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Supplement of

Drivers of future seasonal cycle changes in oceanic $p\mathrm{CO}_2$

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Text S1.

We construct the full pCO_2 Taylor expansion decomposition starting with the carbonate chemistry definitions of DIC and TA as in Egleston et al. (2010):

$$DIC = [CO_2] + \frac{K_1[CO_2]}{[H^+]} + \frac{K_1K_2[CO_2]}{[H^+]^2} \tag{1}$$

$$TA = \frac{K_1[CO_2]}{[H^+]} + 2\frac{K_1K_2[CO_2]}{[H^+]^2} + \frac{B_{tot}K_b}{(K_b+[H^+])} - [H^+] + \frac{K_w}{[H^+]} \tag{2}$$

Where K_1 and K_2 are defined as Millero et al. (2006), K_w as Millero (1995) and K_b according to Dickson (1990). From Eq.(1) we can obtain $[H^+]$ and from Eq.(2) we get $[CO_2]$ respectively as:

$$[H^+] = \frac{K_1[CO_2] + \sqrt{K_1^2[CO_2]^2 + 4K_1K_2[CO_2](DIC-[CO_2])}}{2(DIC-[CO_2])} \tag{3}$$

$$[CO_2] = \frac{[H^+]^2}{K_1[H^+]+2K_1K_2}\left(TA - \frac{B_{tot}K_b}{(K_b+[H^+])} + [H^+] - \frac{K_w}{[H^+]}\right) \tag{4}$$

For $[H^+]$ the positive solution was chosen; the negative root gives a result far from real values. From Eq.(3) and Eq.(4) we can make a Talyor's expansion of $[H^+]$ and $[CO_2]$ respectively as:

$$\delta[H^+] = \left.\frac{\partial[H^+]}{\partial DIC}\right|_{\substack{\overline{CO_2},\overline{DIC}\\ \overline{T},\overline{S}}}\delta DIC + \left.\frac{\partial[H^+]}{\partial[CO_2]}\right|_{\substack{\overline{CO_2},\overline{DIC}\\ \overline{T},\overline{S}}}\delta[CO_2] + \left.\frac{\partial[H^+]}{\partial T}\right|_{\substack{\overline{CO_2},\overline{DIC}\\ \overline{T},\overline{S}}}\delta T + \left.\frac{\partial[H^+]}{\partial S}\right|_{\substack{\overline{CO_2},\overline{DIC}\\ \overline{T},\overline{S}}}\delta S \tag{5}$$

$$\delta[CO_2] = \left.\frac{\partial[CO_2]}{\partial TA}\right|_{\substack{\overline{TA},\overline{H}\\ \overline{T},\overline{S}}}\delta TA + \left.\frac{\partial[CO_2]}{\partial[H^+]}\right|_{\substack{\overline{TA},\overline{H}\\ \overline{T},\overline{S}}}\delta[H^+] + \left.\frac{\partial[CO_2]}{\partial T}\right|_{\substack{\overline{TA},\overline{H}\\ \overline{T},\overline{S}}}\delta T + \left.\frac{\partial[CO_2]}{\partial S}\right|_{\substack{\overline{TA},\overline{H}\\ \overline{T},\overline{S}}}\delta S \tag{6}$$

The overbars indicate the mean values of the variables in which the derivatives are evaluated. Finally, we insert $\delta[H^+]$ from Eq.(5) into Eq.(6), to get $[CO_2]$ in terms of DIC, TA, T and S:

$$\begin{aligned}
\delta[CO_2] = {} & \left[1 - \left.\frac{\partial[CO_2]}{\partial[H^+]}\right|_{\substack{\overline{TA},\overline{H}\\ \overline{T},\overline{S}}}\left.\frac{\partial[H^+]}{\partial[CO_2]}\right|_{\substack{\overline{CO_2},\overline{DIC}\\ \overline{T},\overline{S}}}\right]^{-1} \cdot \left[\left.\frac{\partial[CO_2]}{\partial TA}\right|_{\substack{\overline{TA},\overline{H}\\ \overline{T},\overline{S}}}\delta TA\right. \\
& + \left.\frac{\partial[CO_2]}{\partial[H^+]}\right|_{\substack{\overline{TA},\overline{H}\\ \overline{T},\overline{S}}}\left.\frac{\partial[H^+]}{\partial DIC}\right|_{\substack{\overline{CO_2},\overline{DIC}\\ \overline{T},\overline{S}}}\delta DIC \\
& + \left(\left.\frac{\partial[CO_2]}{\partial T}\right|_{\substack{\overline{TA},\overline{H}\\ \overline{T},\overline{S}}} + \left.\frac{\partial[CO_2]}{\partial[H^+]}\right|_{\substack{\overline{TA},\overline{H}\\ \overline{T},\overline{S}}}\left.\frac{\partial[H^+]}{\partial T}\right|_{\substack{\overline{CO_2},\overline{DIC}\\ \overline{T},\overline{S}}}\right)\delta T \\
& \left. + \left(\left.\frac{\partial[CO_2]}{\partial S}\right|_{\substack{\overline{TA},\overline{H}\\ \overline{T},\overline{S}}} + \left.\frac{\partial[CO_2]}{\partial[H^+]}\right|_{\substack{\overline{TA},\overline{H}\\ \overline{T},\overline{S}}}\left.\frac{\partial[H^+]}{\partial S}\right|_{\substack{\overline{CO_2},\overline{DIC}\\ \overline{T},\overline{S}}}\right)\delta S\right]
\end{aligned} \tag{7}$$

Comparing the terms from Eq.(7) to the desired Taylor's expansion:

$$\delta pCO_2 \approx \left.\frac{\partial pCO_2}{\partial DIC}\right|_{\substack{\overline{TA},\overline{DIC}\\ \overline{T},\overline{S}}}\delta DIC + \left.\frac{\partial pCO_2}{\partial TA}\right|_{\substack{\overline{TA},\overline{DIC}\\ \overline{T},\overline{S}}}\delta TA + \left.\frac{\partial pCO_2}{\partial T}\right|_{\substack{\overline{TA},\overline{DIC}\\ \overline{T},\overline{S}}}\delta T + \left.\frac{\partial pCO_2}{\partial S}\right|_{\substack{\overline{TA},\overline{DIC}\\ \overline{T},\overline{S}}}\delta S \tag{8}$$

We can identify the derivatives from Eq.(8), as follows:

$$
\begin{aligned}
\left.\frac{\partial pCO_2}{\partial TA}\right|_{\overline{TA},\overline{DIC}\atop \overline{T},\overline{S}} &= \overline{pCO}_2 \cdot \frac{-\overline{TA}_c}{\overline{DIC}\cdot\Theta - \overline{TA}_c^2} \\
\left.\frac{\partial pCO_2}{\partial DIC}\right|_{\overline{TA},\overline{DIC}\atop \overline{T},\overline{S}} &= \overline{pCO}_2 \cdot \frac{\Theta}{\overline{DIC}\cdot\Theta - \overline{TA}_c^2} \\
\left.\frac{\partial pCO_2}{\partial T}\right|_{\overline{TA},\overline{DIC}\atop \overline{T},\overline{S}} &= \overline{pCO}_2 \cdot \frac{1}{\overline{DIC}\cdot\Theta - \overline{TA}_c^2}\left[\overline{TA}_c\cdot\Big(\frac{\partial Alk_c}{\partial T} + \frac{\partial[B(OH)_4^-]}{\partial T} + \frac{\partial[OH^-]}{\partial T}\Big) - \Theta\cdot\frac{\partial(DIC-[CO_2])}{\partial T}\right] - \frac{\overline{pCO}_2\cdot}{\overline{K_0}(T,S)}\frac{\partial K_0(T,S)}{\partial T} \\
\left.\frac{\partial pCO_2}{\partial S}\right|_{\overline{TA},\overline{DIC}\atop \overline{T},\overline{S}} &= \overline{pCO}_2 \cdot \frac{1}{\overline{DIC}\cdot\Theta - \overline{TA}_c^2}\left[\overline{TA}_c\cdot\Big(\frac{\partial \overline{TA}_c}{\partial S} + \frac{\partial[B(OH)_4^-]}{\partial S} + \frac{\partial[OH^-]}{\partial S}\Big) - \Theta\cdot\frac{\partial(DIC-[CO_2])}{\partial S}\right] - \frac{\overline{pCO}_2\cdot}{\overline{K_0}(T,S)}\frac{\partial K_0(T,S)}{\partial S}
\end{aligned}
\tag{9}
$$

