Ocean heat uptake driven by redistribution of heat in response to ocean circulation changes

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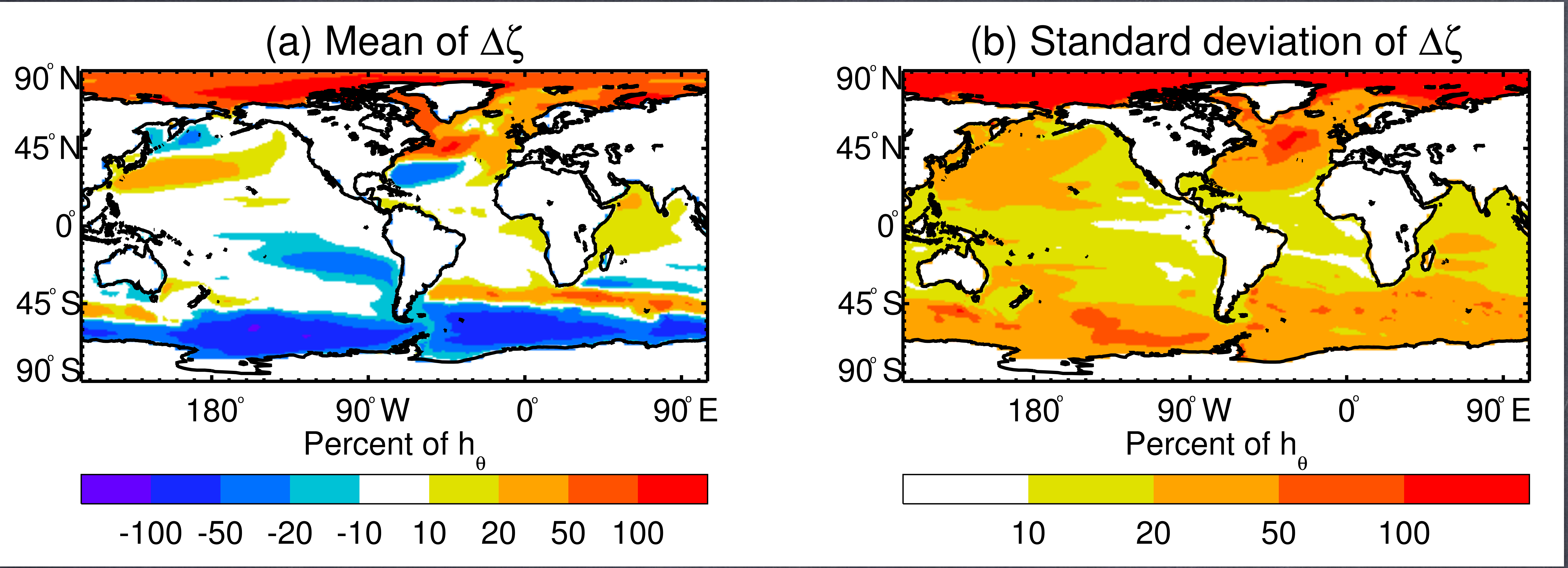
Motivation

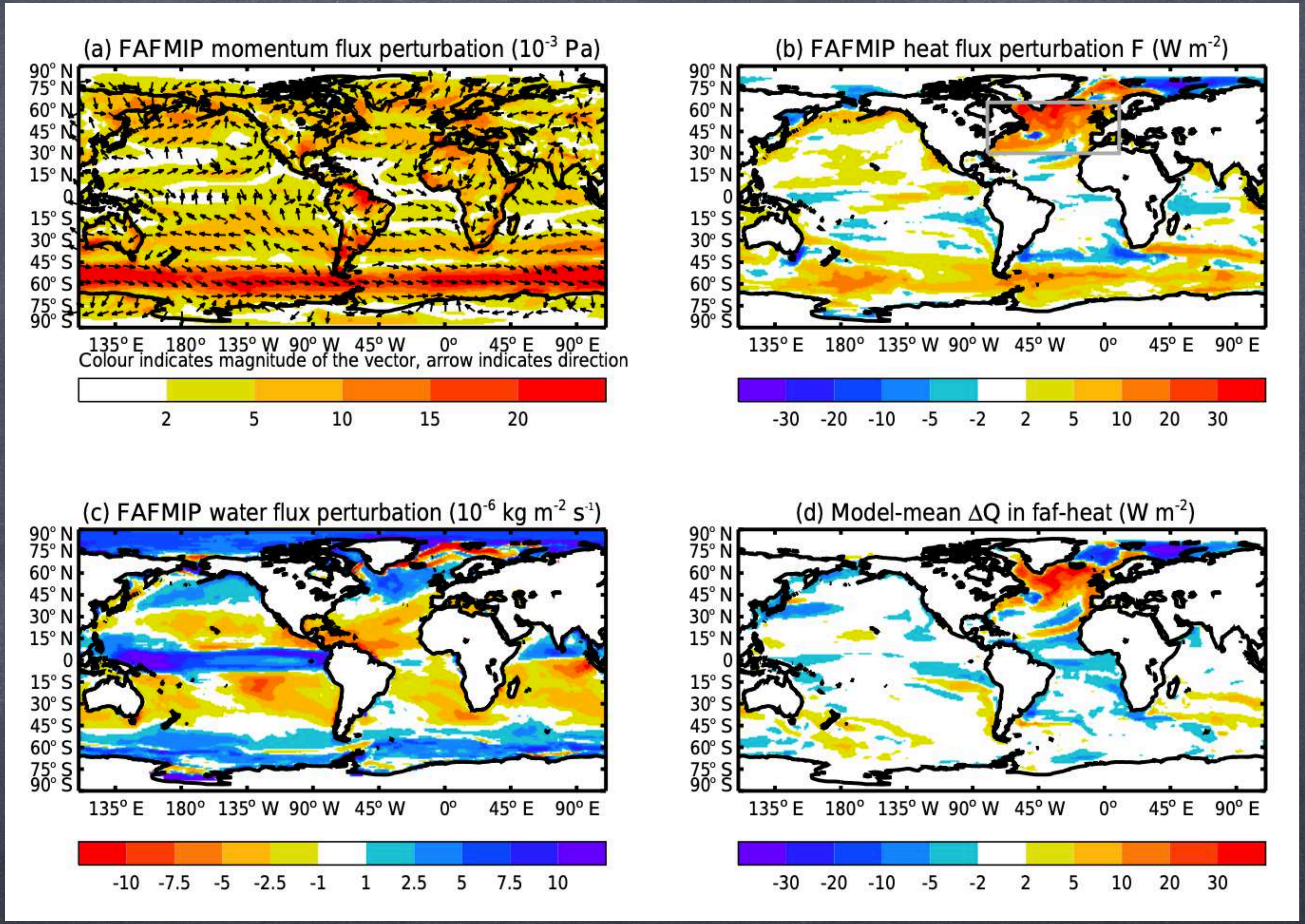


Gregory et al (2016)

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



Gregory et al (2016)

Ocean heat transp.

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

Surface heat fluxes

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

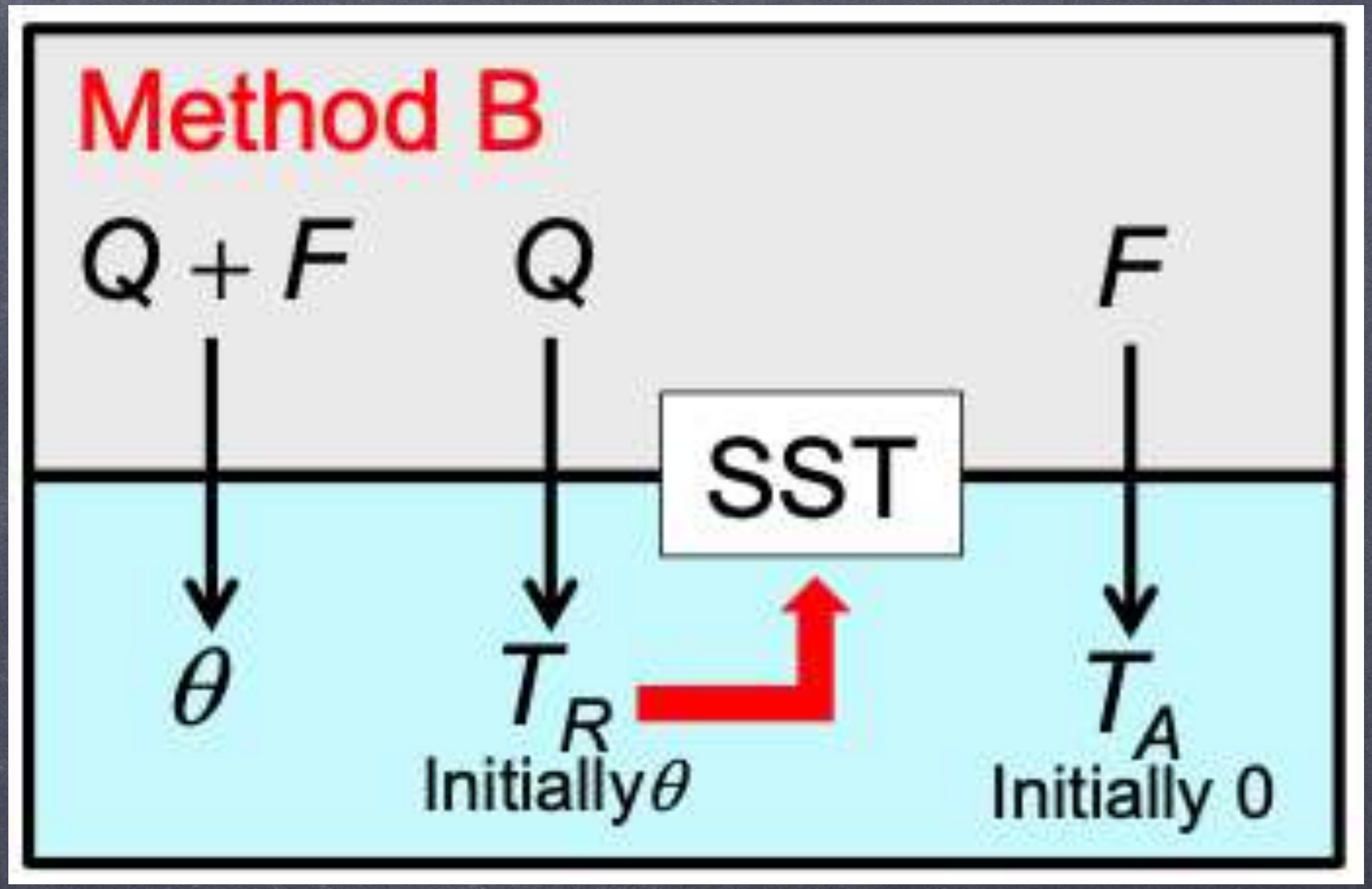
Flux-Anomaly-Forced MIP (FAFMIP)
Decomposition into added (passive) and redistributed heat tracers:

