Supporting Information for

Freshwater forcing along the Indian Coastal Seas: Impacts on Productivity and Acidification

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Text S1: Validation of model Sea Surface Salinity (SSS)

The modelled SSS from the CTRL run (Fig. S4a) is evaluated against satellite-based SMOS retrievals (Boutin et al., 2023) and gridded Argo salinity fields (Szekely et al., 2019). The model is regridded to match the resolution of the observational data for statistical comparison. It can be noted that the model is able to reproduce the large-scale salinity gradients across the study area. It can resolve the high saline waters in the AS and the relatively fresher conditions in the BoB, and captures the key hydrographic features driven by freshwater inputs. The bias comparisons (Fig. S4 b,c) reveal that the model performance is robust across most of the basin. This shows a low mean bias relative to both observations, particularly in the AS. However, a slight positive bias (~1 psu) is observed with SMOS, and a negative bias with Argo is observed along the northwestern BoB (NWBoB), highlighting the challenge of accurately representing riverine plumes across datasets. The RMSE remains below ~1 psu across most of the domain (Fig. S4e,f), indicating strong agreement between the model and observations. A higher RMSE is observed in the NWBoB.

A comparison of SSS frequency distributions (Fig. S4d) further supports the model's performance, showing a distinct bimodal structure that effectively separates the saline AS and the fresher BoB surface waters, a pattern also captured in both observational datasets. This bimodality arises from the regional contrasts maintained by evaporation-precipitation imbalances and substantial riverine discharge from the Ganga and Brahmaputra River systems (Behara and Vinayachandran, 2016). Overall, the validation of CTRL SSS confirms that the model reproduces both the spatial and temporal features of observed SSS across the study area, providing a reliable baseline for subsequent sensitivity experiments. A thorough validation of model-simulated temperature and currents has also been carried out and is detailed in Madkaiker et al. (2024).

Text S2: Inter to intra-seasonal variability in subsurface density structure under freshwater forcing scenarios

As seen in Fig. S7, a-e, the upper-ocean density exhibits a pronounced west-east gradient across the Indian coastal waters. The near-surface waters progressively freshen from the NAS towards the NWBoB, depicted by a gradual decrease in density. This spatial gradient primarily arises from the increasing freshwater influence associated with precipitation and riverine discharge (Behara and Vinayachandran, 2016; Vinayachandran et al., 2002).

In the NAS, the density field remains largely unaffected by freshwater perturbation. Across all SENS experiments, the pycnocline closely coincides with that of CTRL, and the seasonal vertical structure exhibits minimal variation. This insensitivity of freshwater forcing in this region shows the dominance of intense mixing and winter convection, plus the advent of high saline waters from the Persian Gulf (Prasanna Kumar et al., 2001). Therefore, the absence or enhancement of freshwater fluxes has a negligible impact on the upper-layer stability in the NAS. The NEAS exhibits slightly higher sensitivity. During the summer monsoon, when coastal runoff enhances near-surface stratification, the upper layers in CTRL become marginally fresher and less dense. In SENS1-S3, the absence of precipitation and runoff produces positive density anomalies (~0.3-0.5 kg m^{-3}) and a deepening of the pycnocline by ~10 m, suggesting enhanced vertical mixing and weaker haline stratification. Conversely, under SENS4, excess freshwater flux induces a shallow, low-density surface layer extending up to 40 m, particularly between summer and winter. This response is consistent with earlier observations that the NEAS freshens seasonally due to alongshore freshwater transport and runoff (Shankar et al., 2015).

The influence of freshwater becomes more prominent in the SEAS and SWBoB regions. Both regions are influenced by strong monsoonal precipitation and the advection of low-salinity water carried by the East India Coastal Current (EICC), which transports freshwater plumes from the northern BoB to southward along the eastern Indian coast (Vinayachandran and Kurian, 2007). In the CTRL simulation, the pycnocline resides around 60-80 m depth during spring and then shoals rapidly during the summer. In SENS1-S3, the absence of freshwater results in denser surface waters and a deepening of the pycnocline by 20-40 m, particularly during fall and winter, indicating stronger vertical mixing and weaker stratification. Conversely, SENS4 shows a pronounced freshening (an increase in the density anomaly of up to ~1 kg m^{-3}) and a 10 m shoaling of the pycnocline, demonstrating that enhanced freshwater increases stratification.