where $\Theta = [\mathrm{HCO_3^-}] + 4[\mathrm{CO_3^{2-}}] + \frac{[\mathrm{B(OH)_4^-}][\mathrm{H^+}]}{(\mathrm{k_b}+[\mathrm{H^+}])} + [\mathrm{H^+}] + [\mathrm{OH^-}]$ and $\overline{\mathrm{Alk}}_\mathrm{c} = [\mathrm{HCO_3^-}] + 2[\mathrm{CO_3^{2-}}]$. Below are some details of the specific concentrations derivatives.

$$
\begin{aligned}
\frac{\partial Alk_c}{\partial T,S} &= \frac{[CO_2]}{[H^+]^2}\Big(\frac{\partial k_1}{\partial T,S}[H^+] + 2k_1\frac{\partial k_2}{\partial T,S} + 2k_2\frac{\partial k_1}{\partial T,S}\Big) \\
\frac{\partial(DIC-[CO_2])}{\partial T,S} &= \frac{[CO_2]}{[H^+]^2}\Big(\frac{\partial k_1}{\partial T,S}[H^+] + k_1\frac{\partial k_2}{\partial T,S} + k_2\frac{\partial k_1}{\partial T,S}\Big) \\
\frac{\partial[B(OH)_4^-]}{\partial T} &= \frac{B_{tot}[H^+]}{(k_b+[H^+])^2}\frac{\partial k_b}{\partial T} \\
\frac{\partial[B(OH)_4^-]}{\partial S} &= \frac{B_{tot}[H^+]}{(k_b+[H^+])^2}\frac{\partial k_b}{\partial S} + \frac{k_b}{(kb+[H^+])}\frac{\partial B_{tot}}{\partial S} \\
\frac{\partial[OH^-]}{\partial T,S} &= \frac{1}{[H^+]}\frac{\partial k_w}{\partial T,S}
\end{aligned}
\tag{10}
$$