- 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*)

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



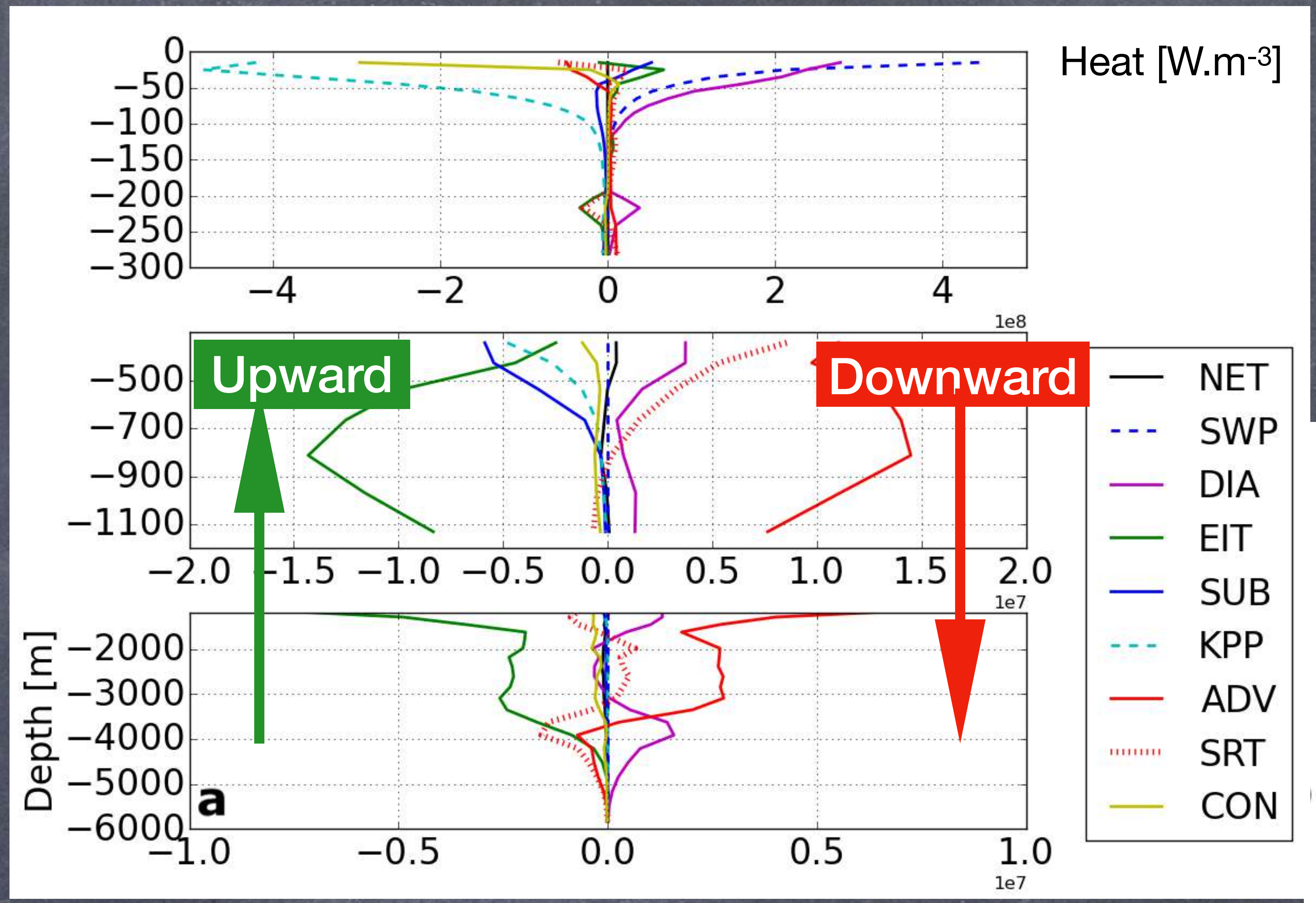
Gregory et al (2016)

Vertical Heat Fluxes

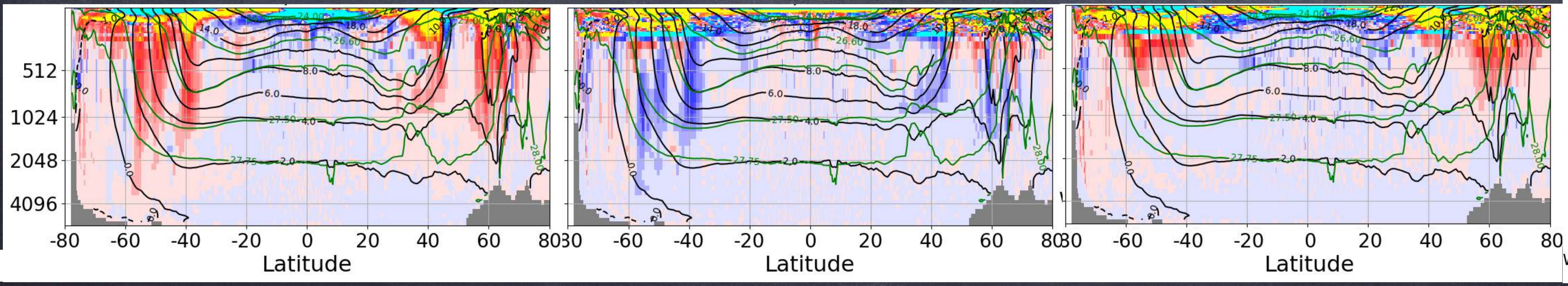
- Previous studies found a global heat balance (in steady state) -> mean advection (ADV) and eddy-induced transport (EIT)
- Framework for process-based studies: Super-residual transport (Kuhlbrodt et al 2015, Dias et al, 2020):