The NWBoB displays a significant response to freshwater forcing. This region is strongly influenced by extensive precipitation and river discharge from the Ganga-Brahmaputra River system (Papa et al., 2012). In CTRL, the pycnocline is consistent at ~80m during winter and spring, but shoals sharply to 10m during fall. In SENS1-S3, where freshwater input is reduced or absent, the upper layer becomes denser by ~1-1.5 kg m^{-3}, and the pycnocline deepens by 10-30 m, thereby reducing stratification through increased mixing. In contrast, SENS4 produces more freshening and shoaling between summer and fall seasons, increasing upper density by 0.4 kg m^{-3} and a shoaling of the pycnocline.

These results show how perturbations in freshwater forcing alter the density profiles in coastal regions. It is to be noted that the density-driven buoyancy structure of SEAS, SWBoB and NWBoB is more sensitive to freshwater variations than NAS or NEAS (Sengupta et al., 2016).

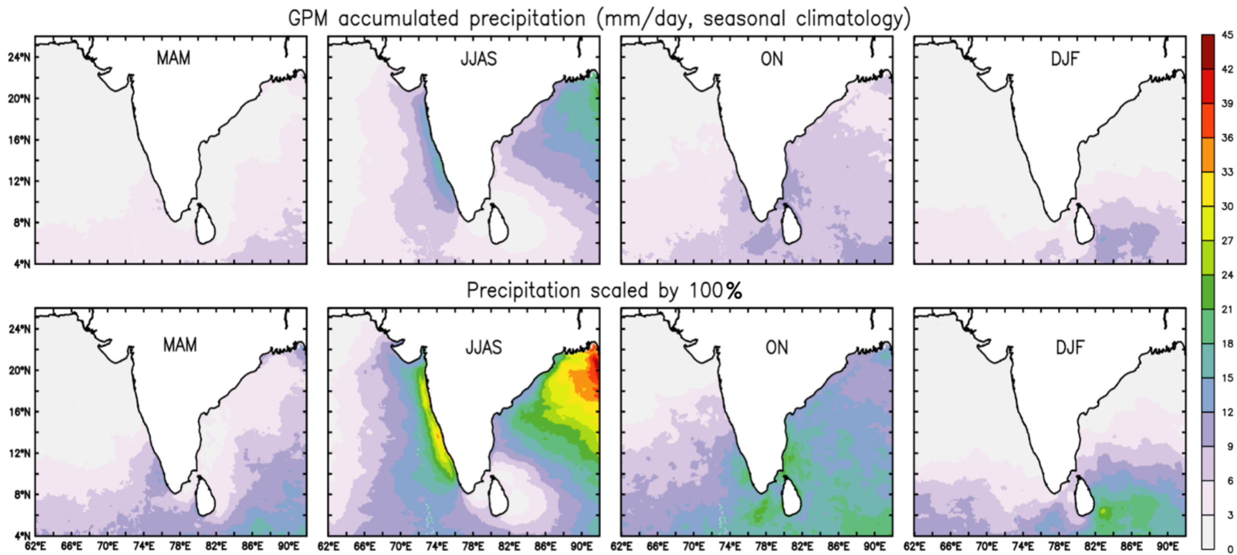

Figure S1. (Top panel) Seasonal climatology of accumulated precipitation over the study area, based on GPM satellite measurements. (Bottom panel) GPM precipitation scaled by 100% for experiment SENS4.