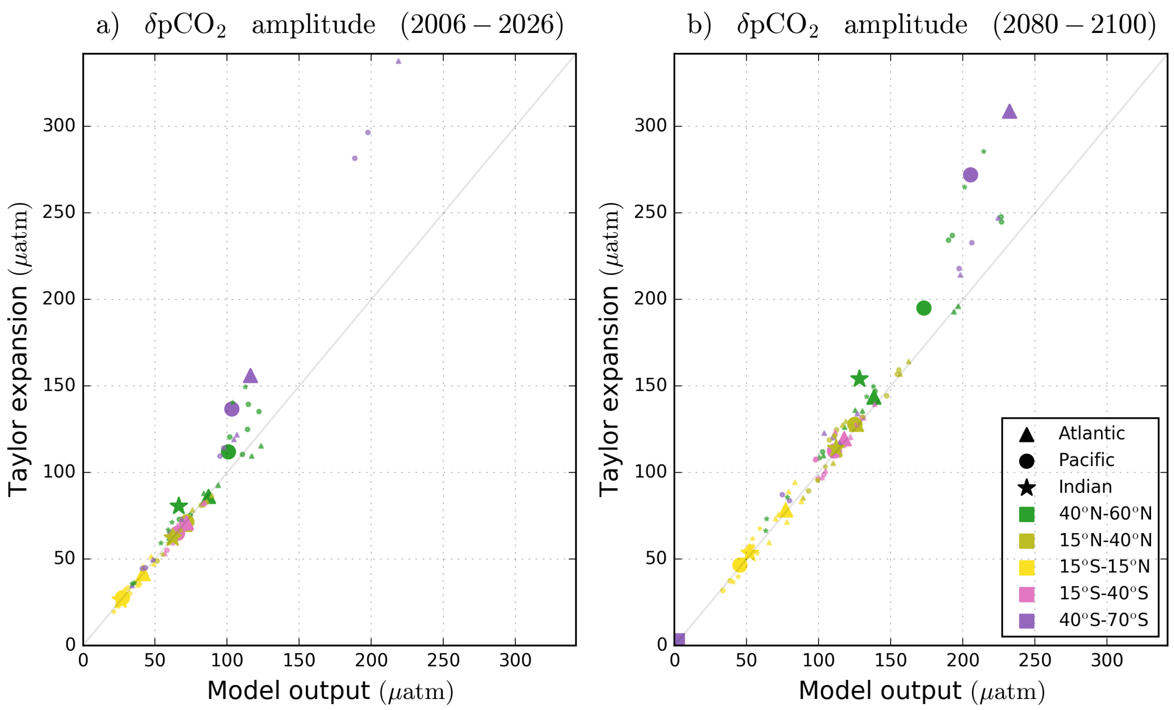

Figure S1. pCO_2 seasonal cycle amplitude calculated from model output compared to its Taylor's expansion reconstruction in a) 2006-2026 and b) 2080-2100. Different colors indicate latitudinal ranges of zonal means, for the Atlantic (triangles), Pacific (circles) and Indian (stars) ocean basins. Large symbols represent the ensemble mean, and small symbols are the result for each model separately.

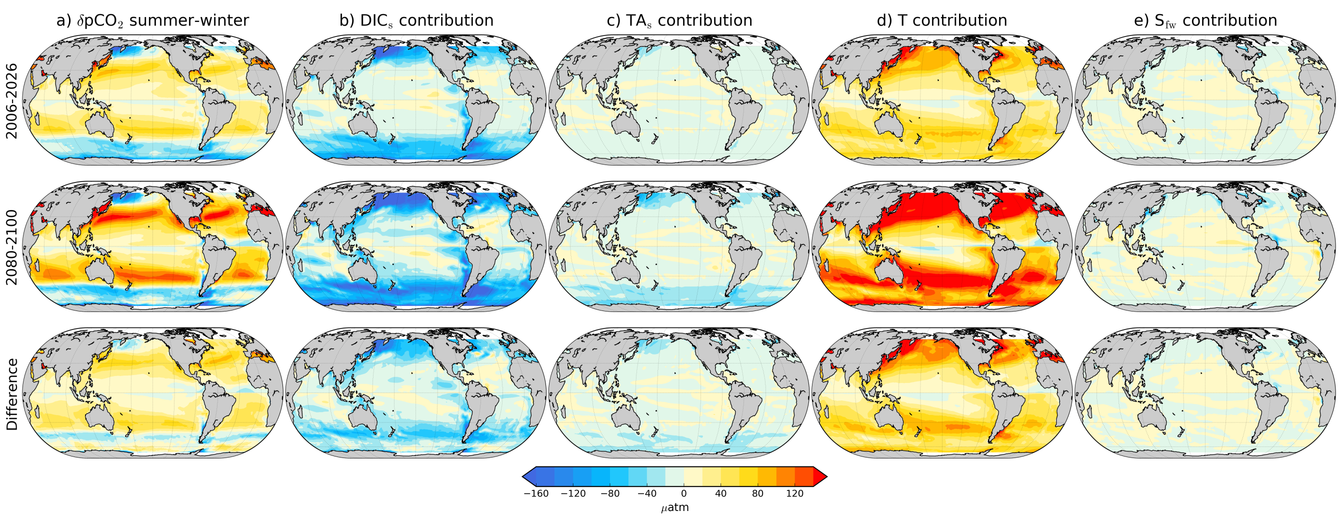

Figure S2. Column a) shows the simulated, ensemble-mean pCO_2 seasonal amplitude calculated as summer minus winter for each hemisphere respectively. b) to e) show DIC$_s$, T, TA$_s$ and S contributions to the pCO_2 summer-minus-winter amplitude. First and second rows represent respectively the 2006-2026 and 2080-2100 periods. Third row shows the difference between second and first rows. The amplitude was calculated from the climatology for periods 2006-2026 and 2080-2100.