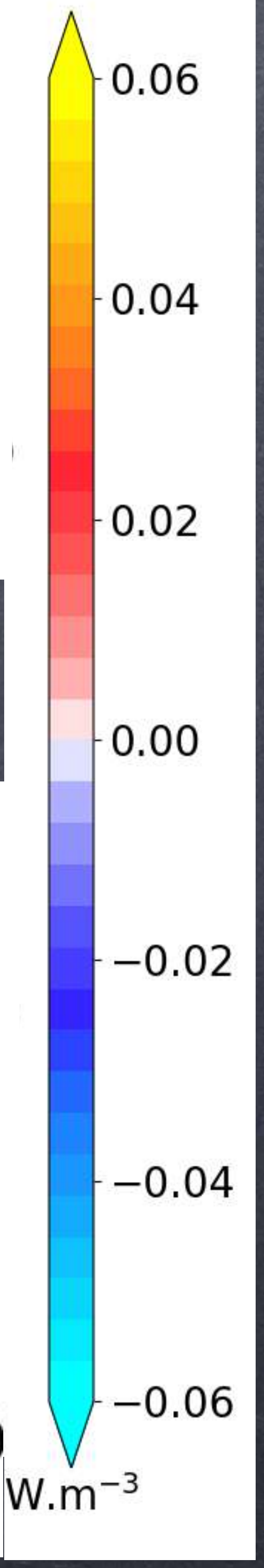
SRT = ADV + EIT

Globally-integ. heat convergences



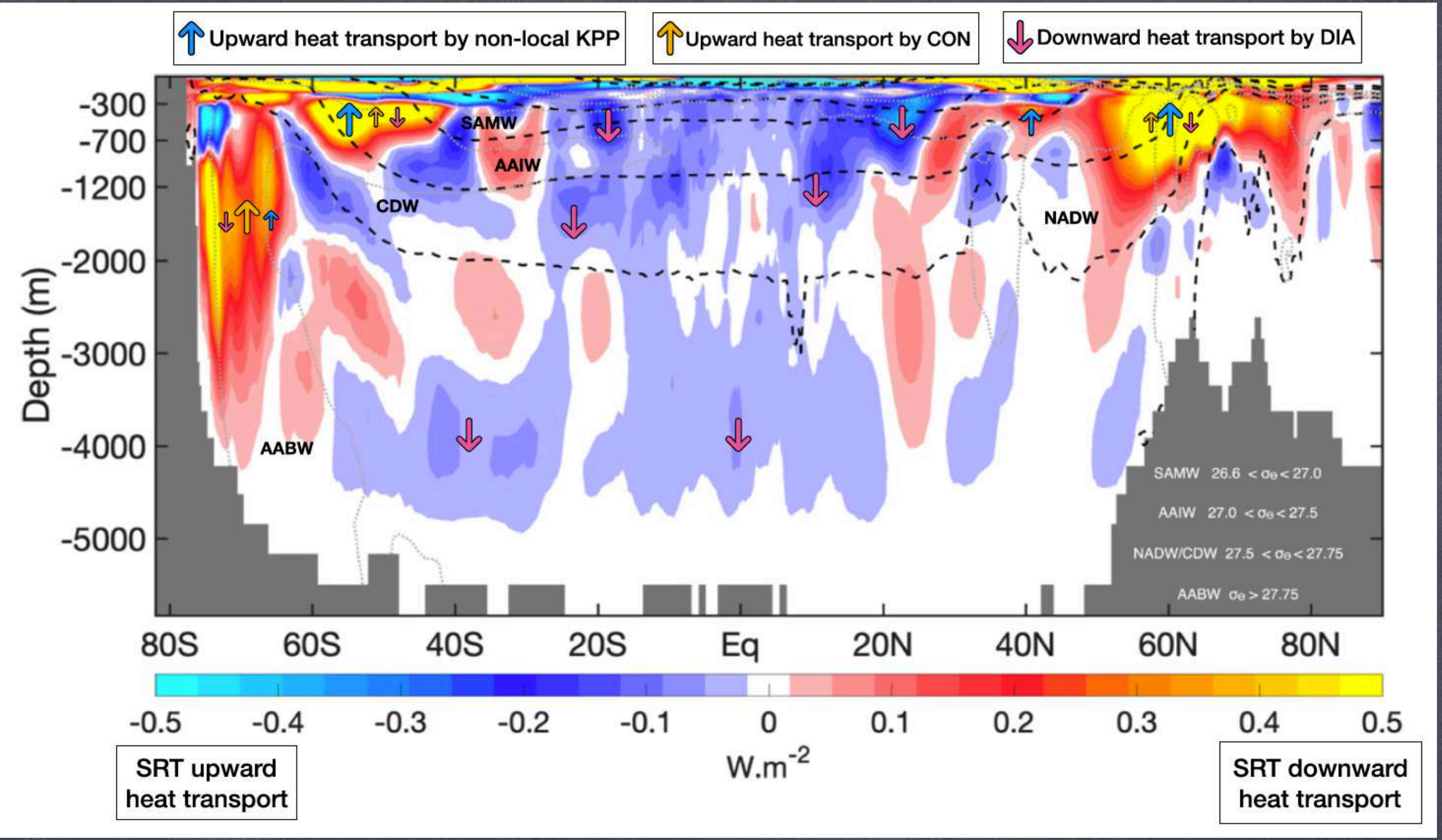
ADV + **EIT** = **SRT**





Dias et al (2020)

SRT framework



Dias et al (2020)

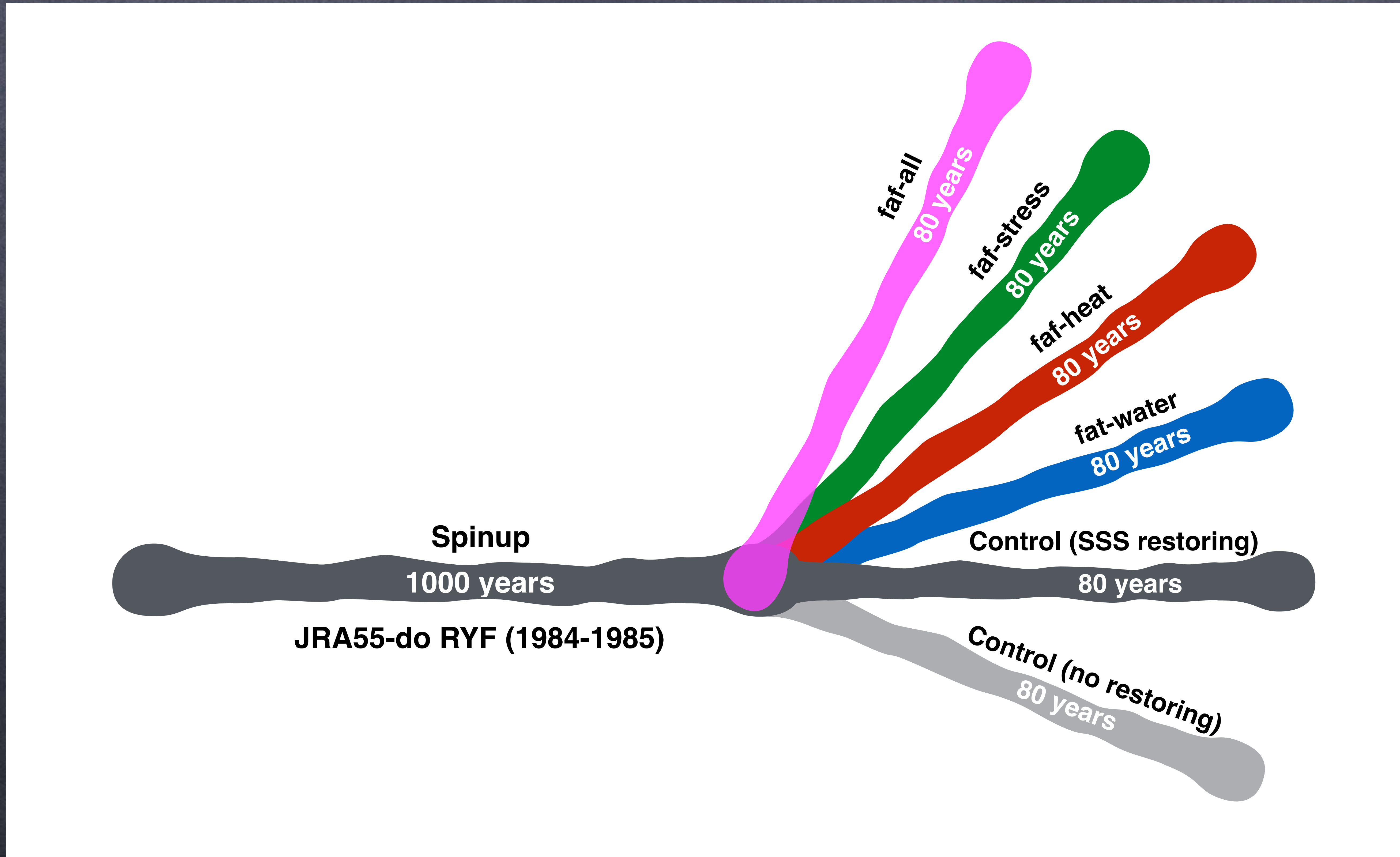
- Two regimes:

1) Deep mixed layers: counterbalance cooling from vertical mixing processes (KPP, SUB, CON) ➡️ 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

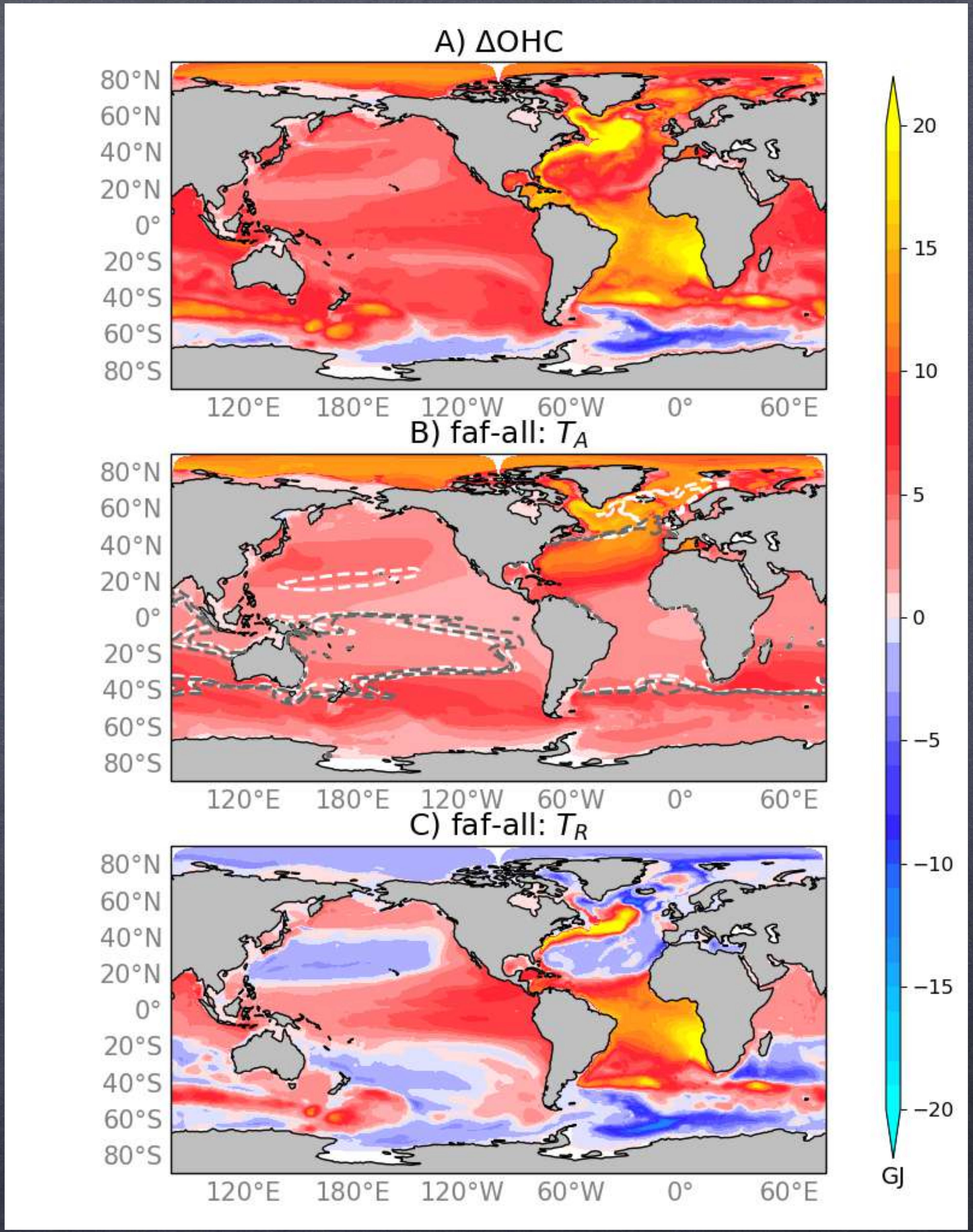


Ocean Heat Content changes:

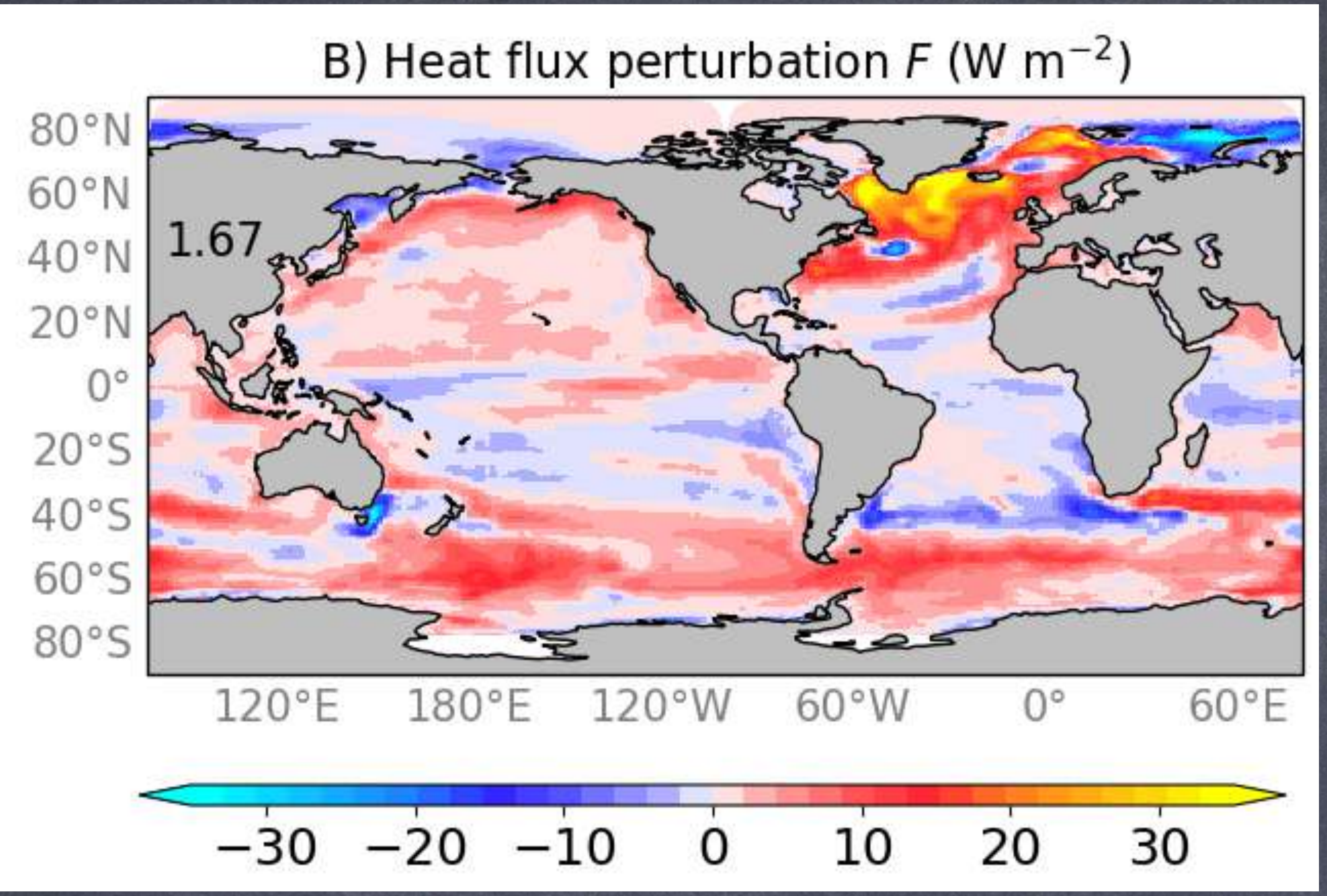
ΔOHC *faf-all* (avg years 61-80)

- 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

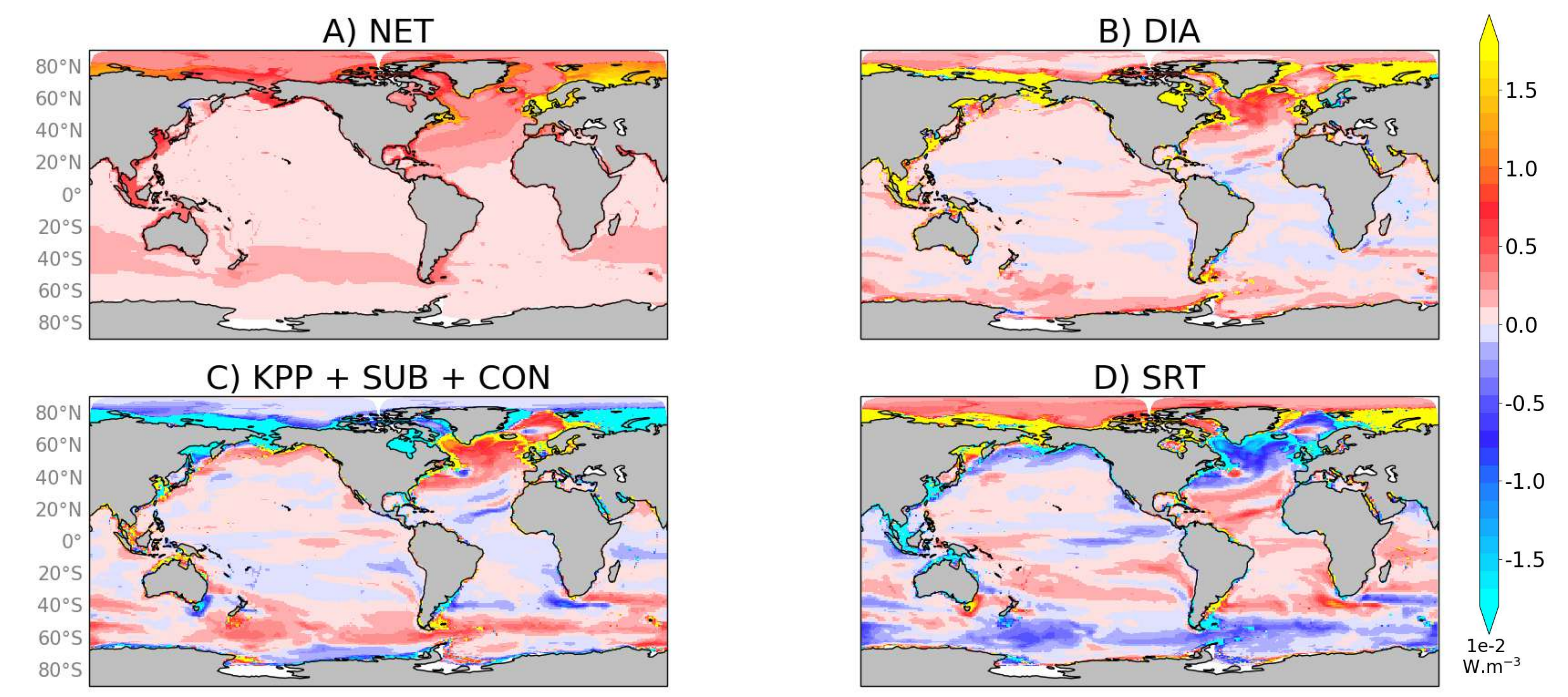
Objective: investigate the mechanisms of redistributed warming at low latitudes and along the northern boundary of the ACC



Sfc heat flux perturbation and T_A heat transport

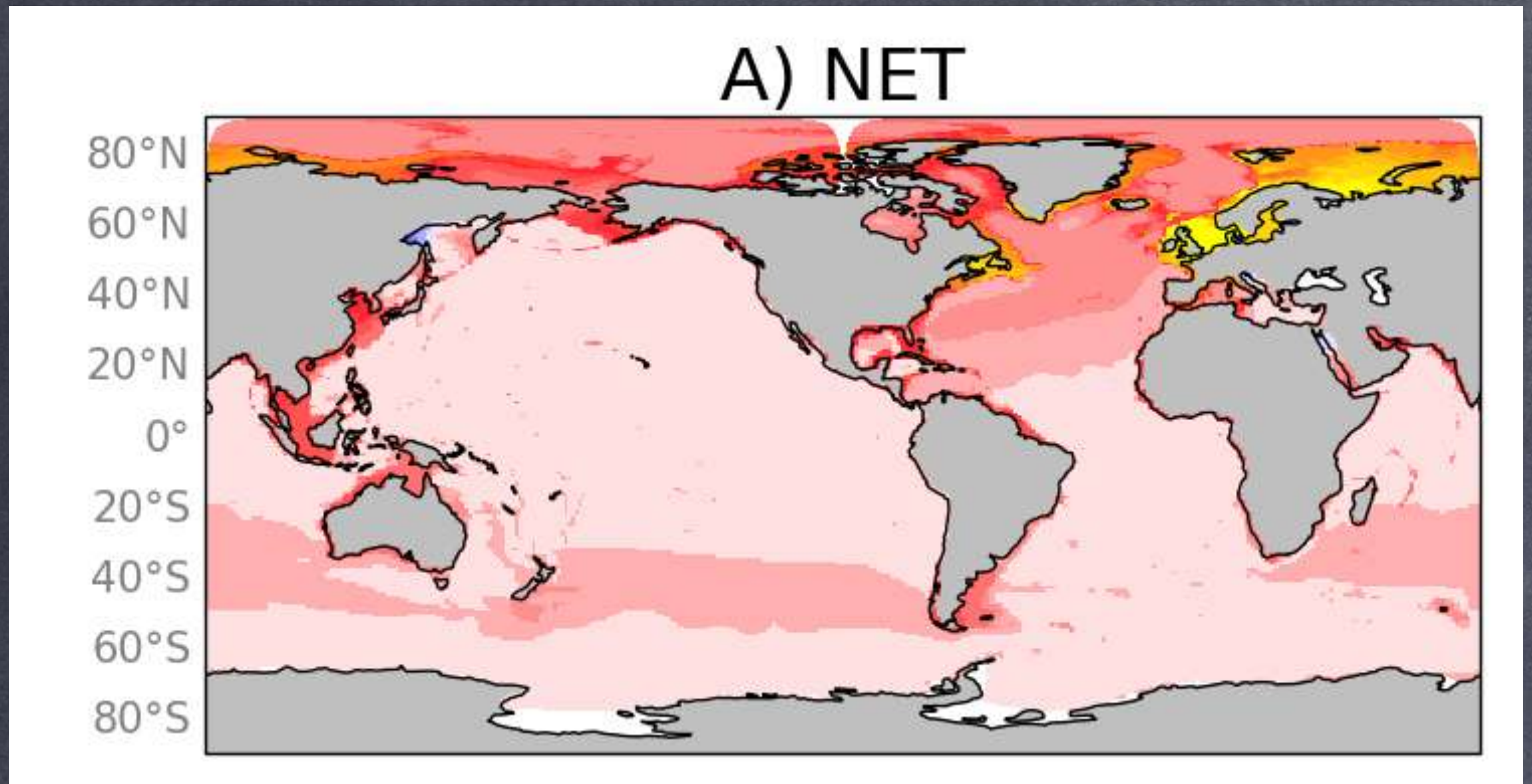


- Added heat storage (NET) at mid-latitudes and North Atlantic/Arctic
    - Heat uptake by vertical mixing processes (DIA, KPP, CON)
    - Advected equatorward by SRT



