Exploring ocean stratification in CMIP6 models: biases and evolution in a warming world

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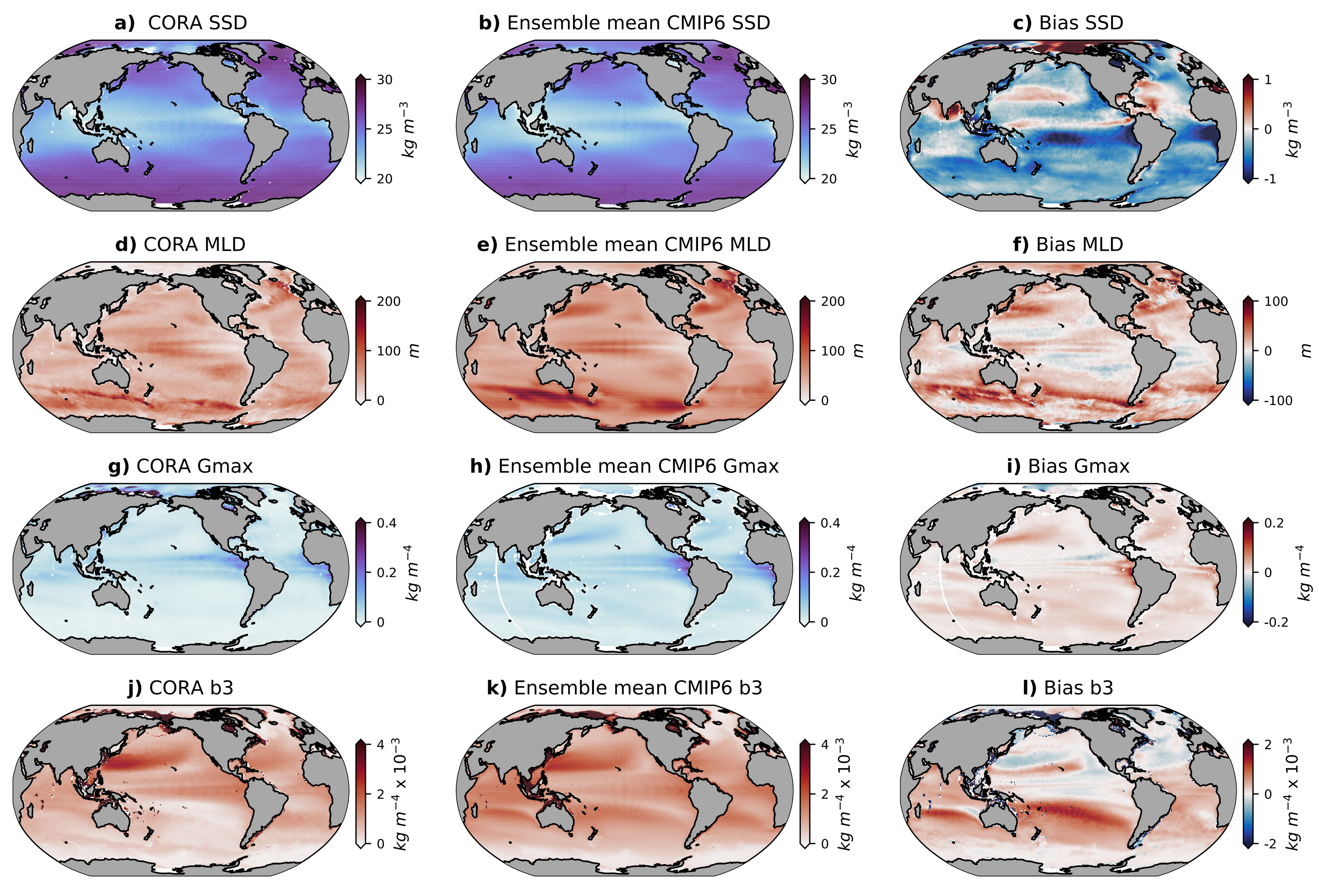
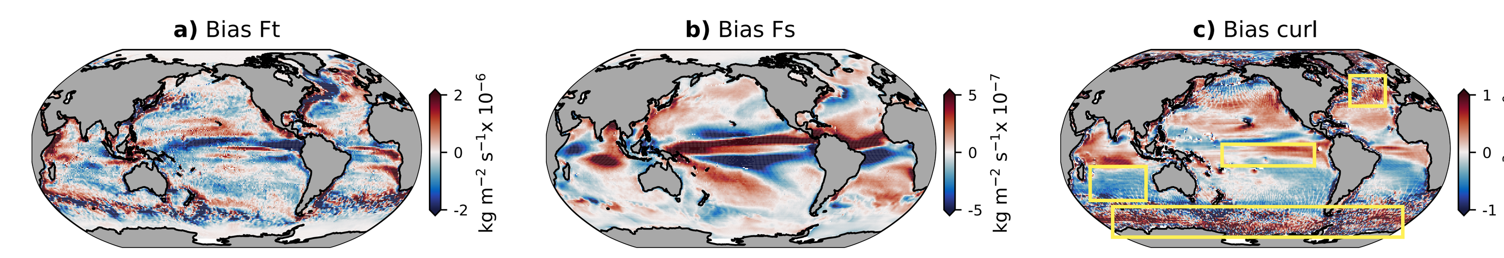
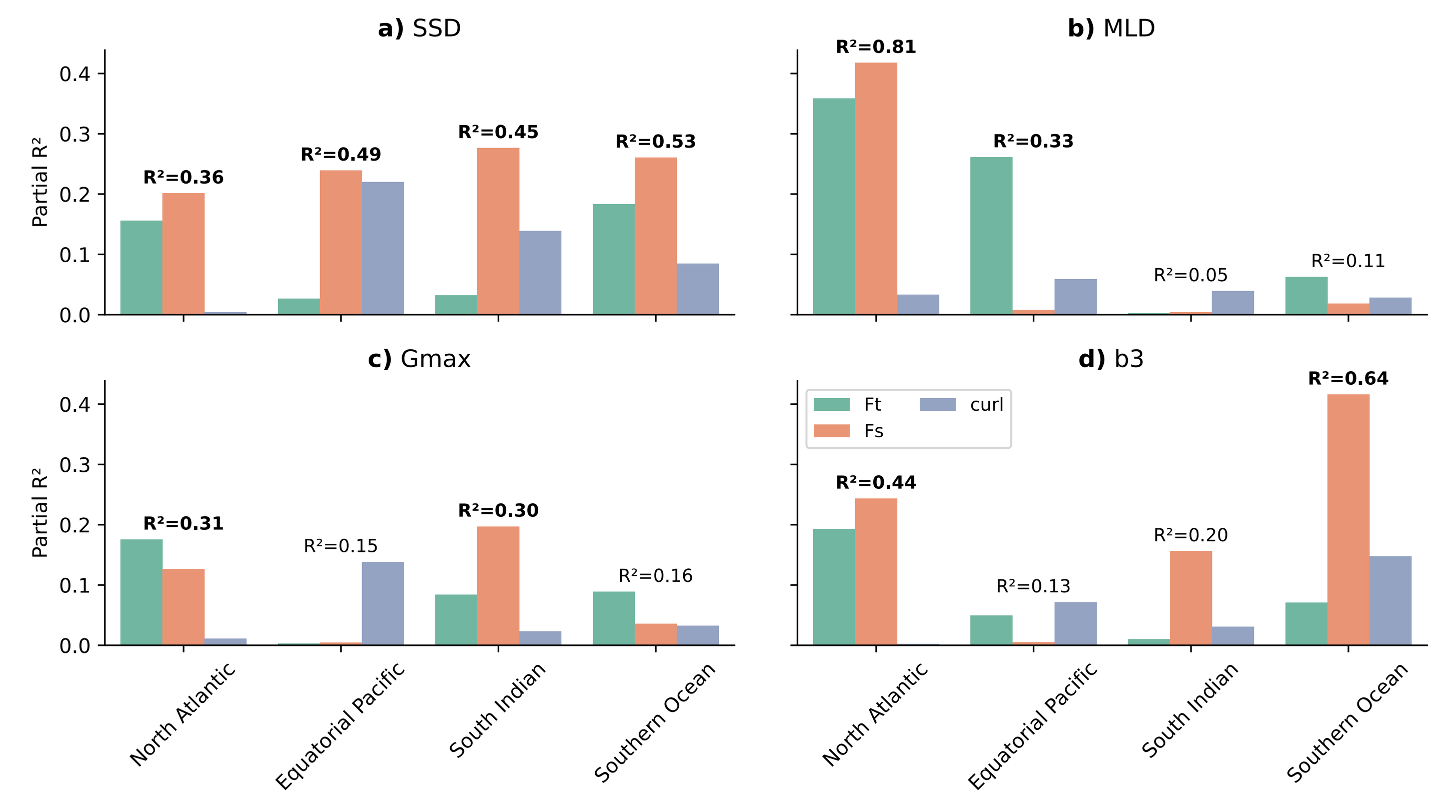
Context: Ocean stratification plays a central role in climate dynamics, influencing heat uptake, vertical mixing, and water mass formation. However, Earth System Models show persistent biases in stratification structure and evolution, which can impact projections of ocean–climate feedbacks. Here, we evaluate stratification biases across 28 CMIP6 models using four key diagnostic parameters derived from a physically consistent functional form of vertical density profiles. We examine the role of surface forcing errors in driving these biases, and assess projected changes under two future warming scenarios (SSP2-4.5 and SSP5-8.5).



