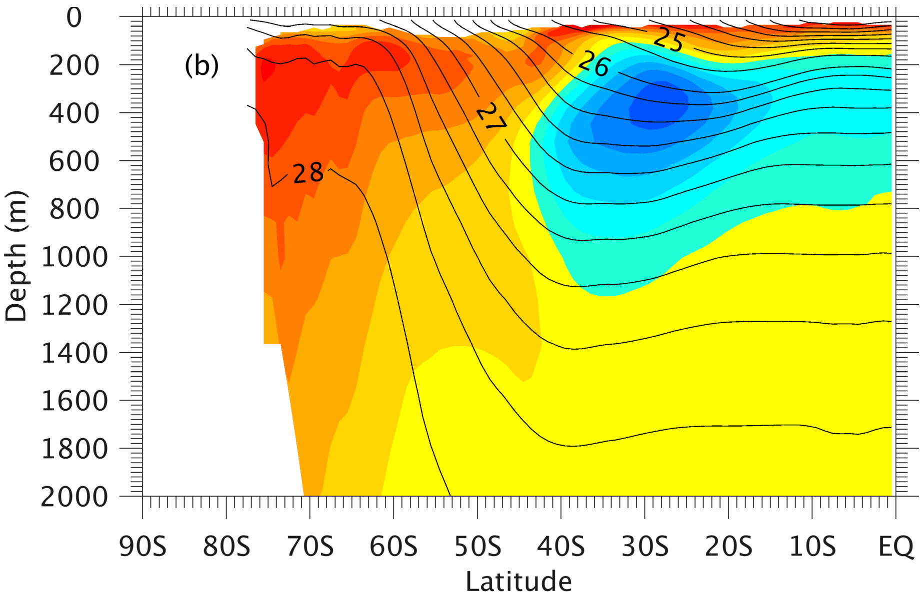
Spiciness and heave components

Heave



Zonal mean heave-related temperature changes: total minus spiciness

Spiciness



Zonal mean spiciness changes at depth levels (Density surface contours)

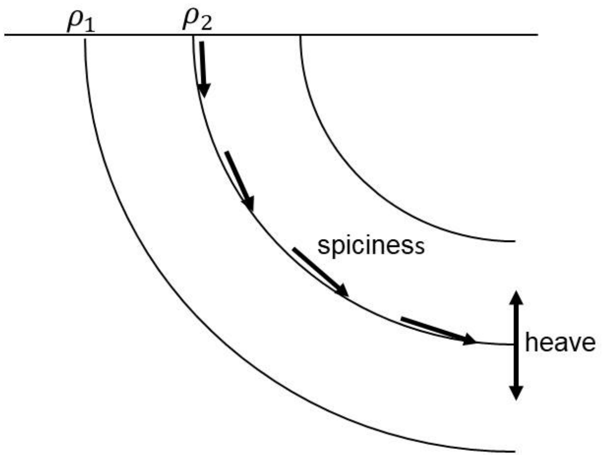
Cooling and freshening within SAMW

A theoretical framework to understand ocean change

- *Bindoff and McDougall (1994)* proposed a theoretical framework to separate subsurface T&S change into three processes on T&S diagram

- **pure warming (PW):** no salinity change at depth level --- generally the warming can be traced back to surface heat flux input
- **pure freshening (PF):** no temperature change at depth level --- generally the salinity change can be traced back to surface freshwater input
- **pure heave (PH):** no spiciness signal / only isopycnal heaving - related to wind; wave propagation; eddy etc.

PW&PF: subductions



- ***Two components*: Heave and Spiciness; *Three processes:* PW, PF, PH**

$$\frac{\rho^{-1}\rho'|_z}{R_\rho - 1}\begin{bmatrix} -(R_\rho - 1) & 0 & -R_\rho \\ 1 & R_\rho & 0 \\ R_\rho & R_\rho & R_\rho \\ 0 & (R_\rho - 1) & -1 \\ 1 & R_\rho & 0 \\ 1 & 1 & 1 \end{bmatrix}\boxed{\begin{bmatrix} A^w \\ A^f \\ A^h \end{bmatrix}} = \begin{bmatrix} \boxed{\alpha\theta'|_z} \\ \boxed{\alpha\theta'|_n} \\ \boxed{N'\alpha\theta_z} \\ \beta S'|_z \\ \beta S'|_n \\ N'\beta S_z \end{bmatrix},$$

