Ocean heat uptake dr heat in response to o

Fabio Boeira Dias et al (submitted to Journal of criditions whereas the two coarser models generally cool during the first few decades. Recall that the global mean temperature, averaged over the full ocean, steadily rises for each of the

Russ Fiedler Simon Marsland Catia Domingues Louis Clement Steve Rintoul Mauricio Mata Richard Matear







$$\sum_{i,j} \frac{d}{d_i d_j} = \sum_{i,j} \frac{d}{d_i d_j} = \sum_{i$$

remains relatively steady in time, largely due to the use of z^* as a vertical coordinate whereby trends in sea level (Figure 4.4) are distributed throughout the full depth. Hence, variability in the averaged surface temperature (5.88) is dominated by variations in dthe numerator, which measures the heat within the top grid cells. It is notable that the CM2.6 simulation exhibits the least drift in Figure 5.17 from initial conditions, whereas the two coarser models generally cool during the first few decades.

Recall that the global mean temperature, averaged over the full ocean, steadily rises for each of the three models (Figure 5.9). Hence, a net uptake of heat into the ocean, thus increasing the global mean ocean temperature according to equation (5.31), does not necessarily mean the surface temperature increases (Figure 5.17). The reason is that surface boundary heating can be readily transported into the ocean interior through vertical advective and subgrid scale transfer, as per the budget shown in equation (5.87).

We illustrate this process in Figure 5.18 by showing a time series for the horizontally integrated heat accumulated in the surface ocean cells, the corresponding heat transported vertically, and the contribution from surface boundary fluxes. The net heat remaining in the surface ocean is indeed a small residual

⁴Since the top grid cell has a time-dependent thickness, this diagnostic is slightly distinct from the area averaged sea surface temperature (SST) computed without the thickness weighting. Nonetheless, the area averaged SST and grid cell averaged surface temperature exhibit very similar quantitative behaviour. The reason is that the top grid cell in a z^* model has a thickness that remains very close to the constant resting value of 10 m in the A CM2-O suite.

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Motivation



- Large spread in thermosteric Sea Level projections (30-50% of GMLSR)
- Part due to climate sensitivity (atmospheric) and part is due to ocean response



Gregory et al (2016)

- Large variation in ocean heat efficiency among CMIP models (Kuhlbrodt & Gregory 2012)



Flux-Anomaly-Forced MIP (FAFMIP)

- Isolate the oceanic response - sfc flux perturbation obtained from CMIP5 MMM (2xCO2) - Force CMIP6/FAFMIP models with same perturbation

- including process-based diagnostics

Ocean heat transp.

 $\partial \theta$ Φ_n θ_n Surface heat fluxes

 $\Phi = ADV + DIA + KPP + SWP + EIT + SUB + CON + PME + RIV + FRZ$



(c) FAFMIP water flux perturbation (10⁻⁶ kg m⁻² s⁻¹) 90° | 75° | 60° | 45° 30° | 15° I 15° 30° 60° 135° W 90° W 45° E -7.5 -10 -5 -2.5 2.5 -1 5

(b) FAFMIP heat flux perturbation F (W m⁻²)



(d) Model-mean ΔQ in faf-heat (W m⁻²)



Gregory et al (2016)



Flux-Anomaly-Forced MIP (FAFMIP) Decomposition into added (passive) and redistributed heat tracers:

- Additional tracers: T_A (added) and T_R (redist.) - Added heat only feels the heat flux perturbation (F)

$$\frac{\partial T_A}{\partial t} = F + \Phi_p(T_A)$$

- Redistributed heat does not feel F, it's only affected by climatological sfc heat flux (Q)

$$\frac{\partial T_R}{\partial t} = Q_p + \Phi_p(T_R)$$



- Previous studies found a global heat balance (in steady state) -> mean advection (ADV) and eddy-induced transport (EIT)

- Framework for process-based studies: Super-residual transport (Kuhlbrodt et al 2015, Dias et al, 2020): SRT = ADV + EIT



Vertical Heat Fluxes



Globally-integ. heat convergences

Dias et al (2020)



SRT framework



- Two regimes:

1) Deep mixed layers: counterbalance cooling from vertical mixing processes (KPP, SUB, CON) is formation of dense water masses 2) Ocean interior (below MLD): re-circulate water masses along isopycnals counterbalanced by dianeutral mixing (erosion) **Munk's advective-diffusive balance**

FAFMIP-OGCM experiments

- ACCESS-OM2 (Kiss et al 2020) 1-degree global model: MOM5 + CICE5.1 - spun up with JRA55-do (Tsujino et al 2018) Repeat Year Forcing for 1000yrs - Perturbed with FAFMIP flux anomalies (Gregory et al 2016) for another 80yrs - SSS restoring switched to flux form - no effect on the FW perturbation

Spinup 1000 years

JRA55-do RYF (1984-1985)



Ocean Heat Content changes:

ΔOHC *faf-all* (avg years 61-80)