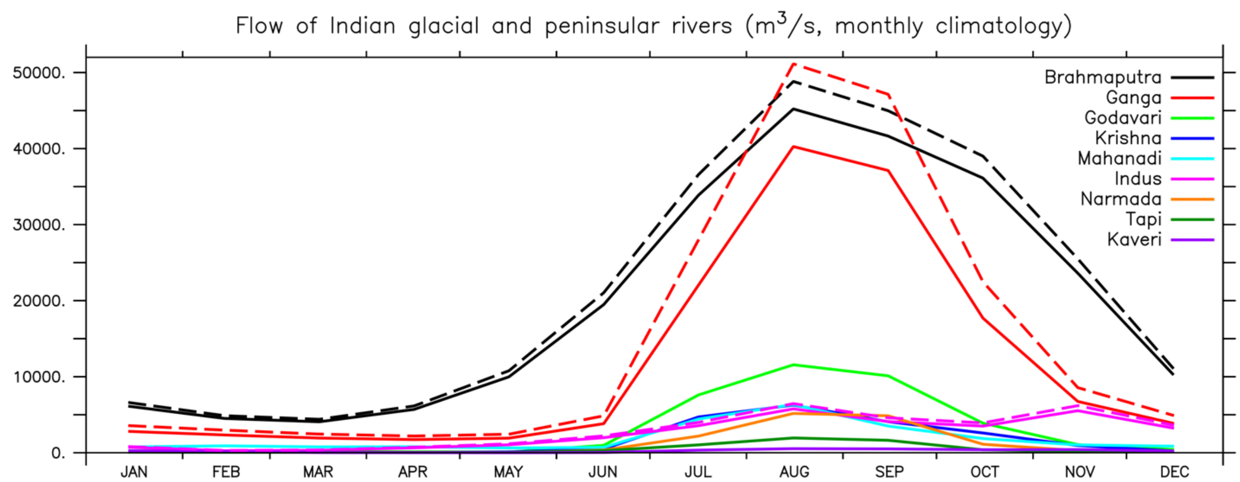

Figure S2. Major Indian glacial and peninsular rivers. Monthly climatological data are sourced from Dai and Trenberth (2002). The three glacial rivers, shown with solid lines, are the Brahmaputra (black), the Ganga (red), and the Indus (pink). The respective dashed lines, in the same colours, indicate an increase in discharge of 8%, 27%, and 12%, respectively, based on estimates from IPCC (2023) and Lutz et al. (2014) for experiment SENS4.