Temperature change

A. at depth levels

B. along isopycnals (spiciness)

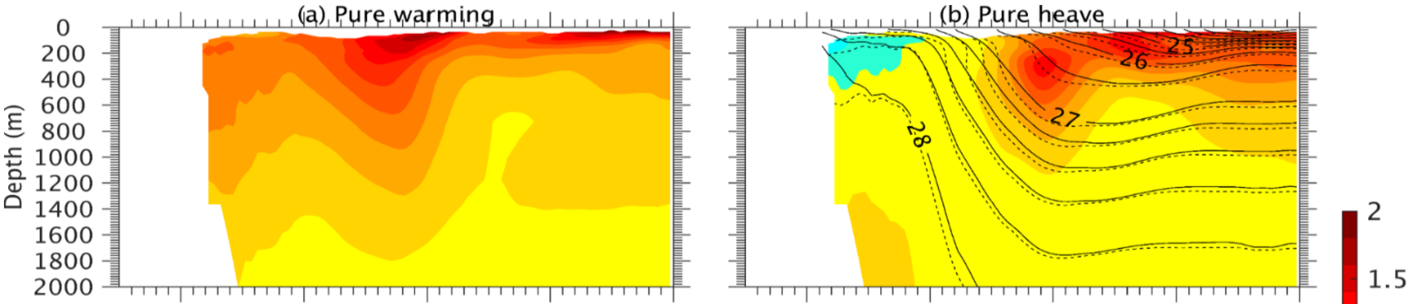
C. related to heave of isopycnals

Salinity change

- Put three processes together in matrix form
- Stability ratio R_ρ: defined as the ratio between vertical gradients of mean temperature and salinity $\alpha\overline{\theta_z} = R_\rho\beta\overline{S_z}$
- Six observables on the right: dependent on each other so there are actually only two pieces of independent information
- therefore this is an underdetermined issue with two obs but three unknowns
- A “possible” (simplest) solution can be derived using SVD method

PW

PH



PW: Heave

PF: Heave

PW: Spiciness

PF: Spiciness

Perturbation experiments -- FAFMIP

The Flux-Anomaly-Forced Model Intercomparison Project (FAFMIP) contribution to CMIP6: investigation of sea-level and ocean climate change in response to CO_2 forcing

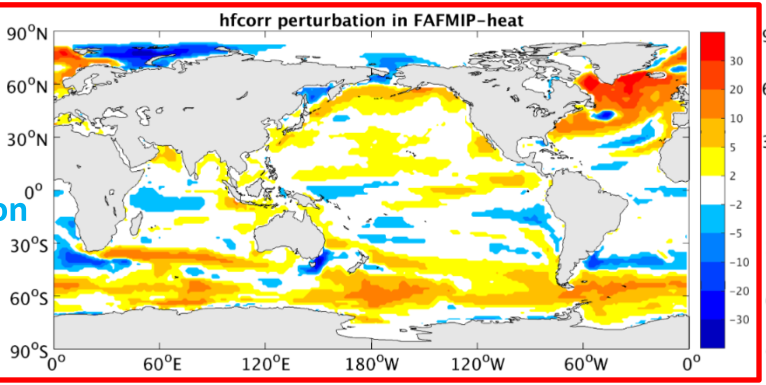
Jonathan M. Gregory[1,2], Nathaelle Bouttes[3], Stephen M. Griffies[4], Helmuth Haak[5], William J. Hurlin[4], Johann Jungclaus[5], Maxwell Kelley[6], Warren G. Lee[7], John Marshall[8], Anastasia Romanou[6], Oleg A. Saenko[7], Detlef Stammer[9], and Michael Winton[4]