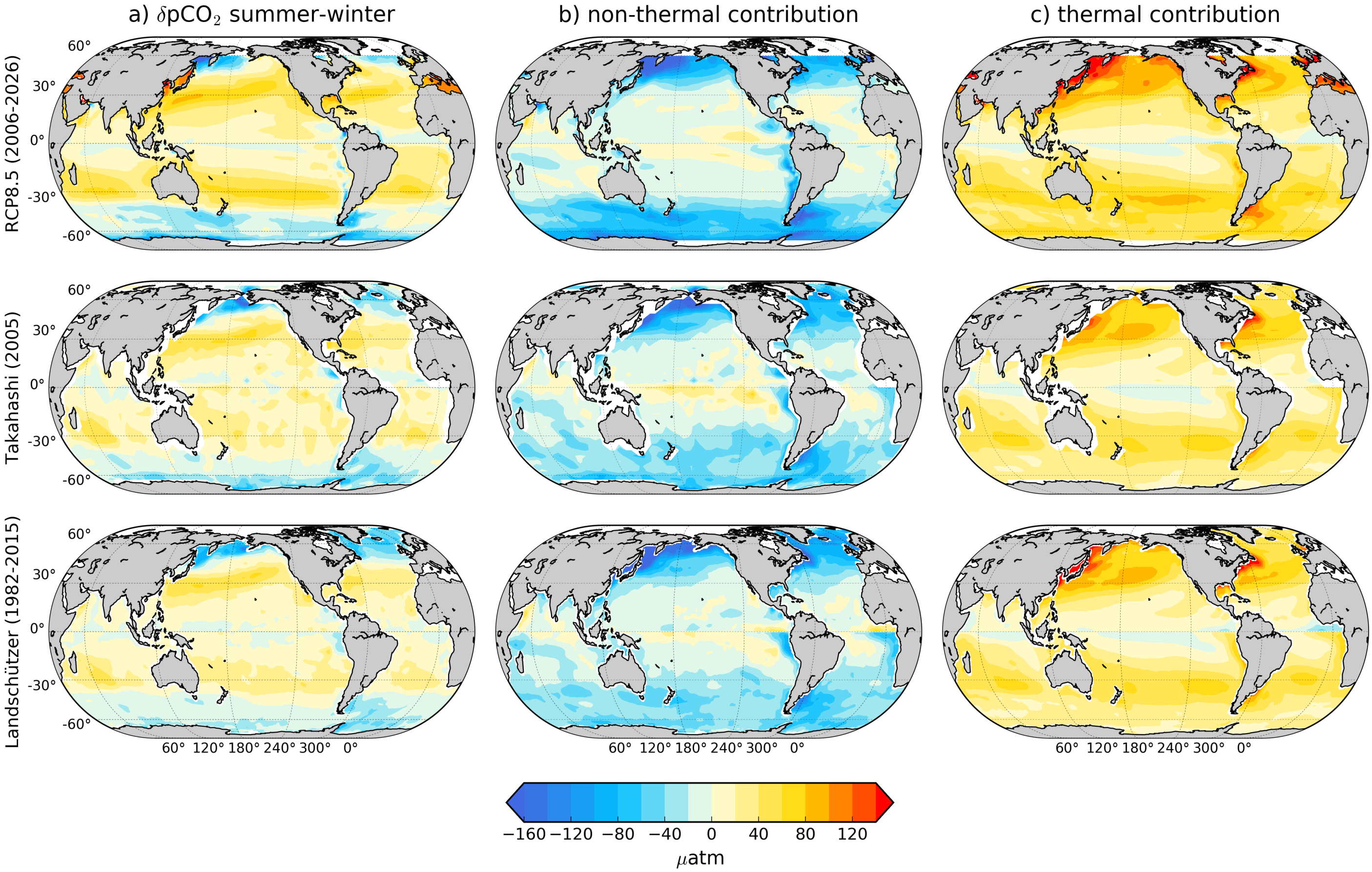

Figure S3. Column a) shows the pCO_2 seasonal amplitude calculated as summer minus winter for each hemisphere respectively. b) and c) show the thermal and non-thermal contributions to pCO_2 seasonality respectively. First row shows CMIP5 models ensemble mean for the 2006-2026 period under the RCP8.5 scenario. Second row shows the estimates from Takahashi et al. (2014) dataset for a reference year 2005, with summer-minus-winter thermal and non-thermal contributions calculated as Takahashi et al. (2002). Third rows show the same components for the Landschützer et al. (2017) pCO_2 data-set, and the thermal and non-thermal estimations that Peter Landschützer facilitated us, for the period 1982-2015.