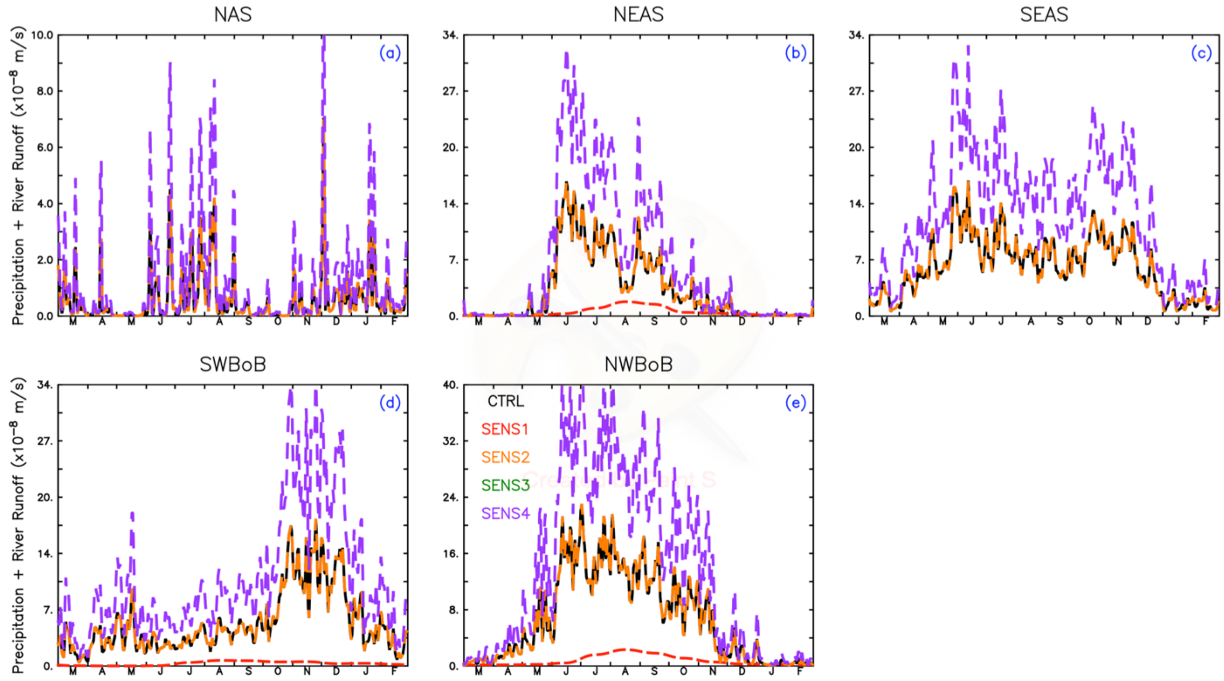

Figure S3. Climatological freshwater flux (m s^{-1}) prescribed to the model in the control (black line) and sensitivity experiments (coloured lines). SENS1: no precipitation; SENS2: no runoff; SENS3: no precipitation and runoff; and SENS4: increased precipitation and runoff. Each panel corresponds to one of the five coastal regions considered along the Indian coastline. Note that the y-axis ranges vary across panels.

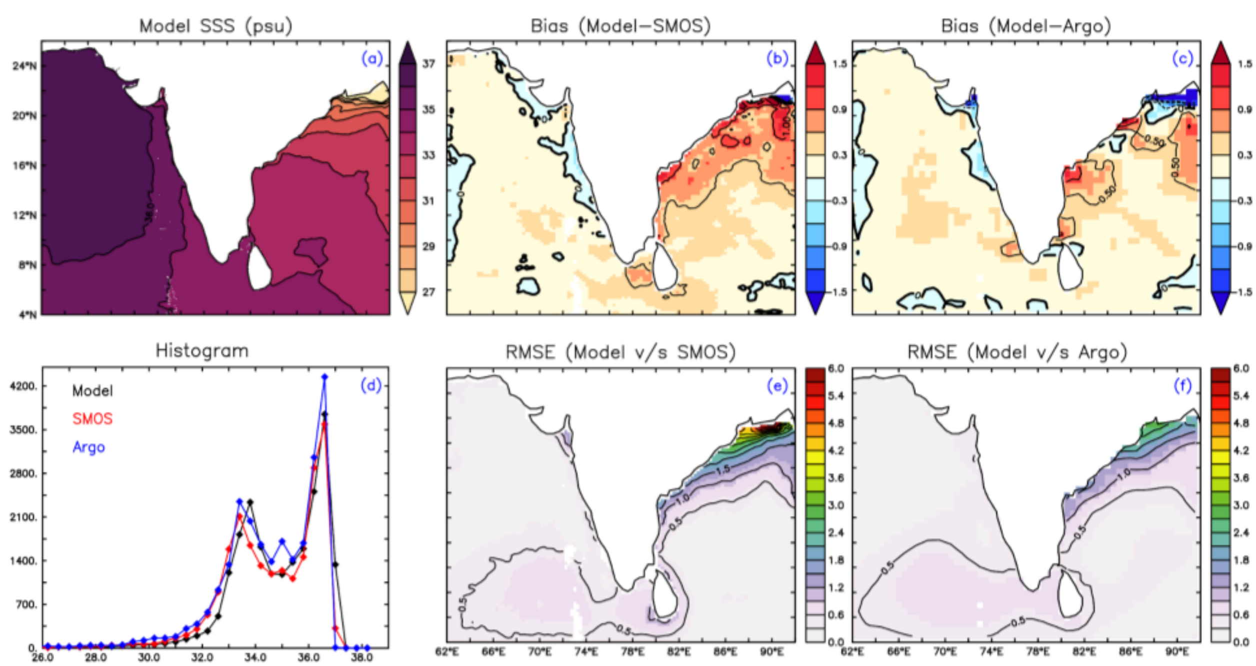

Figure S4. Comparison of (a) model SSS (CTRL experiment) with SMOS satellite and Argo gridded products, showing spatial bias (b, c), histogram (d), and RMSE (e, f) over the study area.