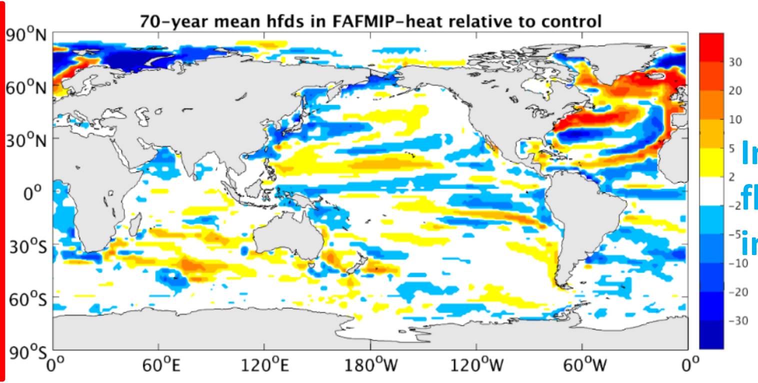
[1]NCAS, University of Reading, Reading, UK
[2]Met Office Hadley Centre, Exeter, UK
[3]Laboratoire des Sciences du Climat et de l'Environnement, Institut Pierre Simon Laplace, Gif-sur-Yvette, France
[4]NOAA Geophysical Fluid Dynamics Laboratory, Princeton, USA
[5]Max Planck Institute for Meteorology, Hamburg, Germany
[6]Goddard Institute for Space Sciences, Columbia University, New York, USA
[7]Canadian Centre for Climate Modelling and Analysis, Victoria, British Columbia, Canada
[8]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, USA
[9]Center for Earth System Research and Sustainability, University of Hamburg, Germany

We analysed HadCM3 results from Dr. Jonathan Gregory (U. Reading, UK): wind stress, heat flux, and freshwater flux perturbation experiments

Perturbation experiments: HadCM3

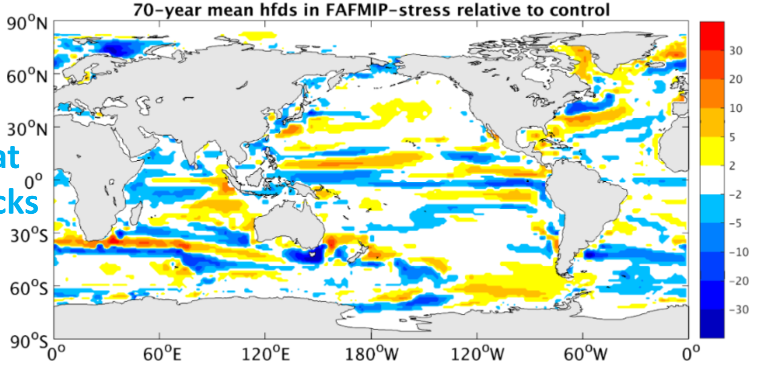
Intended Heat flux perturbation

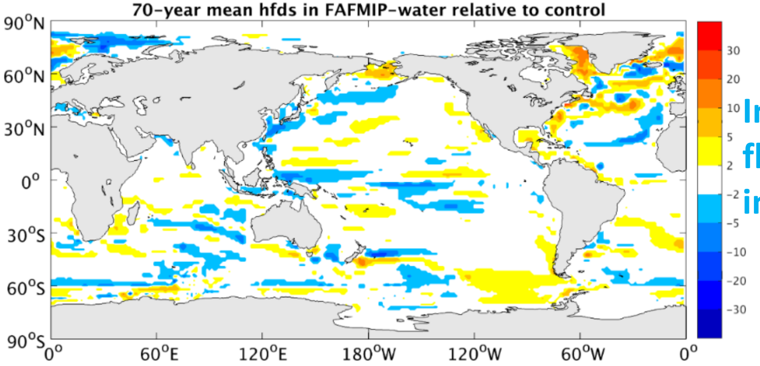




Induced heat flux feedbacks in faf-heat

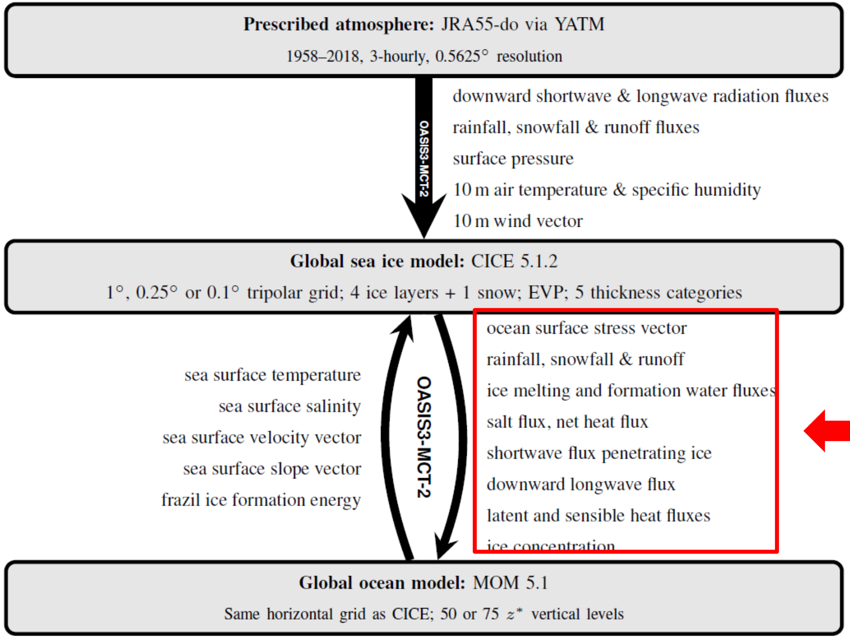
Induced heat flux feedbacks in faf-stress