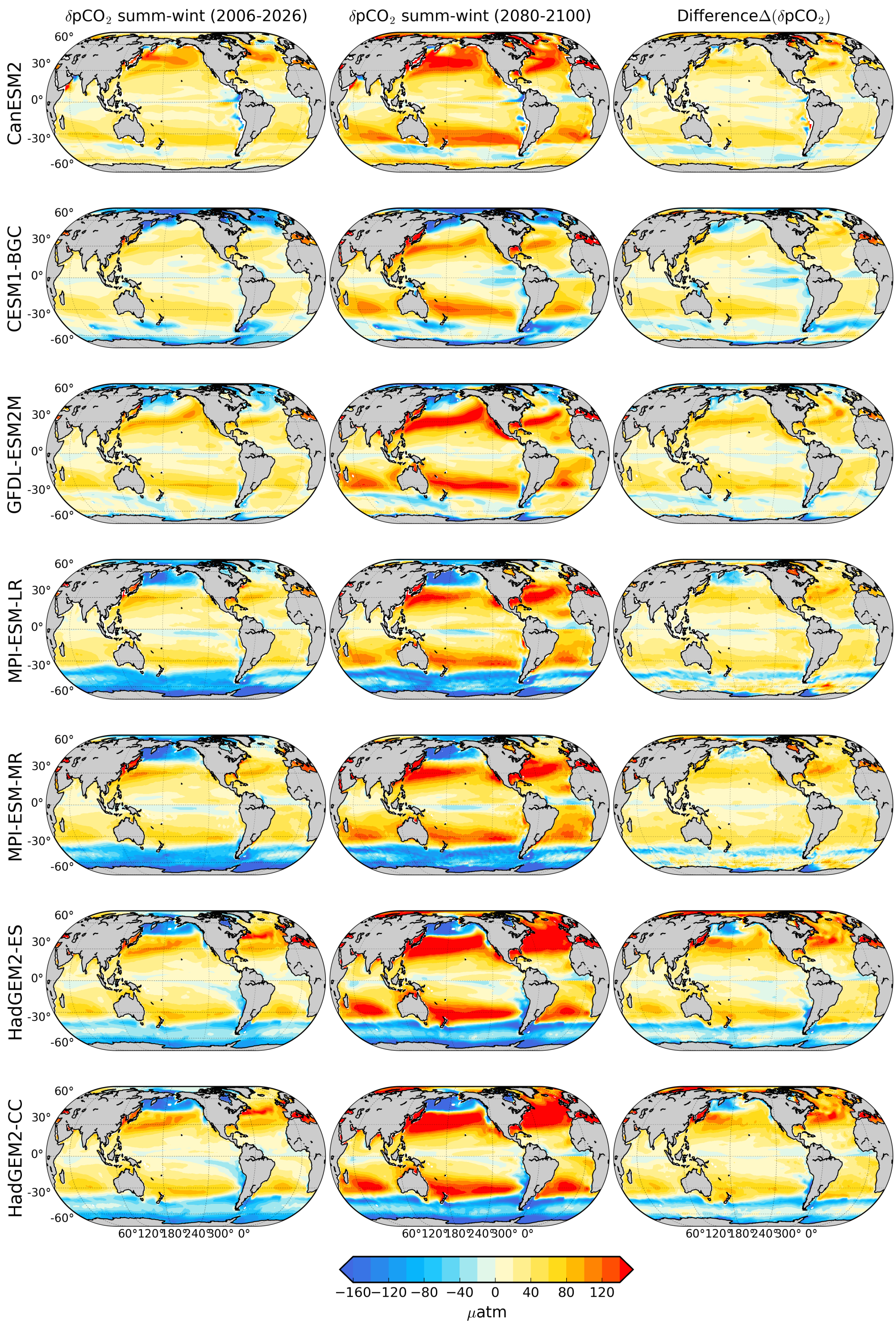

Figure S4. δpCO_2 climatology for column a) 2006-2026 and b) 2080-2100 periods calculated as in Fig. S2; each row is the result for a different model. Column c) shows the differences between column b) and a).