- Ocean heat storage: larger in Atlantic than other basins

- Passive warming: mid-latudes and North Atlantic/Arctic

Redistribution: cooling at subtropical gyres, warming at tropics, ACC and Gulf Stream/NAC

Objective: investigate the mechanisms of redistributed warming at low latitudes and along the northern boundary of the ACC

her basins ntic/Arctic varming at



Sfc heat flux perturbation and T_A heat transport





C) KPP + SUB + CON







*vertically-integrated 10-2000m

- Added heat storage (NET) at mid-latitudes and North Atlantic/Arctic

- Heat uptake by vertical mixing processes (DIA, KPP, CON)

- Advected equatorward by SRT



T_A heat transport: zonal perspective



*vertically-integrated 10-2000m



- Changes in mixed layers = vert. Mixing

processes

- Advected via ventilation pathways = SRT

Atlantic Ocean Zonally-integrated



Sfc heat flux perturbation and T_R heat transport





C) KPP + SUB + CON



B) DIA + SWP





*vertically-integrated 10-2000m

- Redistribution of heat:

- cools subtropical gyres
- warm tropical latitudes (+ SPNA)
- stronger cooling (North Atlantic); warming

in the South Atlantic Gyre

- warming at Subtropical Front of the ACC



T_R heat transport: zonal perspective



*vertically-integrated 10-2000m





- upper-1000m: redistribution of heat from subtropics (passive heat gain) to tropics - 1000-2000m depth: changes in mode and deep water formation/sink of isopycnals

> **Atlantic Ocean** Zonally-integrated



Mechanisms of heat redistribution



Reduced poleward heat 1) - Decrease of poleward SRT by the Gulf Stream (and transport Northern North Brazil/Guiana C.) **Hemisphere = Tropical** - Increase of SRT via EBCs and Equatorial Currents warming

A) 0-1000m integrated



Mechanisms of heat redistribution



- Increase of poleward SRT by Brazil Current: - part of the heat goes back to tropics via stronger transport by EBCs

- part converges at the subtropical front

A) 0-1000m integrated

2) Increased poleward heat transport Southern Hemisphere = Tropical and subtropical front warming





Changes in upper-ocean stratification

- Increasing stratification in the subtrop. Gyres
 - all basins except the South Atlantic
 - strengthen barrier at the gyre circulation between upper/lower thermocline
 - intensified EBCs (shallower than WBCs)
- Opposite changes in stratification where heat is stored due to redistribution:
 - Decrease stratification in the tropics & in the northern boundary of the ACC





Conclusions

- Importance of heat redistribution:
 - main mechanism (65%) of tropical warming, that results in an redistribution "feedback" (e.g. Garuba & Klinger 2018)
 - contributes to heat storage (25%) in the mid-latitude Southern Ocean (aligned with recent work of Chen et al
- 2019)
- Redistribution is dominated by the Super-residual Transport (ADV + EIT)
 - Increased heat transport from EBCs and Equatorial currents play a key role in store heat at low latitudes
 - WBCs have distinct responses to 2xCO2 scenario depending on basin (Yang et al 2016)
 - Increased stratification of the Gyres accelerates surface currents (e.g. Wang et al 2015, Luo et al 2018, Li et al 2019).
 - Brazil Current heat transport increases at all depths -> heat convergence and storage in the STF
 - in addition to a strengthened and poleward shifted ACC





Thanks for your attended the models of







$$\sum_{i,j} dA \ \partial_t \left(\Theta \rho \, dz\right) = \sum_{i,j} dA \left[\rho \left(w^{(0)} \Theta + F^{(0)}\right)\right]_{s=s_{k=1}} + \sum_{i,j} dA \left(Q_{advect} + Q_{non-advect}\right), \tag{5.87}$$

boundary fluxes heat tendency vertical transport

where we dropped the source term. Global surface ocean heat is thus impacted by vertical transport through advection and subgrid scale processes, and by boundary fluxes. This decomposition of ocean heating follows that proposed in Section

Figure 5.17 shows the annual mean time series for the global mean temperature within the ocean surface in the CM2-O suite of simulations, with this diagnostic computed according to

$$\Theta\rangle^{k=1} = \frac{\int_{k=1}^{\infty} \Theta \,\mathrm{d}A \,\mathrm{d}z}{\int_{k=1}^{\infty} \mathrm{d}A \,\mathrm{d}z}.$$
(5.88)

The global volume of the surface grid cell,

$$\mathcal{V}_{k=1} = \int_{k=1} \mathrm{d}A\,\mathrm{d}z \tag{5.89}$$

remains relatively steady in time, largely due to the use of z^* as a vertical coordinate whereby trends in sea level (Figure 4.4) are distributed throughout the full depth. Hence, variability in the averaged surface b) is dominated by variations in dthe numerator, which measures the heat within the temperature (5. top grid cells. It is notable that the CM2.6 simulation exhibits the least drift in Figure from initial s the two coarser models generally cool during the first few decades.

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