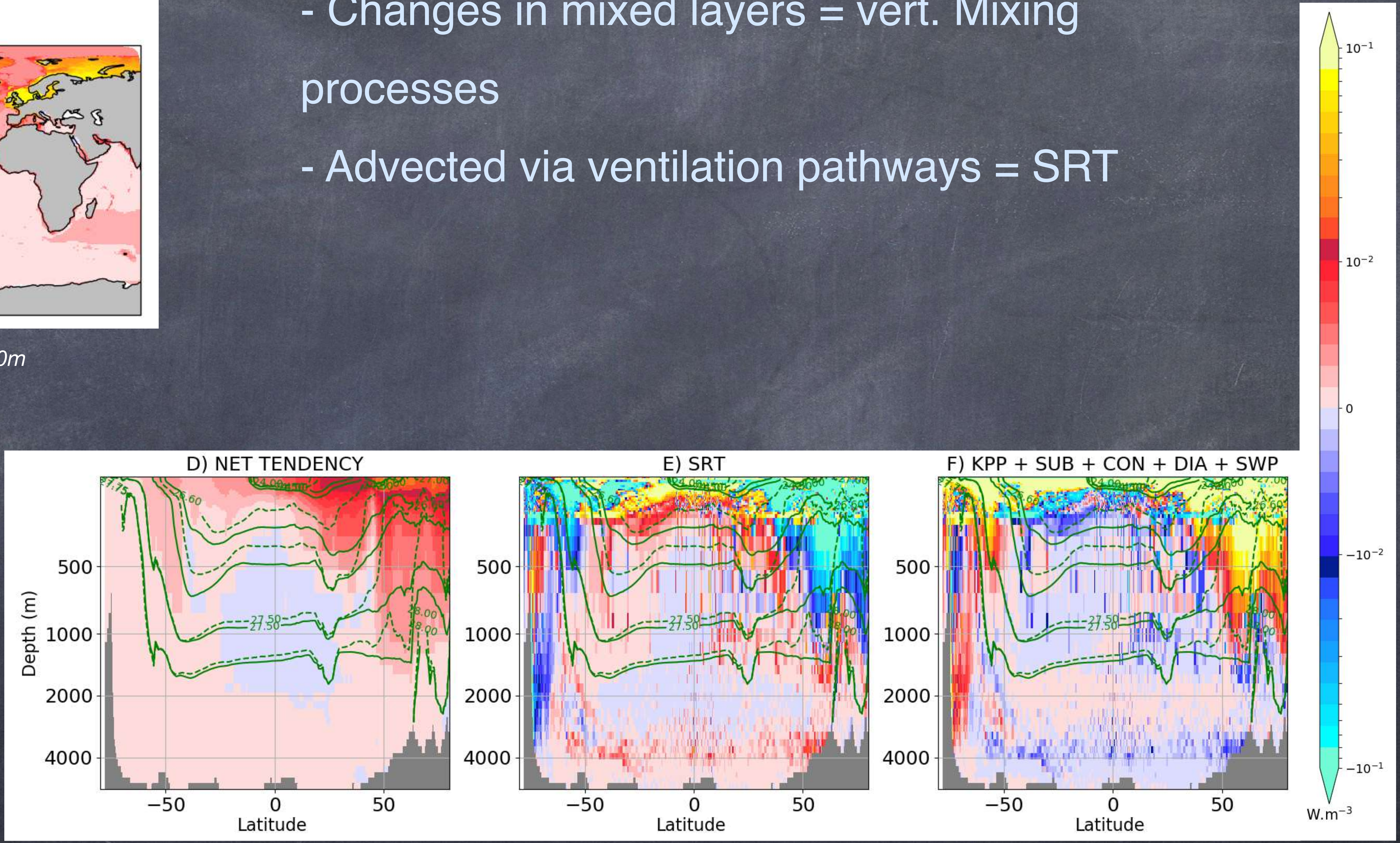
vertically-integrated 10-2000m

T_A heat transport: zonal perspective



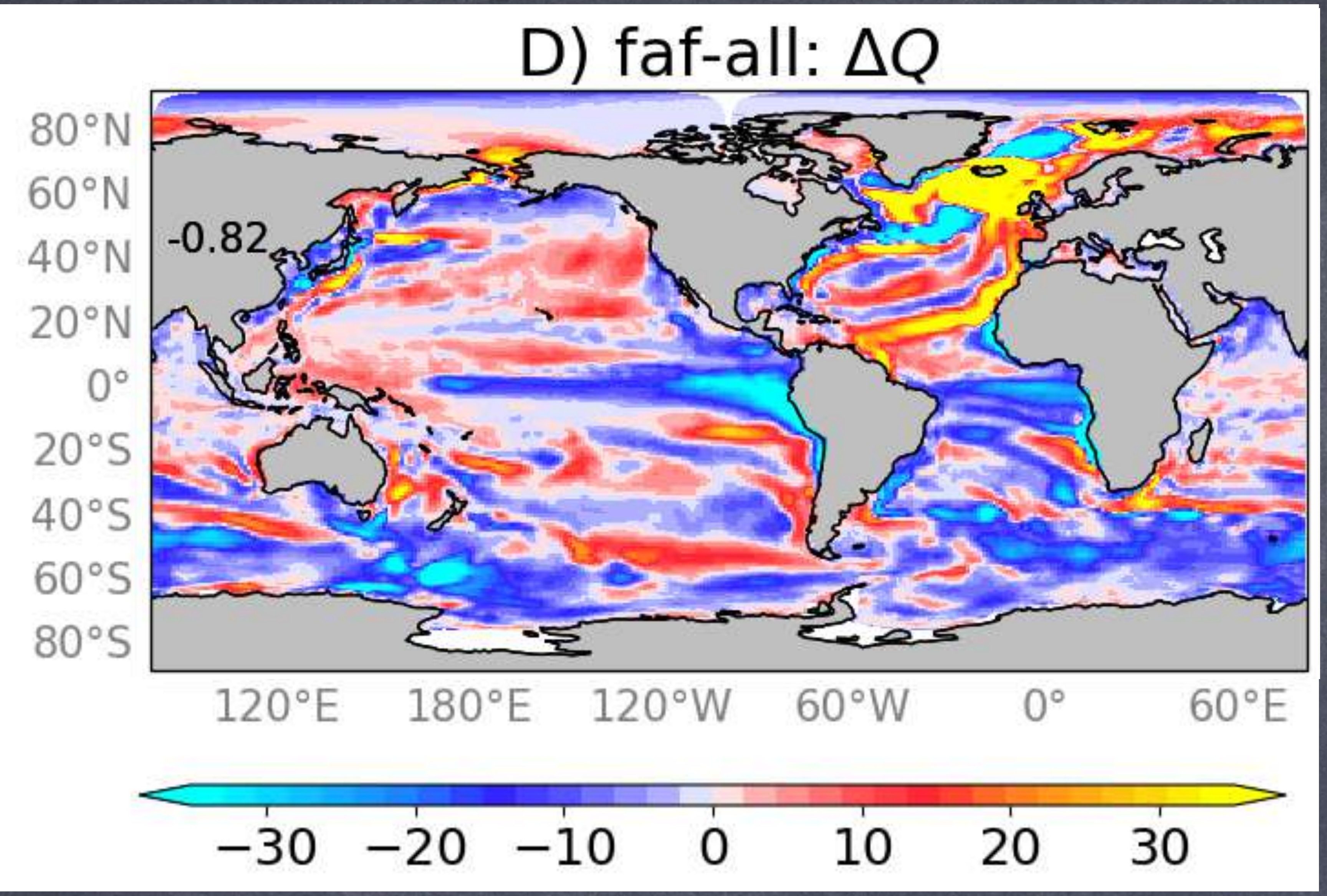
**vertically-integrated 10-2000m*

- Changes in mixed layers = vert. Mixing processes
- Advected via ventilation pathways = SRT

