5 Framework of CO_2 flux drivers

PRE-LIMINARY!!!

Purpose of CO_2 flux separation The previous analysis of thermal, physical and biological controls of the Southern Ocean carbon sink asks for an estimate on the relative contributions of change. As the interconnected processes always influence and change each other directly, a clear and clean separation cannot be taken precision, but rather for an *estimate of the first-order drivers* in CO_2 flux. In this chapter, I adapt the CO_2 flux diagnostics framework from Lauderdale et al. [2016a] for transient changes, as the heat flux formulation in the existing framework contradicts the logic of the thermal pump.

5.1 Explanation of the framework and its assumptions

Lauderdale et al. [2016a] assumes an euphotic zone zonal carbon budget box where at the upper boundary CO_2 enters and at the lower boundary biology export production leaves the system. The CO_2 flux with the atmosphere is further linearly decomposed into heat flux and fresh water contributions. From knowing the actual CO_2 flux, the residual is calculated and attributed to ocean circulation and changes in atmospheric pCO_2:

$$
\begin{aligned}
\mathrm{CO_2flux} = &\underbrace{\underbrace{\gamma_\theta \frac{\overline{F_{\mathrm{heat}\,pi,timmean}}}{\rho C_p}}_{\text{climatological heat flux}} + \underbrace{\frac{\mathrm{CO_2flux}}{dpCO_2}\left(pCO_{2,\mathrm{thermal}} - pCO_2\right)}_{\text{transient temperature flux}}}_{\text{temperature flux}} \\
&+ \underbrace{\frac{F_W}{\rho_{fw}}\left(\gamma_S S + \gamma_{A_T} A_T - C_T\right)}_{\text{fresh water flux}} \\
&+ \underbrace{\left(\frac{1}{2}\text{calcium export} - \text{organic export}\right)}_{\text{biology}} \\
&+ \underbrace{\text{residual}}_{\text{circulation \& pCO2 atmospheric increase}}
\end{aligned}
$$

- **Temperature Flux**: The CO_2 flux due to temperature is separated into a contribution due to climatological long-term heat flux as in [Lauderdale et al., 2016a] and transient contribution for short-term SST changes [Takahashi, 2002].

  The climatological heat flux contribution is derived from the advection-diffusion formula and assumes a thermal equilibrium, therefore the net air-sea heat flux is a constant mean over the pre-industrial period. ρ is the potential density and C_p the heat capacity for sea-water. The linear solubility coefficients γ_θ=8.72 mmol C m^{-3} °C^{-1} is empirically diagnosed [Lauderdale et al., 2016a].

The transient temperature flux is calculated based on $pCO_{2,\text{thermal}}$ instead of pCO_2 (see section 2.5.2).

$$
\begin{aligned}
\text{CO}_2\text{flux}_{\text{thermal}} &= \text{CO}_2\text{flux}(pCO_{2,\text{thermal}}) - \text{CO}_2\text{flux}(pCO_2) \\
&= k_w \left(pCO_{2,\text{thermal}} - pCO_{2,\text{atm}} - (pCO_{2,\text{ocean}} - pCO_{2,\text{atm}})\right) \\
&= \frac{\text{CO}_2\text{flux}}{dpCO_2} \left(pCO_{2,\text{thermal}} - pCO_{2,\text{ocean}}\right)
\end{aligned}
$$

$$
pCO_{2,\text{thermal}} = \overline{pCO_2}_{runmean12months} \cdot \exp\left[0.0423°C^{-1}\left(T - \overline{T}_{pi,mean}\right)\right]
$$

- **Fresh water flux**: The formulation of CO_2 flux changes due to freshwater changes remains unchanged. The empirically diagnosed linear solubility coefficients γ_S=-5.93 mmol C m^{-3} psu^{-1} and γ_{A_T}=+0.81 mmol C m^{-3} (mmol eq)$^{-1}$ reflect dilution effects: When freshwater is added (F_W>0), the alkalinity concentration decreases which increases CO_2 flux and the DIC (C_T) concentration decreases which decreases CO_2 flux. Due to opposing signs for alkalinity and DIC, the fresh water CO_2 nearly annihilates [Lauderdale et al., 2016a].