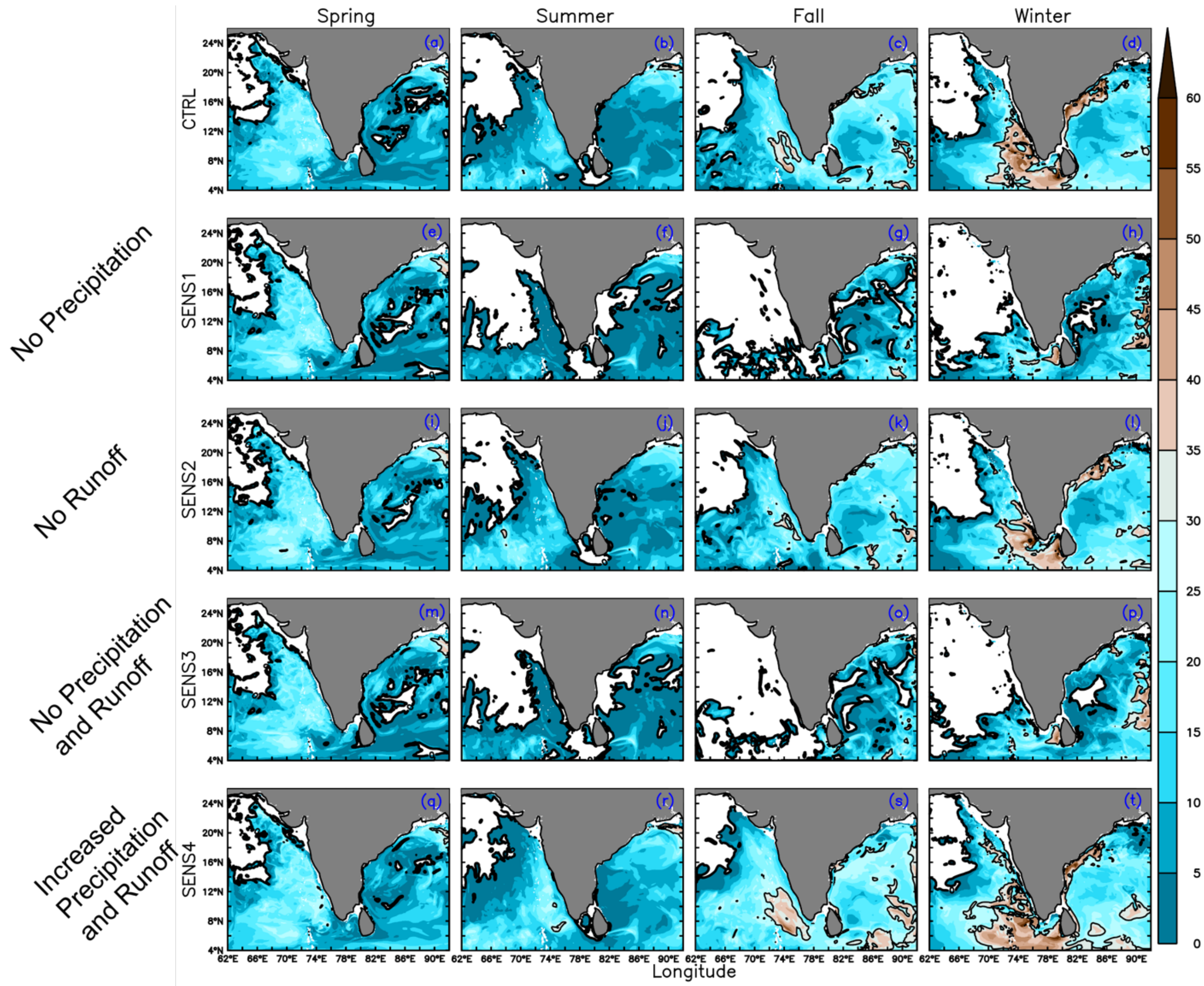

Figure S5. Seasonal climatology of BLT (in m) from (a-d) CTRL, followed by the SENS experiments (e-t), showing their spatial distribution. White colour indicates no BLT formation.