Induced heat flux feedbacks in faf-water

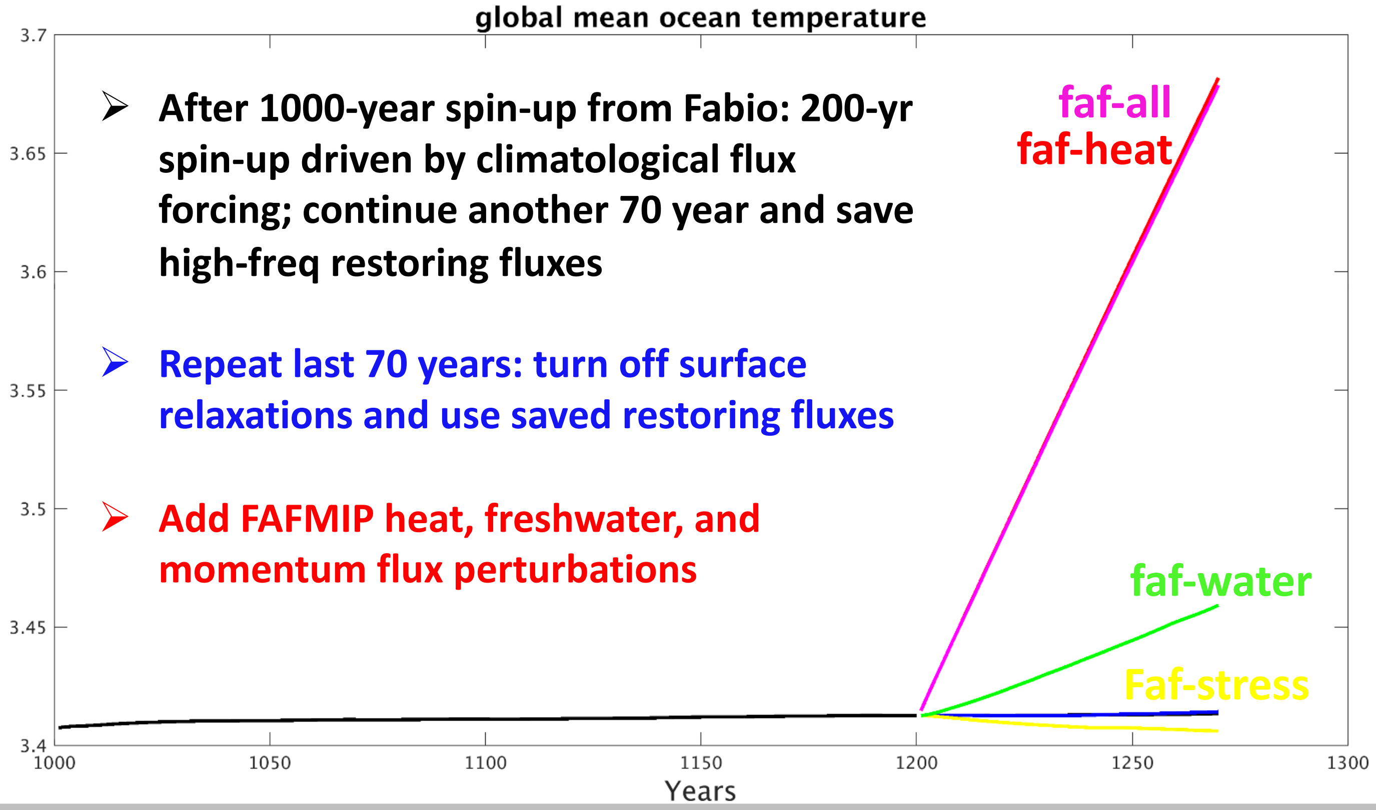
Perturbation experiments: ACCESS-OM2



Using climatological air-sea and sea ice fluxes to override interactive bulk formula