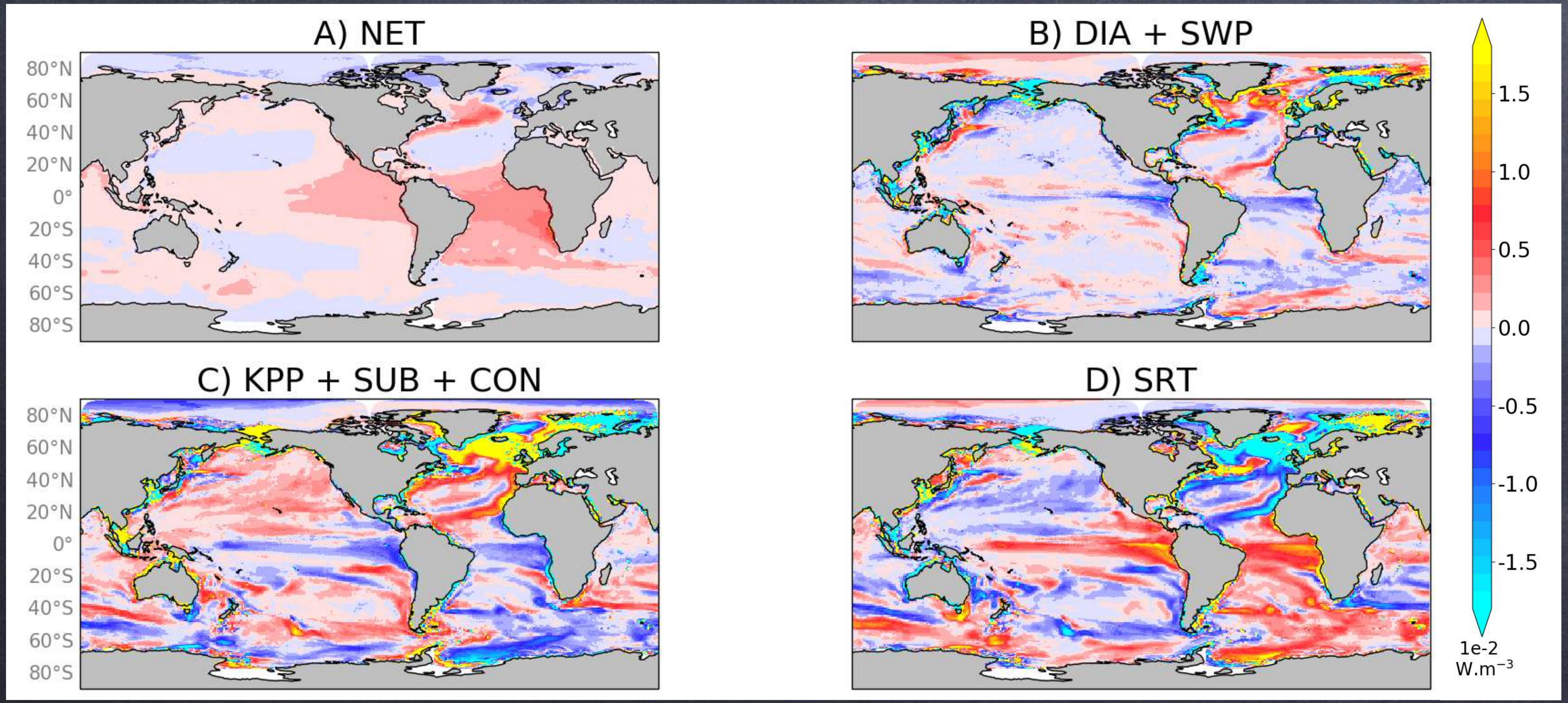


Atlantic Ocean *Zonally-integrated*

Sfc heat flux perturbation and T_R heat transport



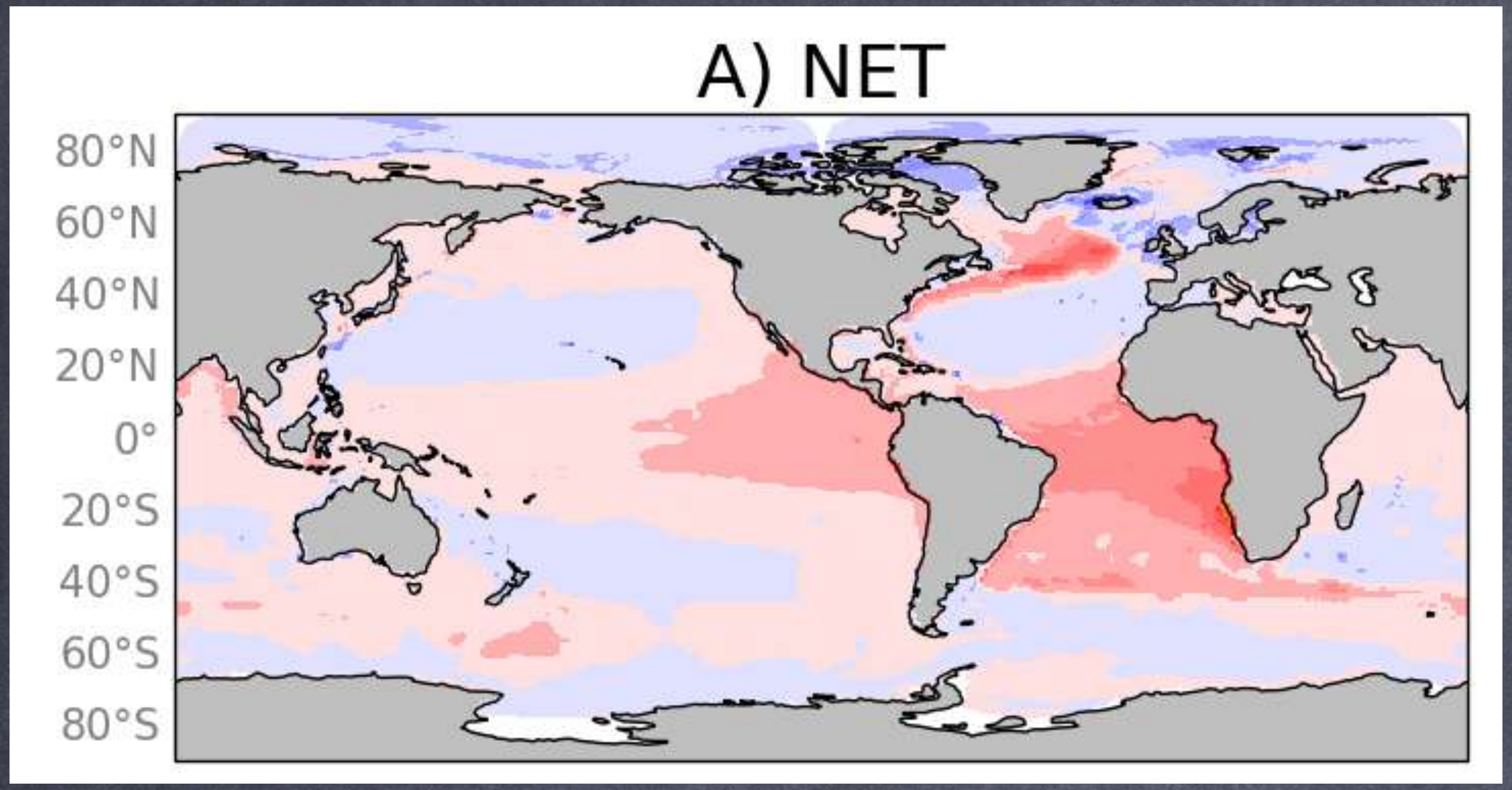
- Redistribution of heat:
  - cools subtropical gyres
  - warm tropical latitudes (+ SPNA)
  - stronger cooling (North Atlantic); warming in the South Atlantic Gyre
  - warming at Subtropical Front of the ACC



**vertically-integrated 10-2000m*

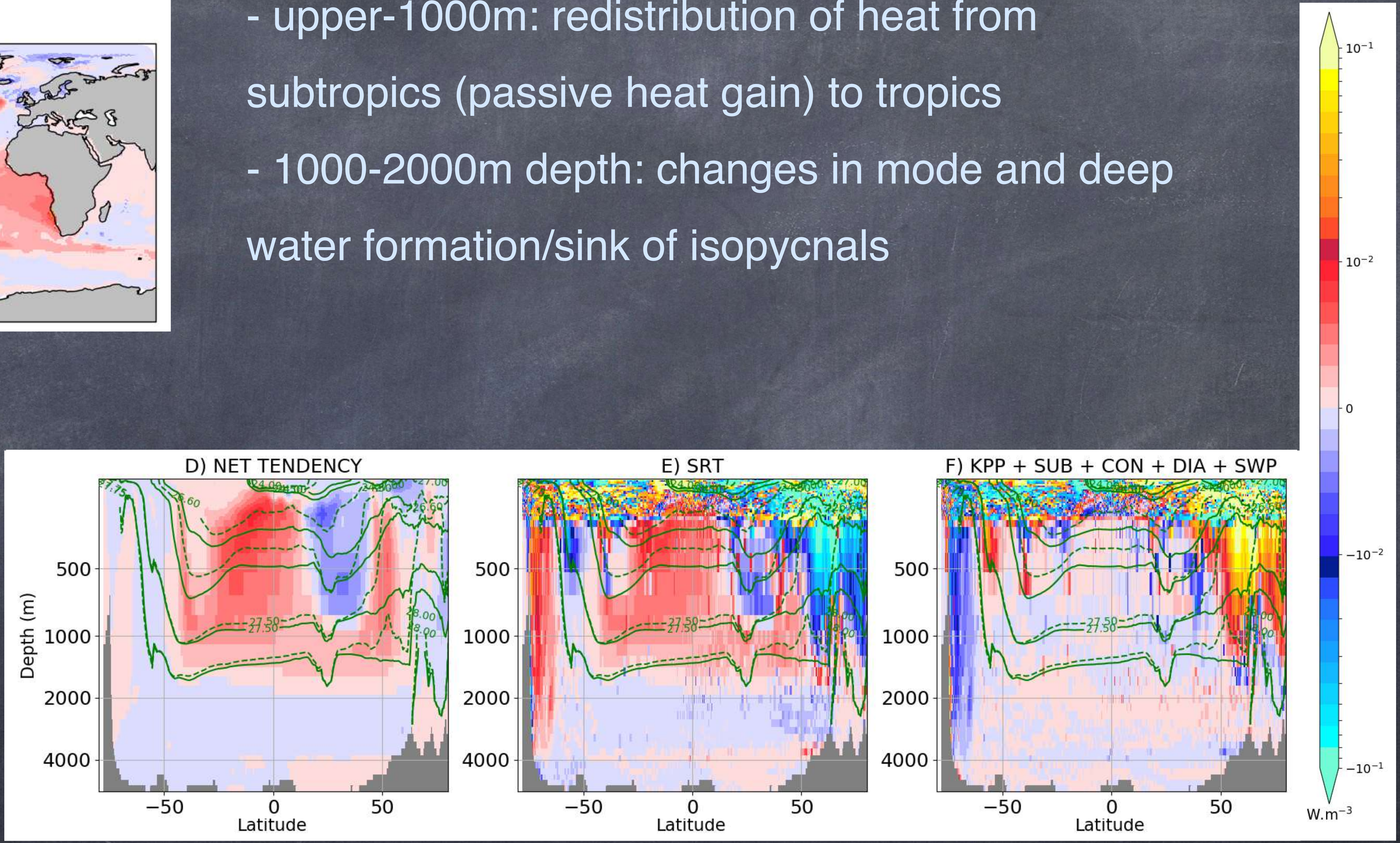
- Primarily driven by advective changes (SRT), rather than changes in vertical mixing
- results in an ocean-driven surface heat flux “feedback” (even it’s an OGCM)