- **Biology**: There is a bug-fix impacts of export due to primary production. All particulate matter that sinks below the euphotic zone boundary of 90m is considered to contribute to the biological CO_2 flux. The soft-tissue pump takes up DIC and transports it out of euphotic zone by organic matter export and thereby increases CO_2 flux, whereas the calcium carbonate counter pump does the same, but decreases alkalinity by two units in the euphotic zone which results in an increase in CO_2 flux.

- **Residual**: Knowing the total CO_2 flux and the processes explained above, I can calculate the residual to attribute changes in circulation, e.g. increased upwelling would supply more DIC to the euphotic zone which would then increase CO_2 flux. Comparing to the control simulation, the residual also comprises the CO_2 increase due to increase $pCO_{2,\text{atm}}$. [Note: I would really like to separated this! Any idea how?]

This approach assumes:

- steady state of C_{sat} over seasonal cycle [Lauderdale et al., 2016a]
- all changes in DIC in the box directly reflect a change 1:1 in CO_2 flux

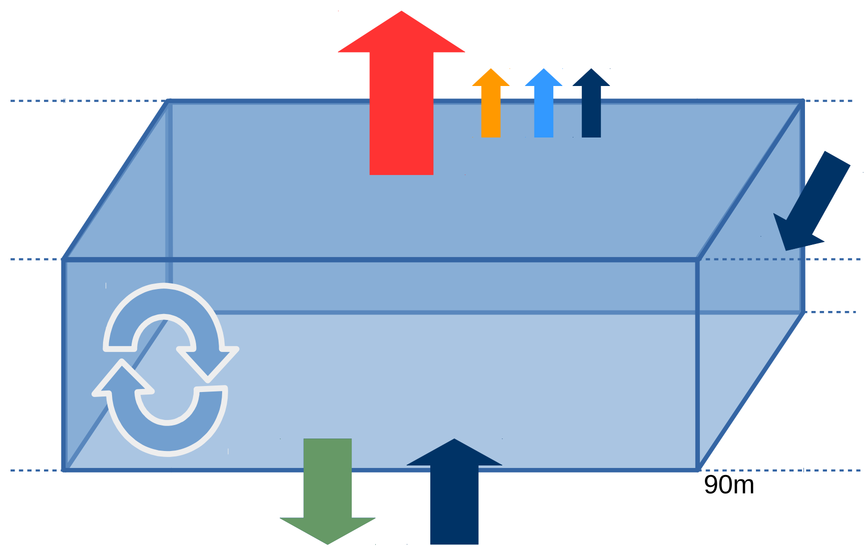

Figure 27: Schematic illustration of CO_2 flux separation after [Lauderdale et al., 2016a]; it assumes a well-mixed zonal carbon box of the upper-ocean, where CO_2 flux (red) is separated in contributions due to heat flux (orange), freshwater (light blue), climate change (gray), biology (green) and a residual for circulation (dark blue)

- no change of pCO_2(Alk,DIC) regime, no shift to different part of Deffeyes diagrams
- linearizations of non-linear processes
- residual as combined contribution of circulation and CO_2 due to atmospheric increase

5.2 Validation of the framework in the pre-industrial control state

Everything below needs a redo!! Except for figures fig. 28 - 30
Description (fig. 28)

5.3 Application of the framework in historical 1980-2004

Description (fig. 29)
Changes in climate change (fig. 30)

5.4 Internal Variability in CO_2 flux drivers

timstd map sigma DIV

5.5 Quantifying drivers in positive and negative CO_2 flux trends

Internal variability in circulation dominates over biology By applying the framework from [Lauderdale et al., 2016a] to the chosen negative and positive carbon sink trends, I aim to separate the relative contribution of first-order driving mechanisms.

The mean state CO_2 flux due to biology and circulation drive and equalize the carbon system (Table 1). Freshwater contribution is negligible, heat flux has a low mean state and climate change predictably has a negative contribution. Looking at internal variability changes importance of contributors: Heat flux, which has a large relative internal variability, becomes more relevant and circulation variations much larger than biology. This suggests that the impact of circulation on the carbon sink is more variable than the impact of biology.