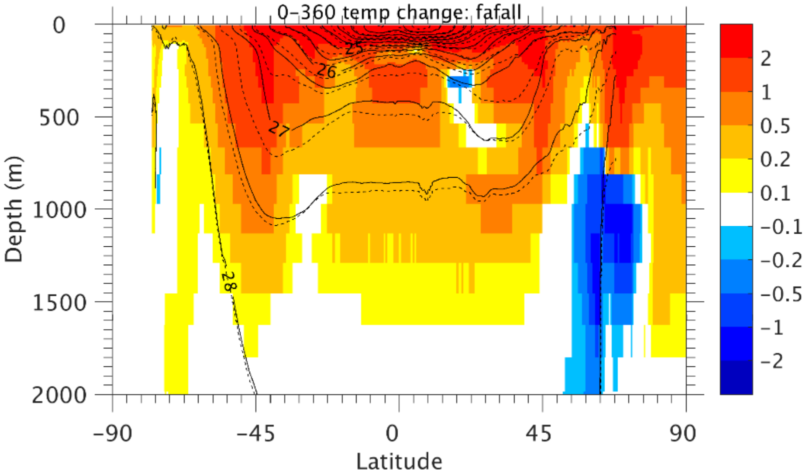
Target: suppress air-sea-ice feedbacks so ocean only responses to added flux perturbation!

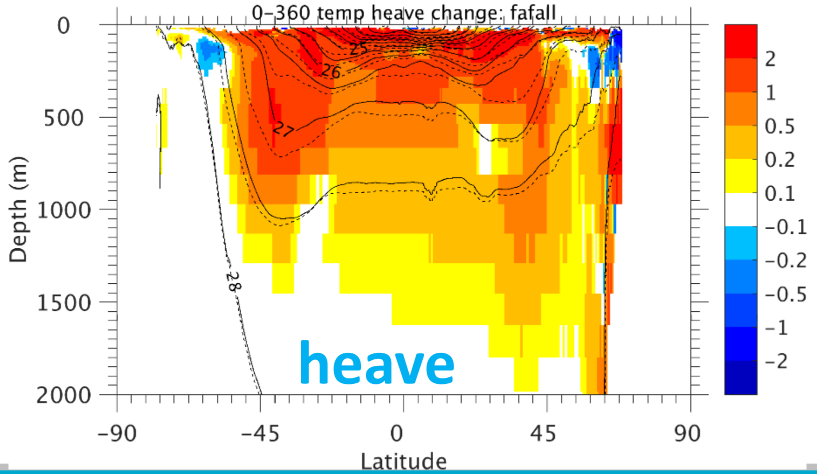
Perturbation experiments: ACCESS-OM2

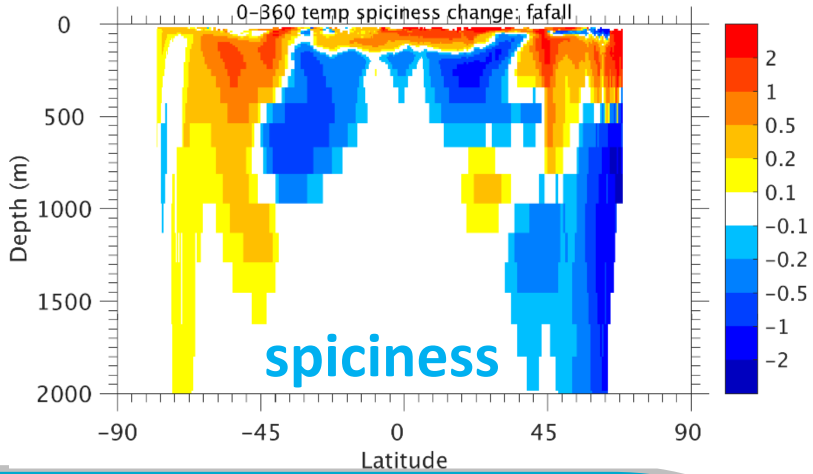


- After 1000-year spin-up from Fabio: 200-yr spin-up driven by climatological flux forcing; continue another 70 year and save high-freq restoring fluxes
- Repeat last 70 years: turn off surface relaxations and use saved restoring fluxes
- Add FAFMIP heat, freshwater, and momentum flux perturbations