Global maps of stratification parameters based on the observational dataset CORA, the CMIP6 historical ensemble mean, and the corresponding model biases.



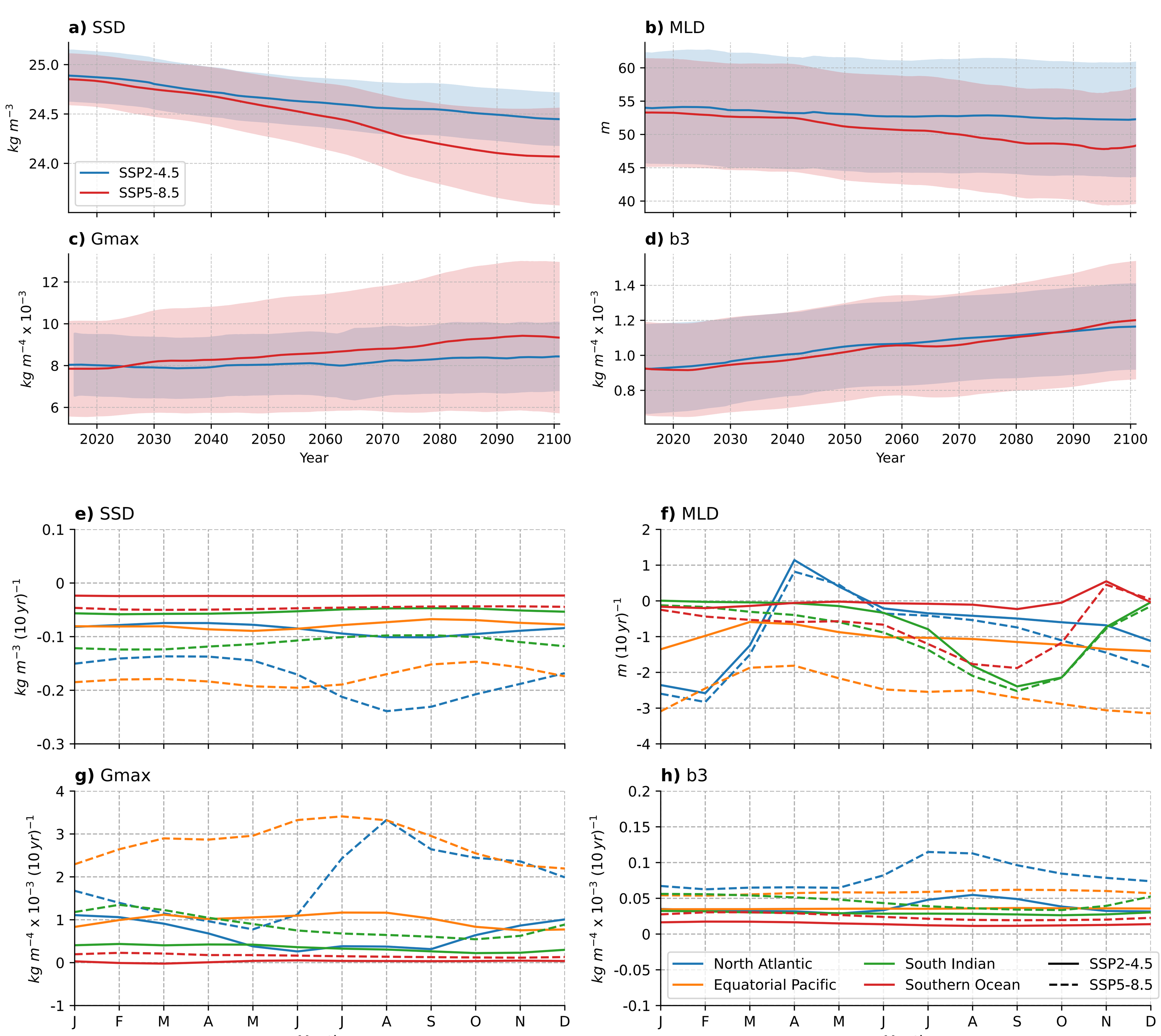
Global maps biases of the three main surface forcing components: thermal buoyancy flux (Ft), salinity-driven buoyancy flux (Fs), and wind stress curl. Target regions used for the analysis are indicated by yellow boxes.