Contributions to positive CO_2 flux trend figures: SH polar, co2flux, heatflux, bio, residual

Contributions to negative CO_2 flux trend figures: SH polar, co2flux, heatflux, bio, residual

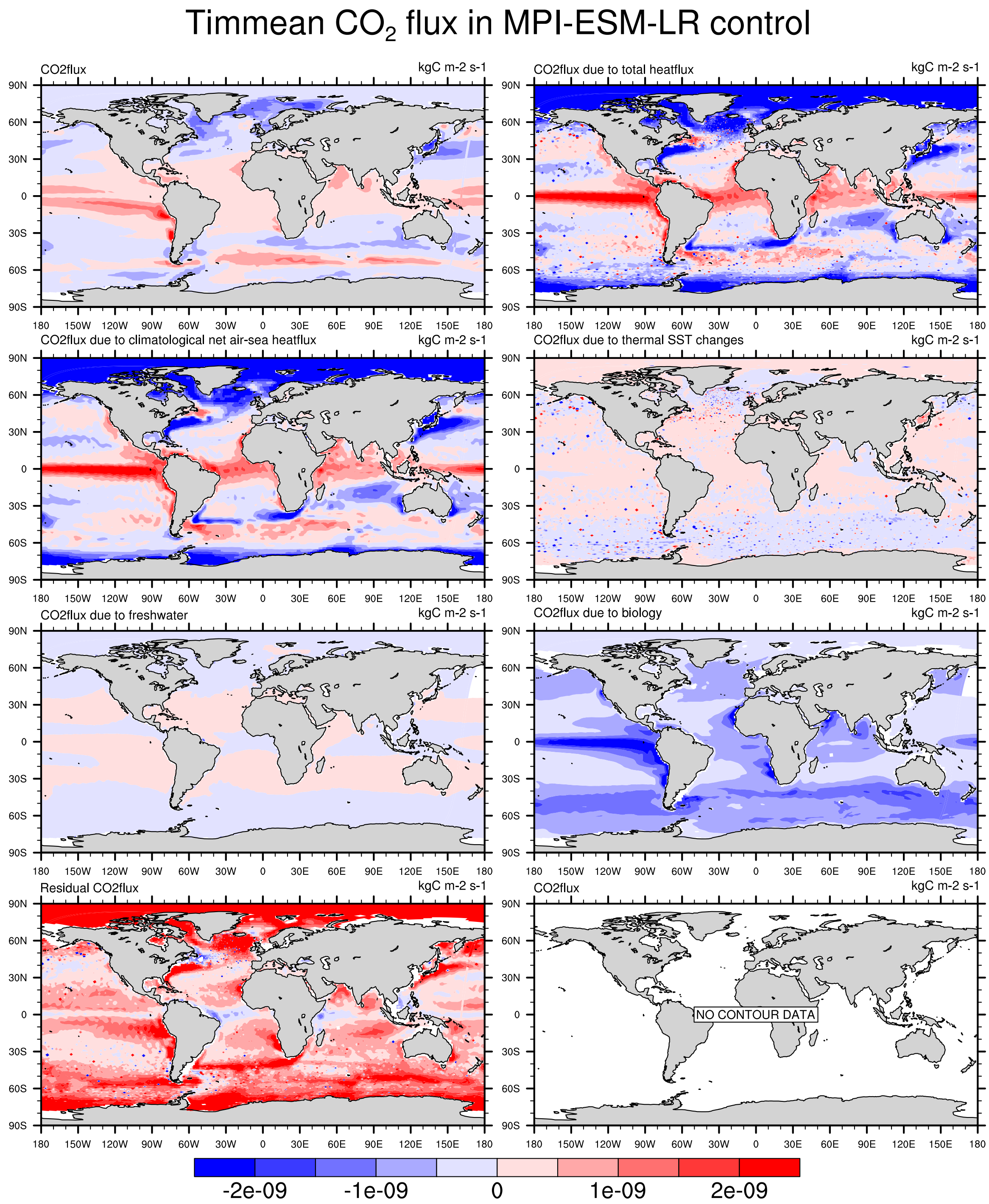

Figure 28: CO_2 flux separation in MPI-ESM LE control

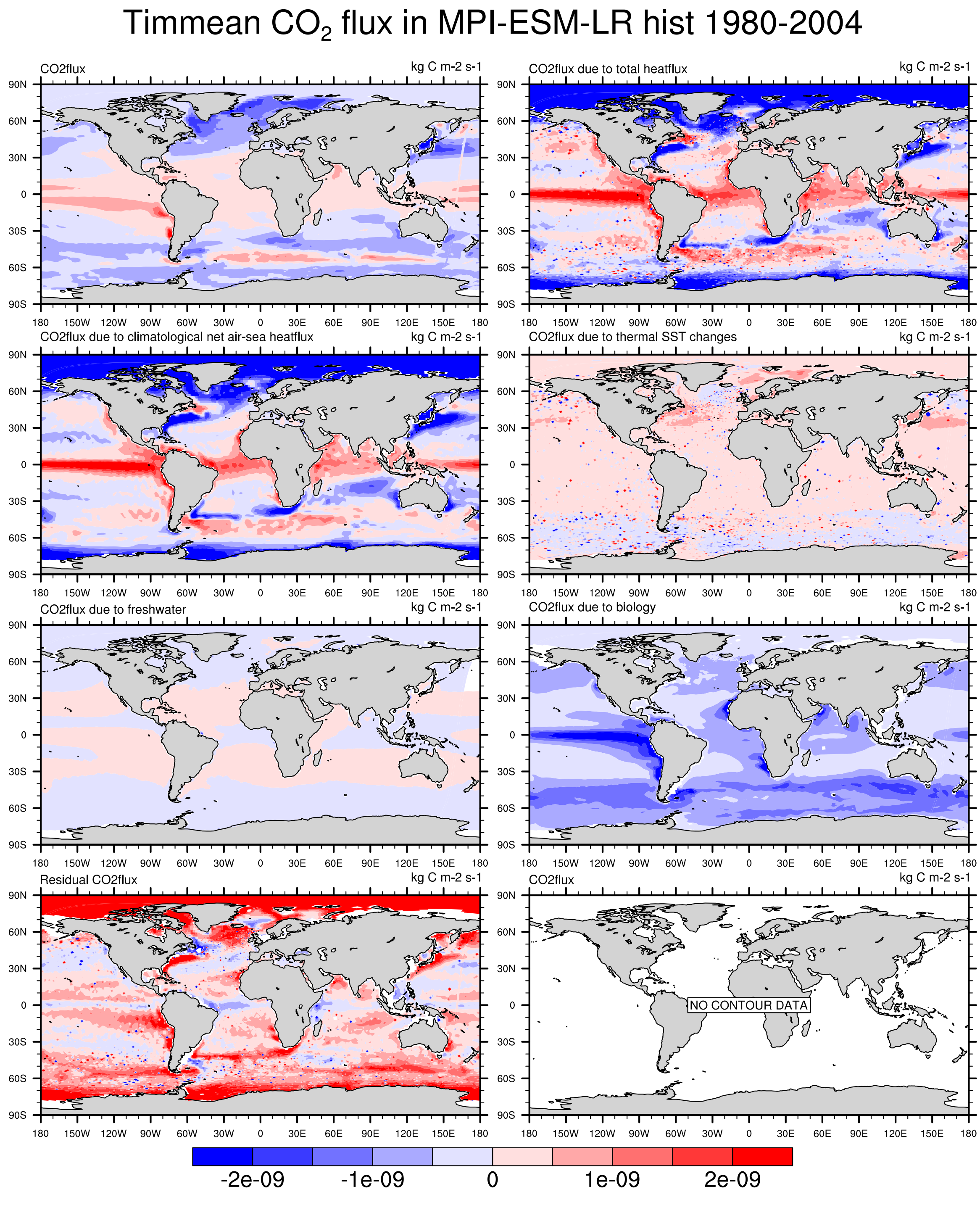

Figure 29: CO_2 flux separation in MPI-ESM LE historical period 1980 - 2004

50-60°S	positive carbon sink trend		negative carbon sink trend		MPI-ESM LE
	PgC/8yrs	% contribution	PgC/8yrs	% contribution	PgC/yr
CO_2 flux	-0.43	100	0.58	100	-0.05±0.19
heat flux	0.04	-9	-0.06	-11	-0.14±0.05
fresh water	0.00	-1	-0.00	-1	-0.04±0.00
biology	-0.17	39	0.17	30	-0.76±0.08
climate change	-0.06	13	-0.01	-2	-0.22±0.02
circulation	-0.26	59	0.48	60	1.11±0.12

Table 1: The trends of CO_2 flux and its contributions for the zonal band of 50-60°S indicate circulation as the most variable contribution

40-50°S	positive carbon sink trend		negative carbon sink trend		MPI-ESM LE
	PgC/8yrs	% contribution	PgC/8yrs	% contribution	PgC/yr
CO_2 flux	-0.15	100	-0.03	100	-0.46±0.06
heat flux	-0.04	25	0.12	-366	0.13±0.06
fresh water	0.01	-4	-0.01	27	0.02±0.00
biology	0.03	-19	-0.07	197	1.09±0.03
climate change	-0.03	17	-0.01	16	-0.23±0.01
circulation	-0.12	83	-0.08	225	0.72±0.06