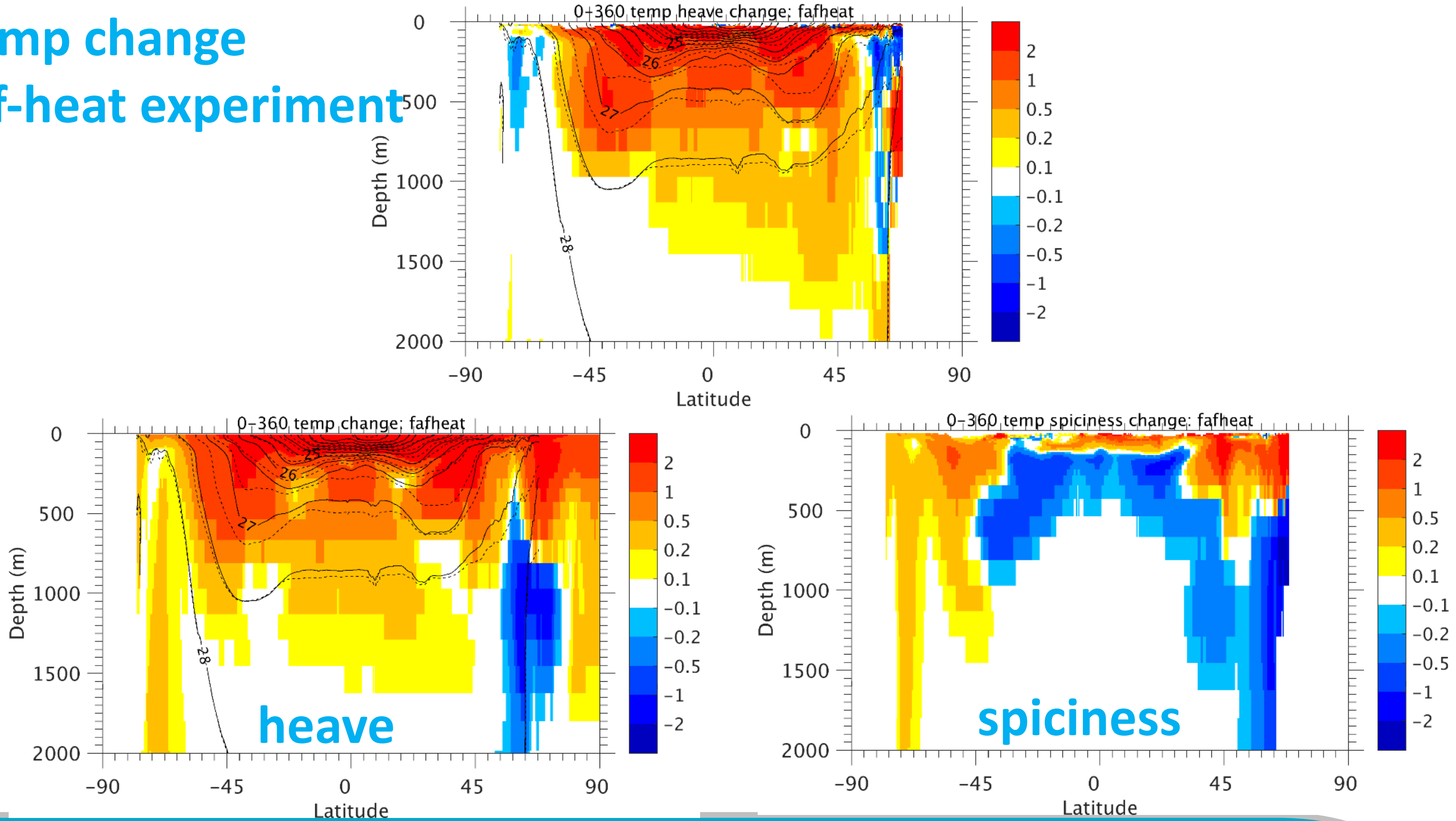
Temp change
faf-all experiment



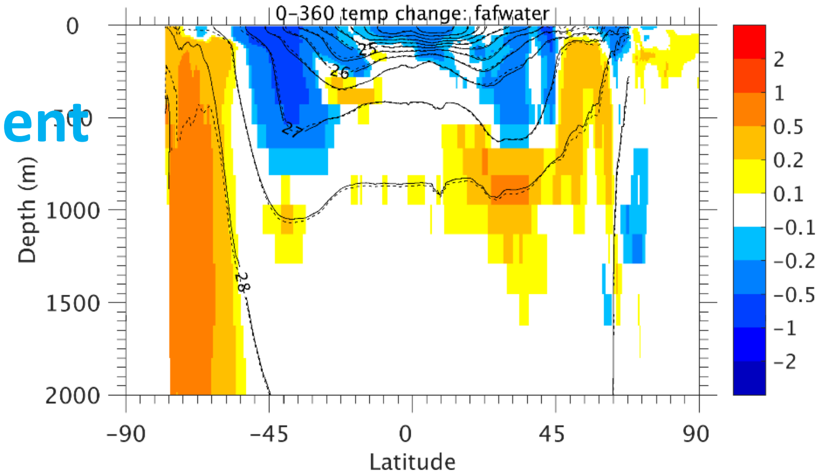


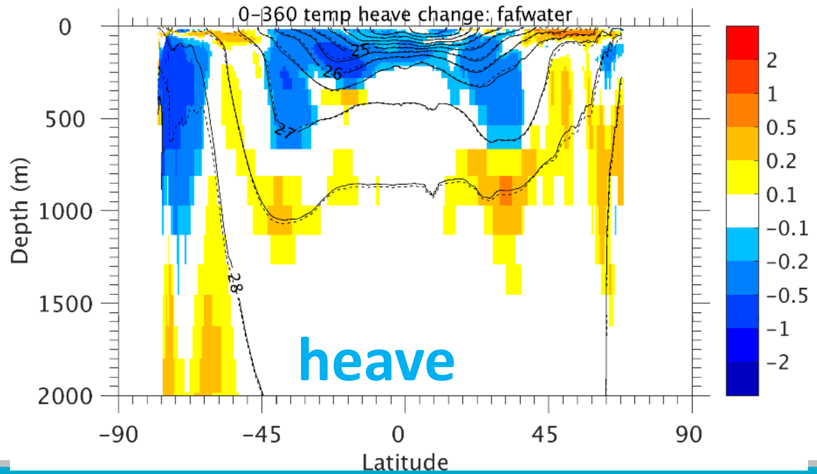


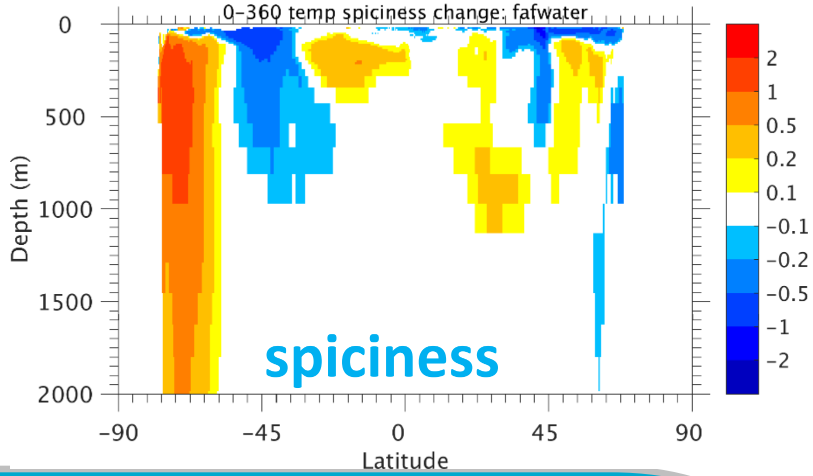
Temp change
faf-heat experiment



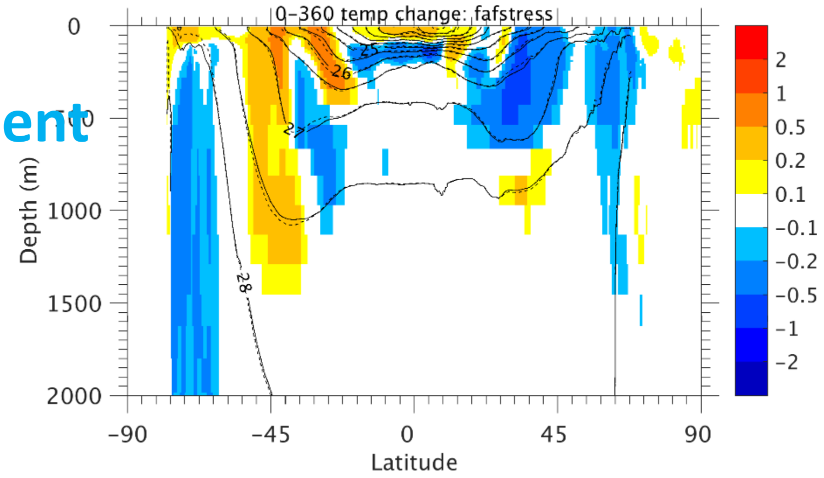
Temp change faf-water experiment

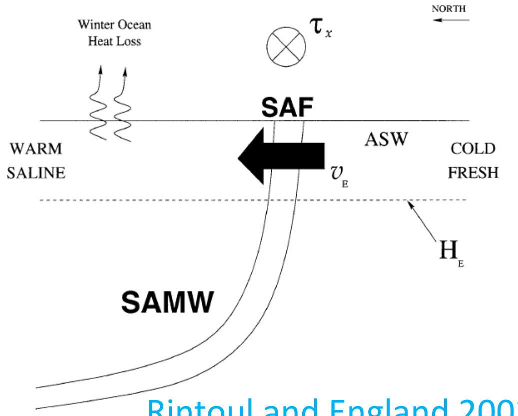




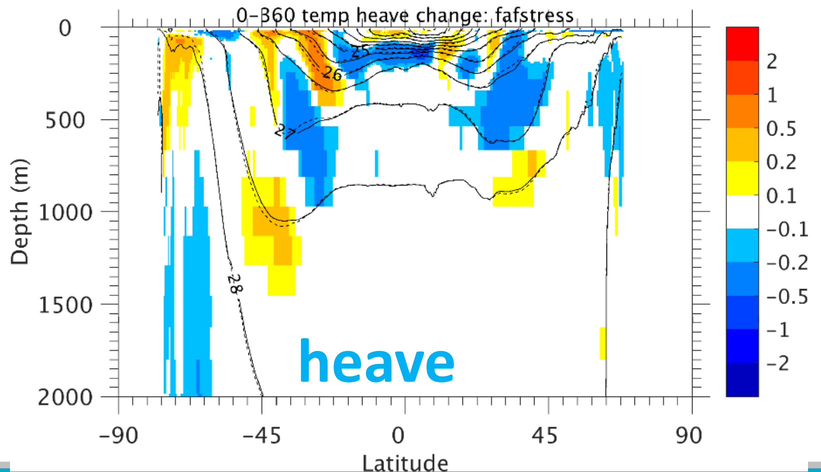