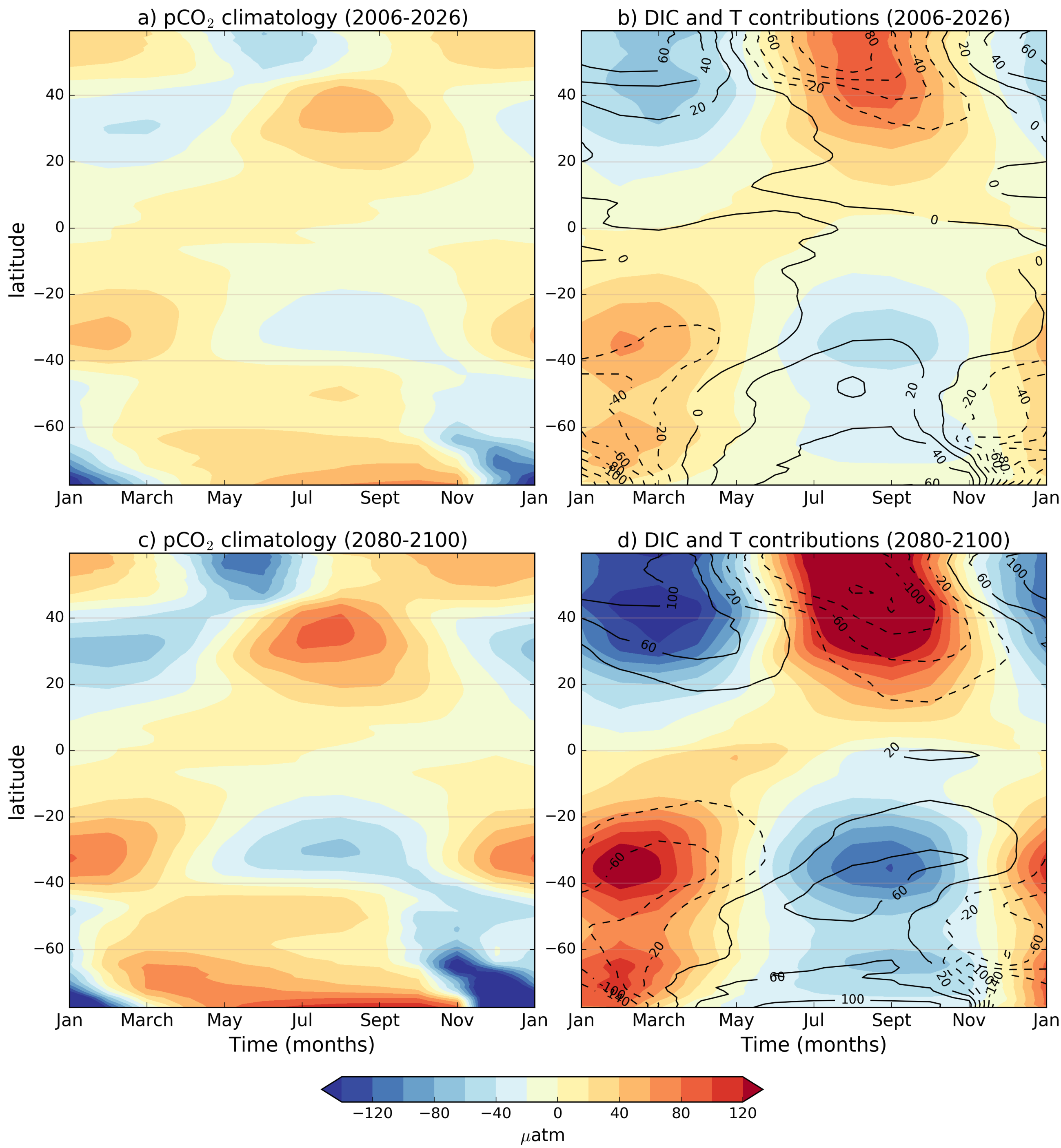

Figure S5. a) Ensemble zonal mean, zonal average of pCO_2 climatology and b) DIC contribution in color with overlying black contours of T contribution for 2006-2026 period. c) and d) same as a) and b) but for the 2080-2100 period.