T_R heat transport: zonal perspective



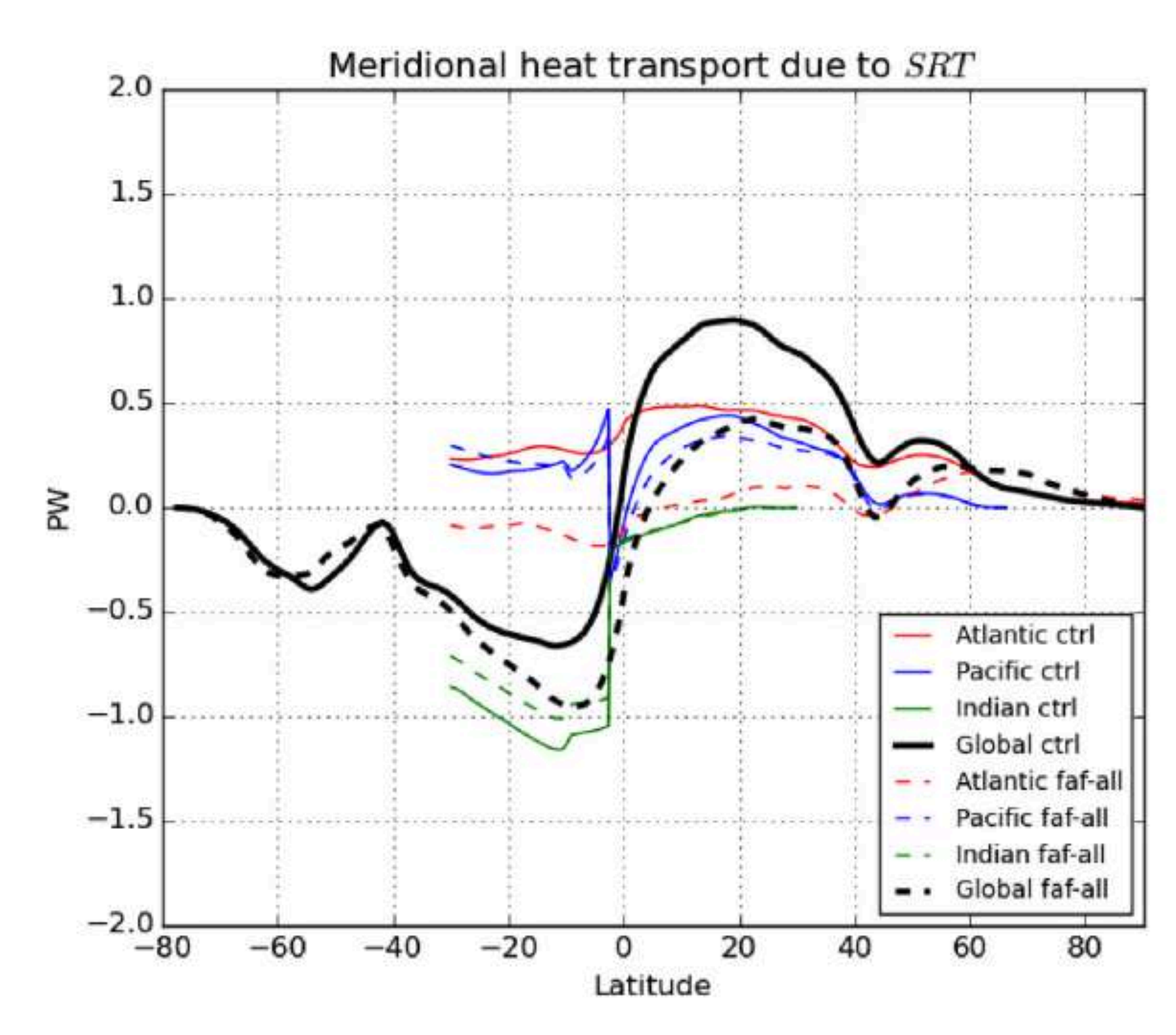
*vertically-integrated 10-2000m

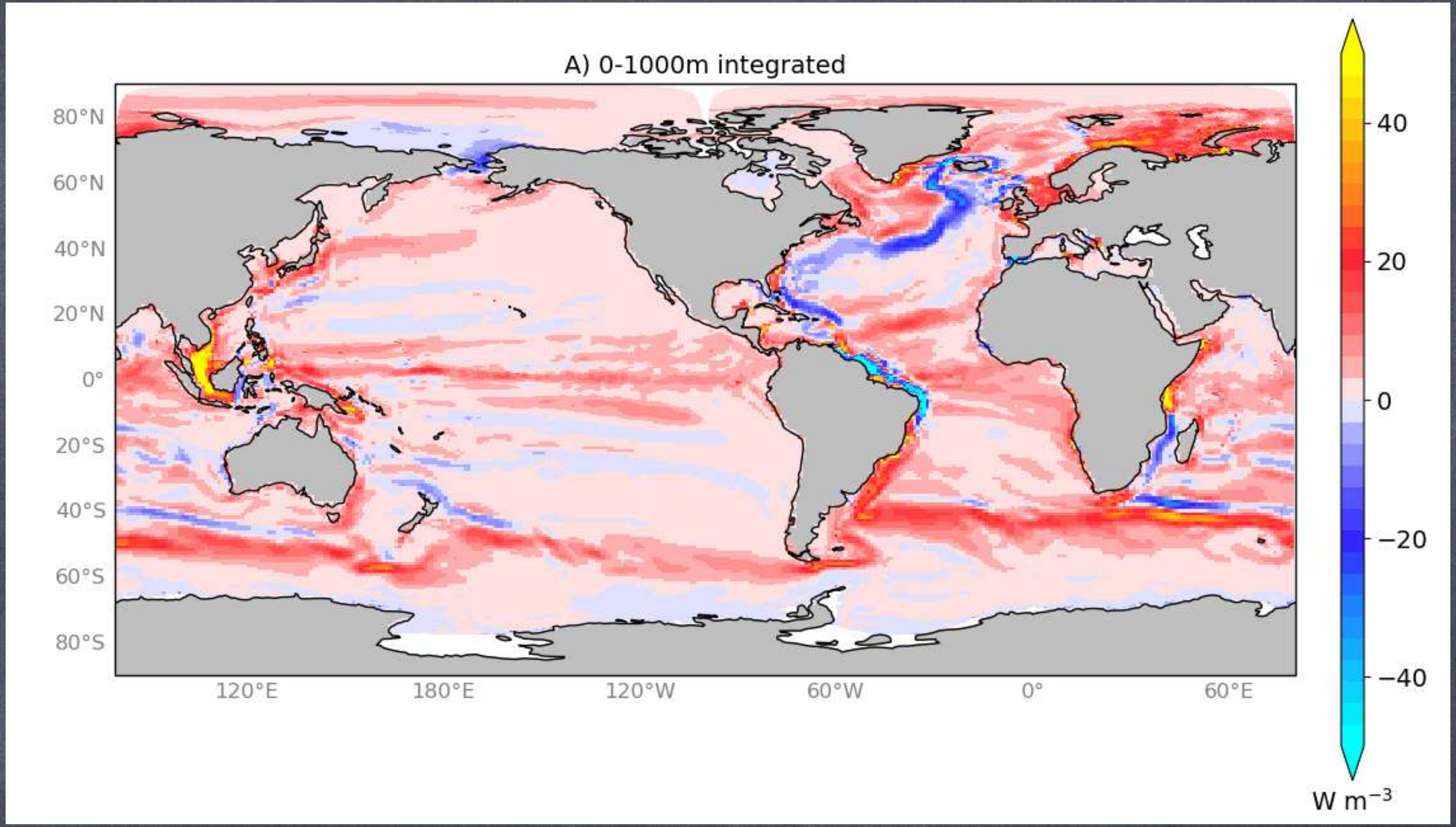
- upper-1000m: redistribution of heat from subtropics (passive heat gain) to tropics
- 1000-2000m depth: changes in mode and deep water formation/sink of isopycnals