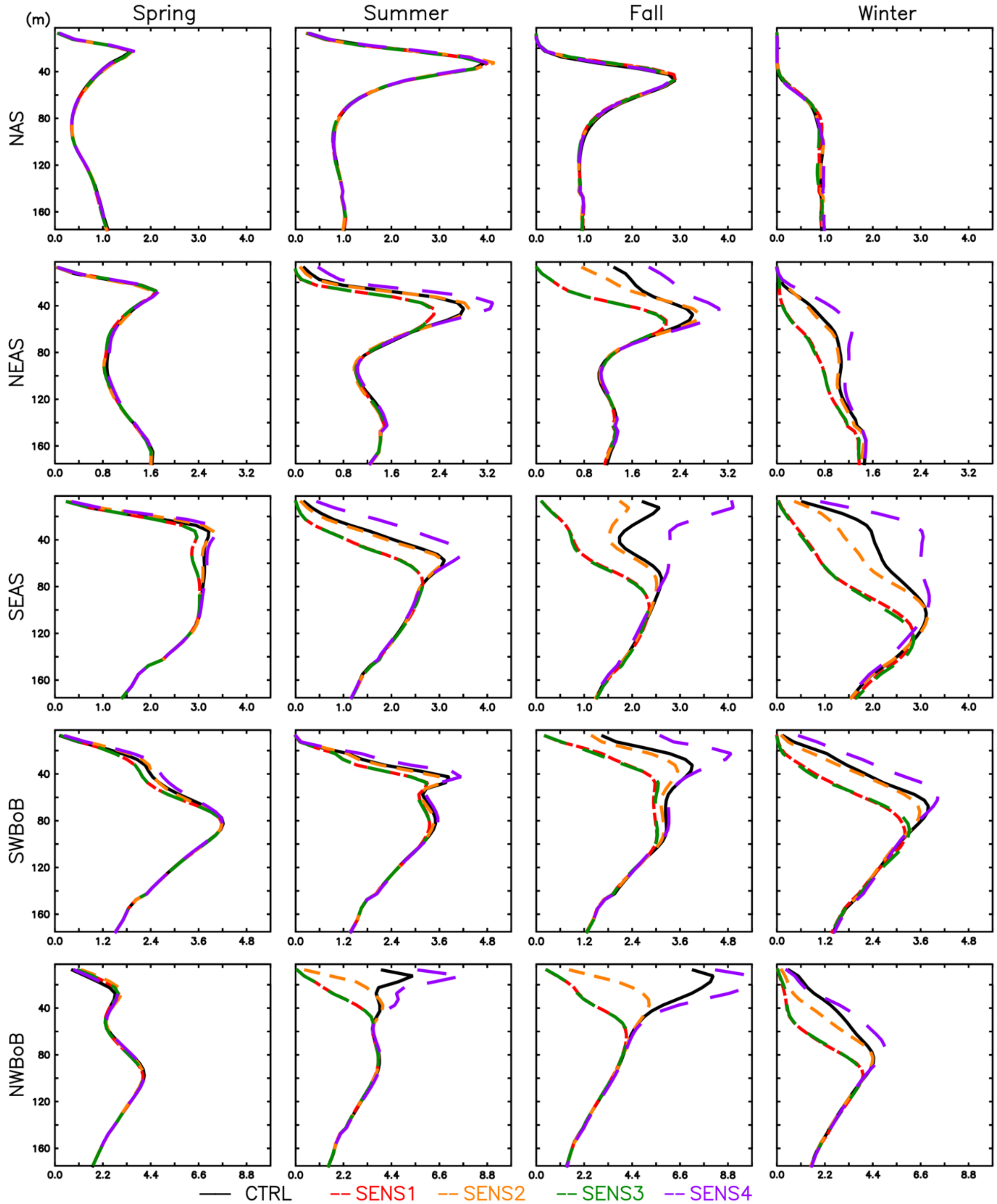

Figure S6. Seasonal vertical profiles of N^2 ($x10^{-4}$ s^{-2}) averaged over five coastal masks for CTRL and SENS experiments. Note that the x-axis ranges vary across panels.