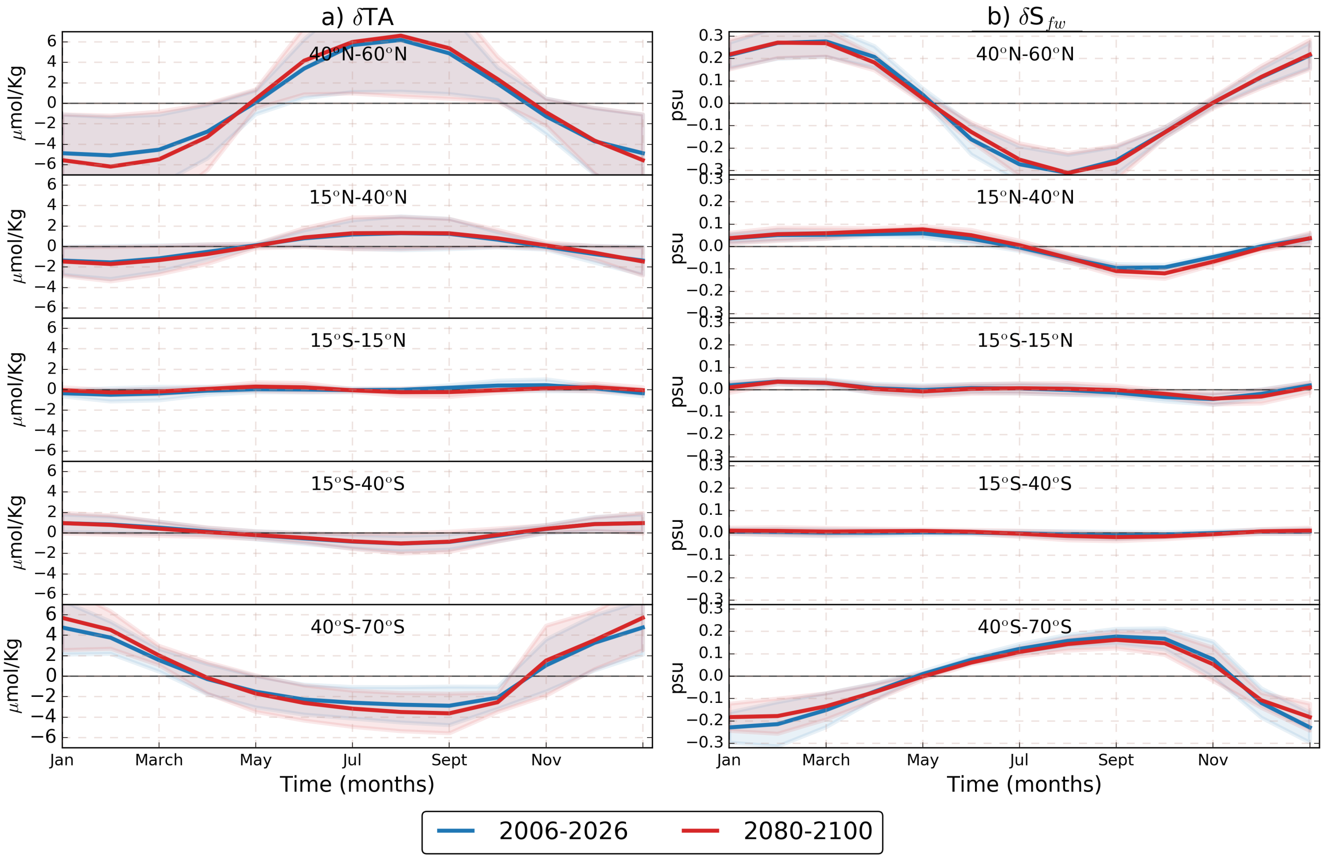

Figure S6. RCP8.5 ensemble zonal mean seasonal cycles: a) δTA_s and b) δS, for different latitudinal bands. Blue lines represent the 2006-2026 period, depicted for comparison with the 2080-2100 period shown by red lines. Different panels represent different latitudinal sections. δTA_s is projected to slightly increase in all the bands, while δS is projected to slightly decrease. The shading represents one standard deviation across the models.

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