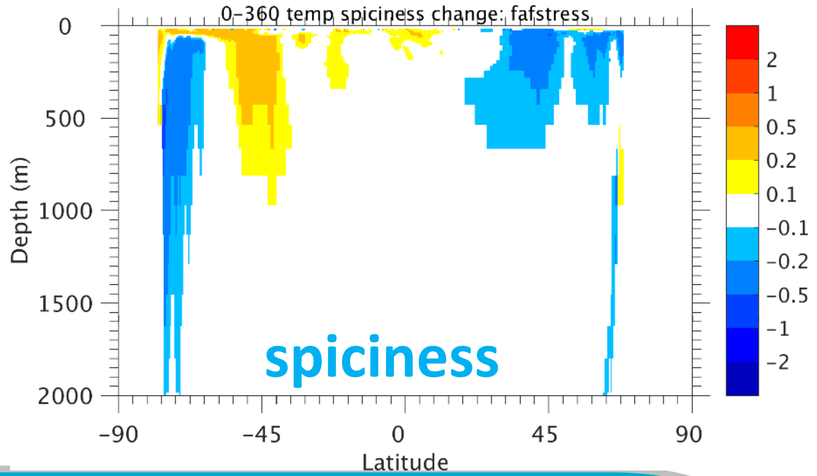
Temp change
faf-stress experiment





Rintoul and England 2002





Summary

- **The theoretical framework reveals:**
- (1) spiciness changes due to equatorward and downward subductions of the surface heat and freshwater input at high latitudes, i.e. PW and PF;
- (2) enhanced mid-latitude warming and isopycnal deepening due to both wind-driven heat convergence (PH) and the subduction and transport of surface heat input (PW)
- **Limitations: idealised “pure” processes with assumptions; under-determined issue so only qualitative decompositions**

- **Coupled model FAFMIP experiments: large flux feedbacks in addition to added flux perturbation**
- **Ocean-only experiments using ACCESS-OM2 better suit our purpose to attribute ocean changes to a single type of flux forcing**