Table 2: The trends of CO_2 flux and its contributions for the zonal band of 40-50°S indicate circulation as the dominant driver over biology and highlights the importance of heat fluxes at lower latitudes

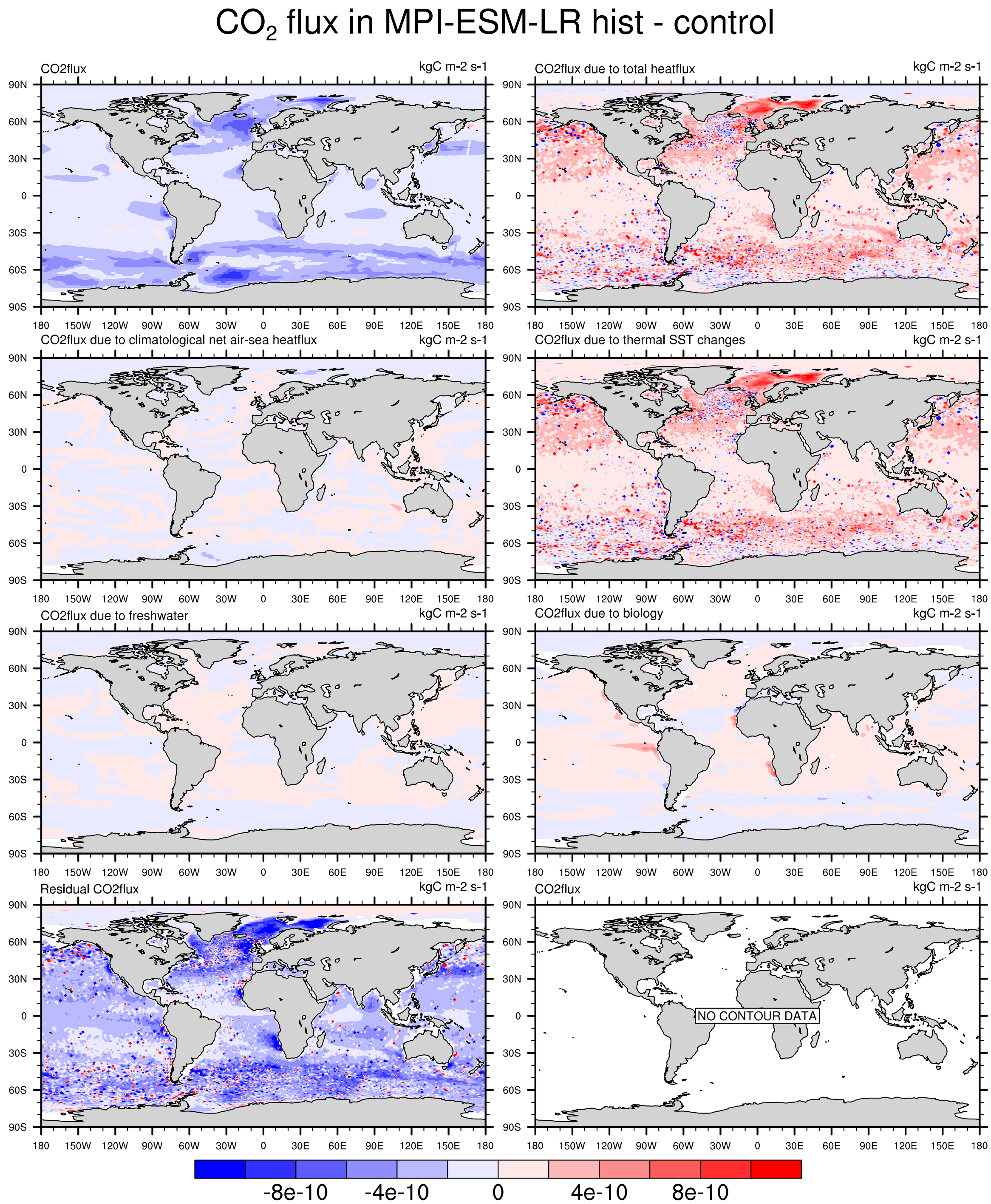

Figure 30: Changes in CO_2 flux separation in MPI-ESM LE: historical period 1980 - 2004 minus control