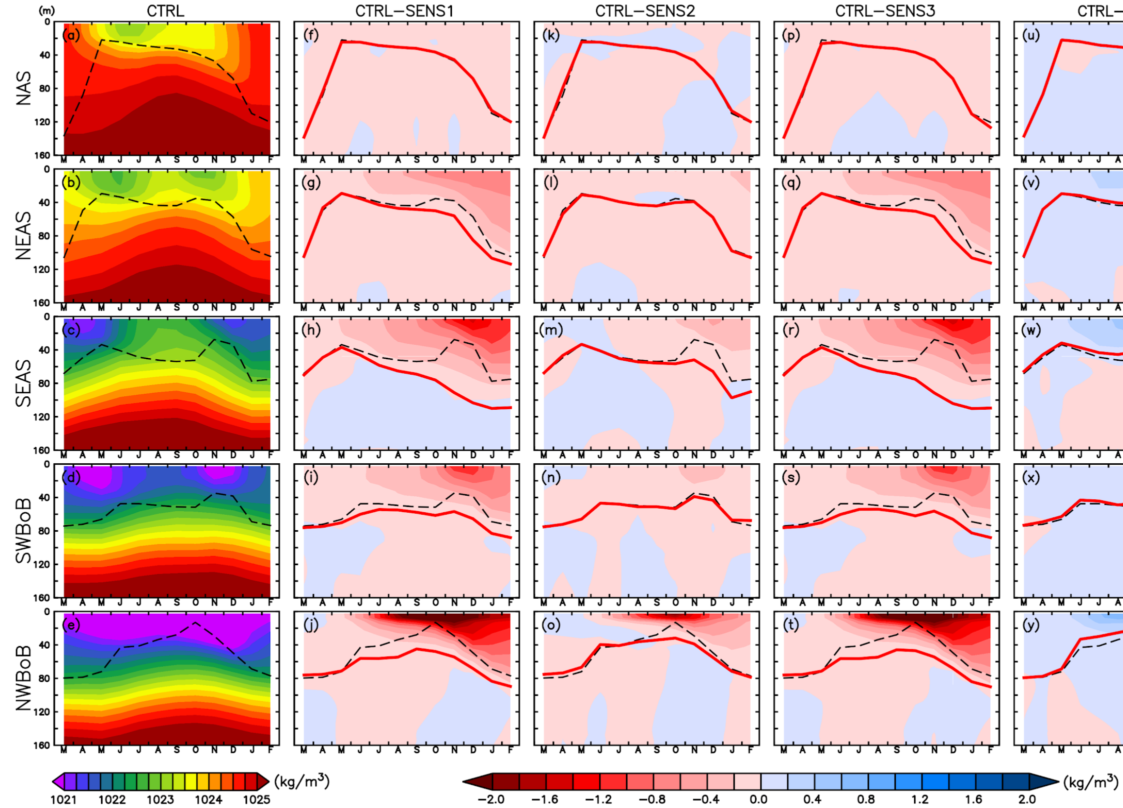

Figure S7. Monthly variability of subsurface density (kg m^{-3}) in the upper 160 m averaged across the five coastal masks. The first column shows the CTRL density structure, while subsequent columns represent CTRL-SENS differences. Red shading indicates increased density in the SENS runs relative to CTRL, whereas blue shading indicates a reduction. The dashed black line denotes the CTRL pycnocline, and solid red lines indicate pycnocline depths in the SENS experiments.

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