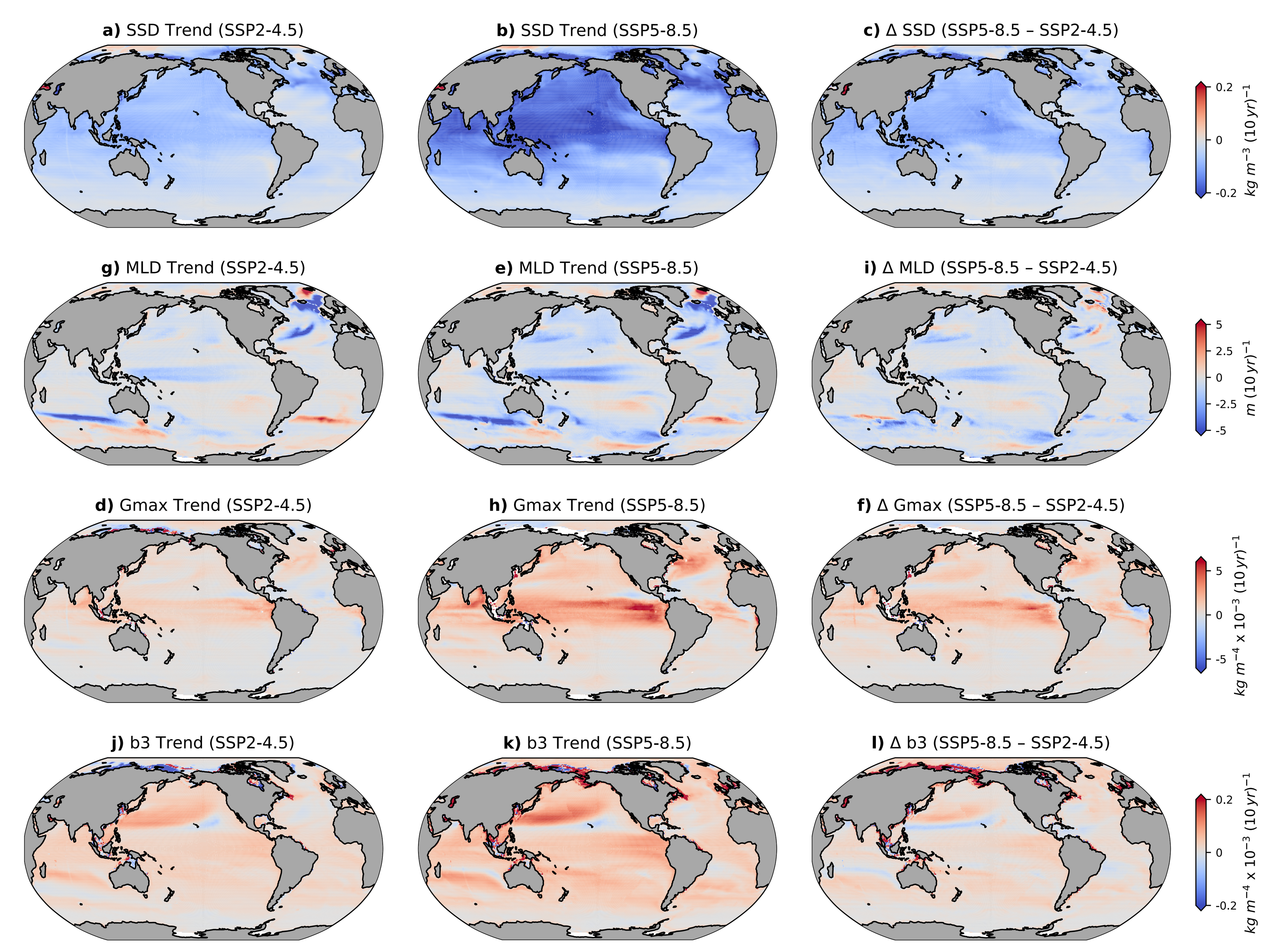
Dominance analysis showing the relative influence of buoyancy fluxes (*Fs*, *Ft*) and wind stress curl on stratification parameter biases across regions. Significant R^2 values are highlighted in bold.

We use dominance analysis to reveal the role of local diabatic (buoyancy forcing) and mechanical (wind stress curl) processes in shaping stratification biases across target regions. Only *SSD* is consistently influenced by surface forcings in all regions, with *Fs* (salinity-driven buoyancy flux) as the dominant driver. *MLD* only shows strong regional correlations particularly with *Fs* and *Ft* (thermal-driven buoyancy flux) in the North Atlantic, and with *Fs* in the Equatorial Pacific, suggesting biases likely linked to mixing parametrizations. Parameters like *Gmax* and *b3*, which reflect deeper stratification structure, show weaker connections to local forcing, except in the Southern Ocean, where *Fs* significantly influences the permanent thermocline.