Atlantic Ocean *Zonally-integrated*

Mechanisms of heat redistribution

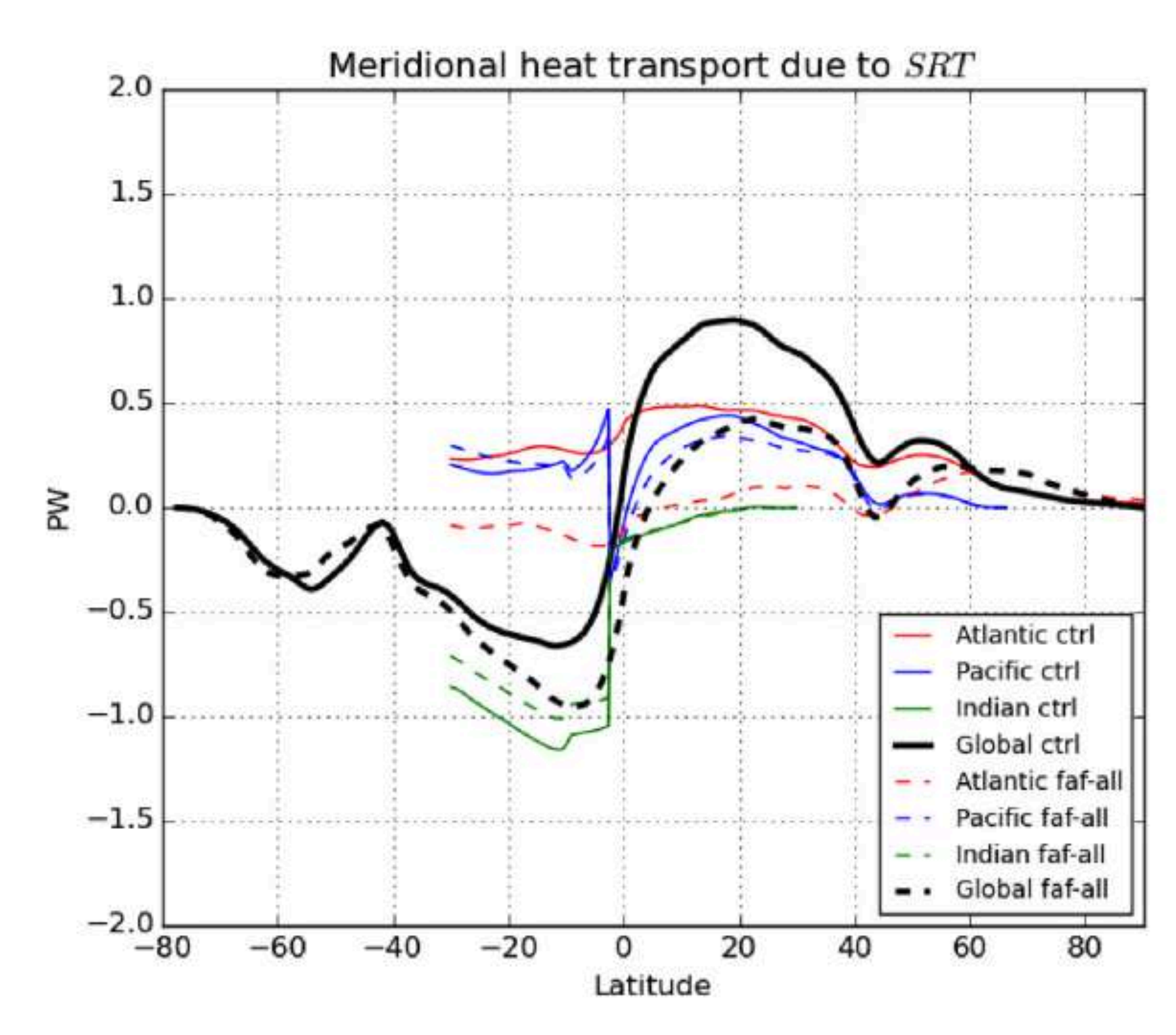


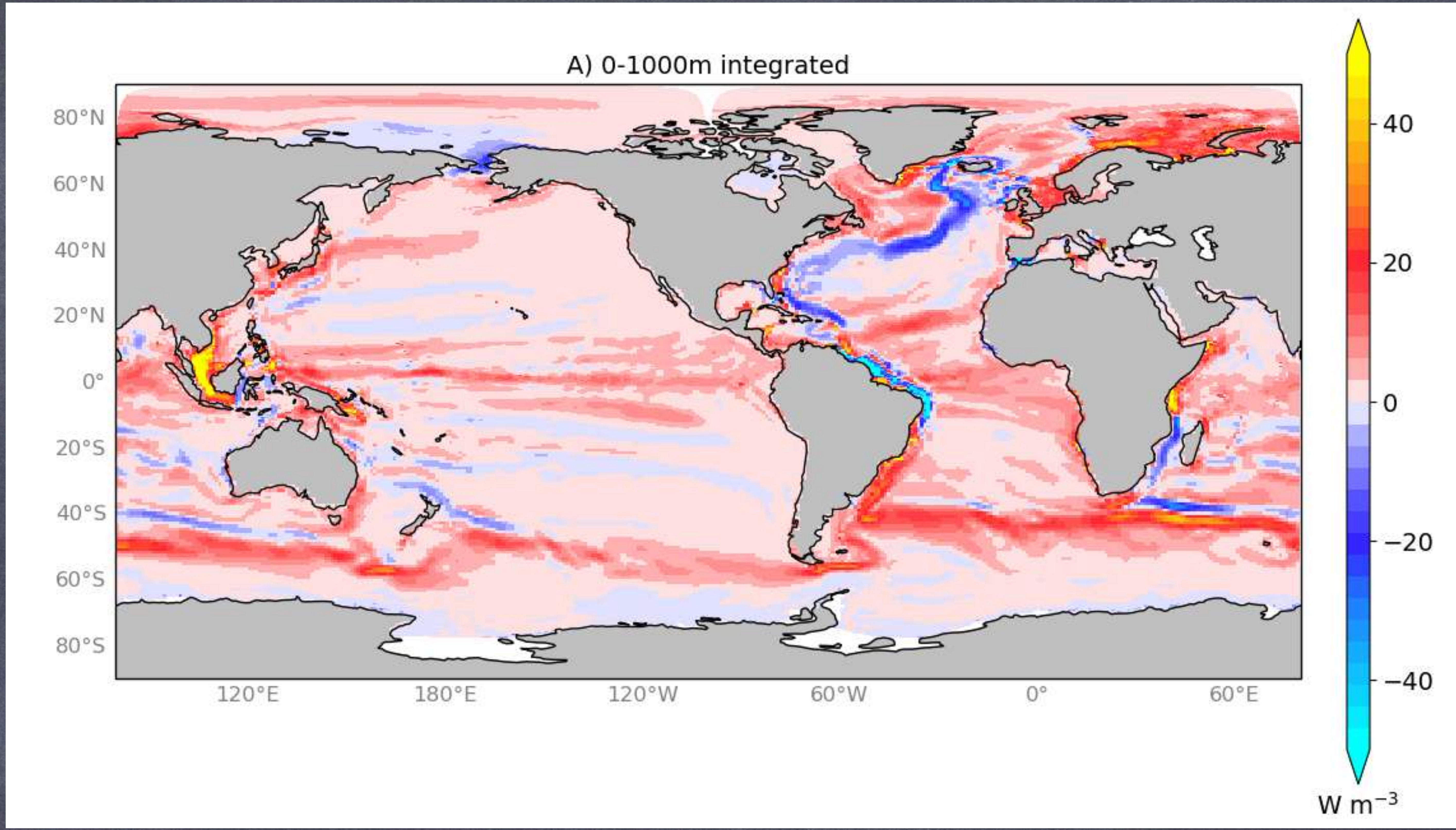


- Decrease of poleward SRT by the Gulf Stream (and North Brazil/Guiana C.)
- Increase of SRT via EBCs and Equatorial Currents

1) Reduced poleward heat transport Northern Hemisphere = Tropical warming

Mechanisms of heat redistribution





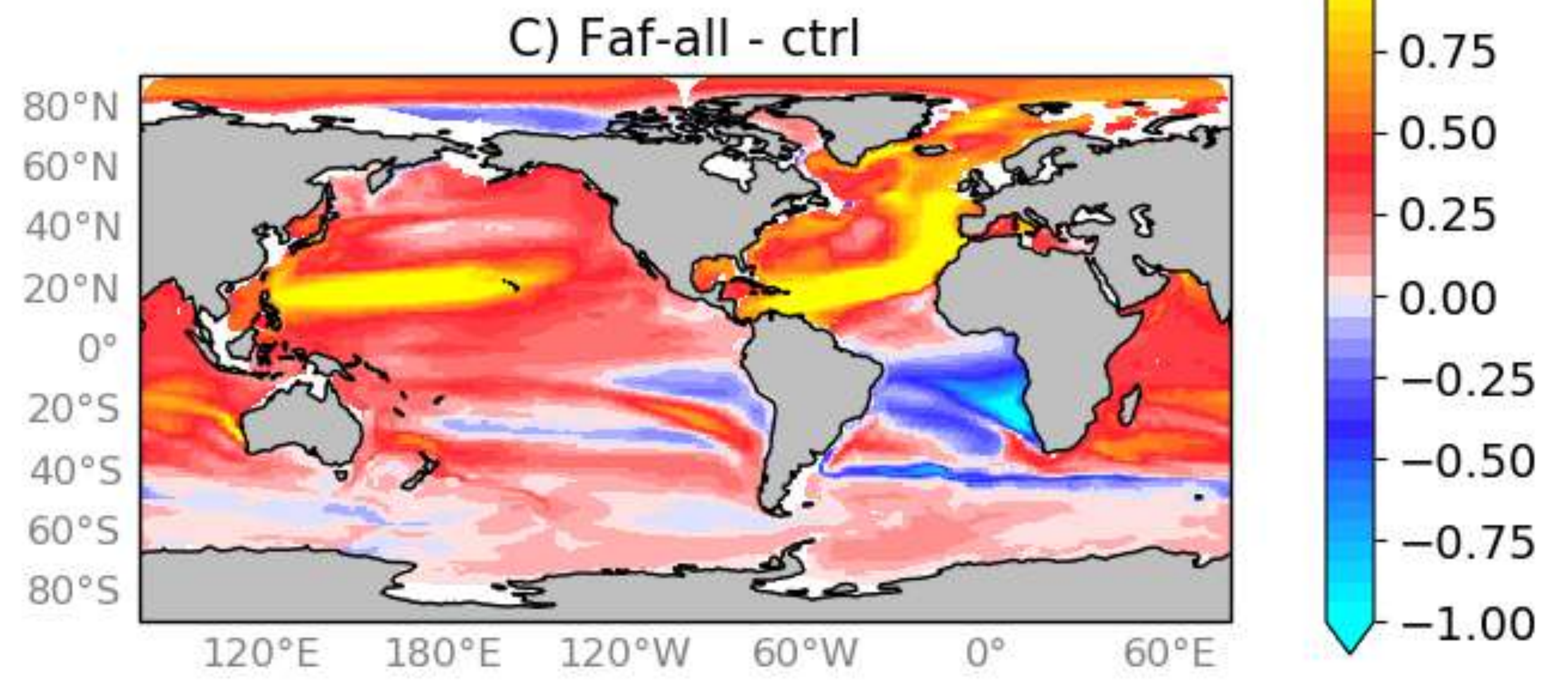
- Increase of poleward SRT by Brazil Current:
   - part of the heat goes back to tropics via stronger transport by EBCs
   - part converges at the subtropical front

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

$S = [\rho_{300m} - \rho_{sfc}]$



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 2xCO_2 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 attention!

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