Decadal Trends in Stratification Under SSP2-4.5 and SSP5-8.5



Global trends of stratification parameters under SSP2-4.5 and SSP5-8.5 (a–d), and seasonal decadal trends in target regions (e-h).



Global maps of decadal trends of stratification parameters for SSP2-4.5 and SSP5-8.5 scenarios and its difference

All parameters except *b3* show noticeable differences in decadal trends between SSP2-4.5 and SSP5-8.5. The most pronounced variability appears in *MLD*, which exhibits strong regional and seasonal dependence, with some regions even showing opposing trends across different months.

Discussion: Dominance analysis reveals that stratification biases are primarily driven by surface forcings, with a widespread sensitivity of surface stratification to freshwater input (*Fs*).

MLD, though expected to respond to local forcing, shows strong correlations only in specific regions—particularly with *Fs* and *Ft* in the North Atlantic—while its weaker links elsewhere suggest model-dependent variability, likely tied to mixing parametrizations.

Stratification metrics related to the thermocline structure generally show weaker connections to local forcing, except in the Southern Ocean, where *Fs* significantly shapes the permanent thermocline.

Overall, stratification parameters exhibit a regionally and seasonally dependent response to global warming, highlighting the complex dynamics of upper-ocean vertical structure. This underscores the need to improve—and better understand—the representation of surface forcing and mixing processes in Earth System Models.

Methods: Stratification metrics are derived using the SHDR algorithm, which fits upper-ocean density profiles to a physically consistent functional form. This allows extraction of parameters such as SSD (a1), MLD (D), Gmax, and b3.

$$f(z) = \begin{cases} a_1, & z \leqslant D, \\ a_3 + b_3(z-D) + a_2\exp(-b_2\times(z-D) - c_2(z-D)^2), & z \geqslant D. \end{cases}$$

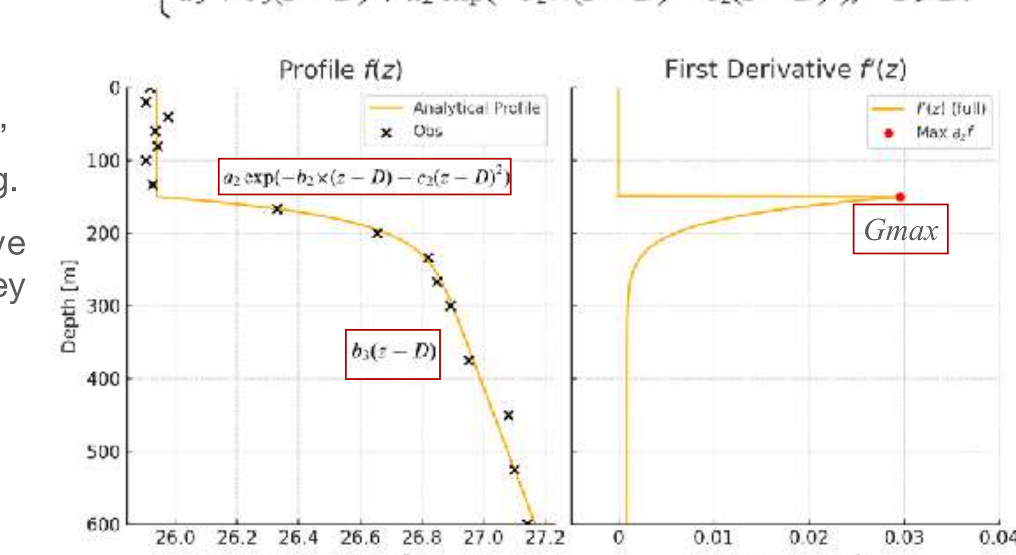
Surface buoyancy flux components were computed separately:

- The thermal flux (*Ft*) from net surface heat flux,
- The saline flux (*Fs*) from evaporation and precipitation,
- And wind stress curl as a proxy for mechanical forcing.

These forcings were used to assess their relative contribution to model bias via dominance analysis in key ocean regions.

$$F_t = -\alpha\frac{Q_0}{C_p}, \quad F_s = \rho\cdot\beta\cdot S\cdot\frac{E-P}{1-S/1000}$$

$$\mathrm{curl}(\tau) = \frac{\partial\tau_y}{\partial x} - \frac{\partial\tau_x}{\partial y}$$



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