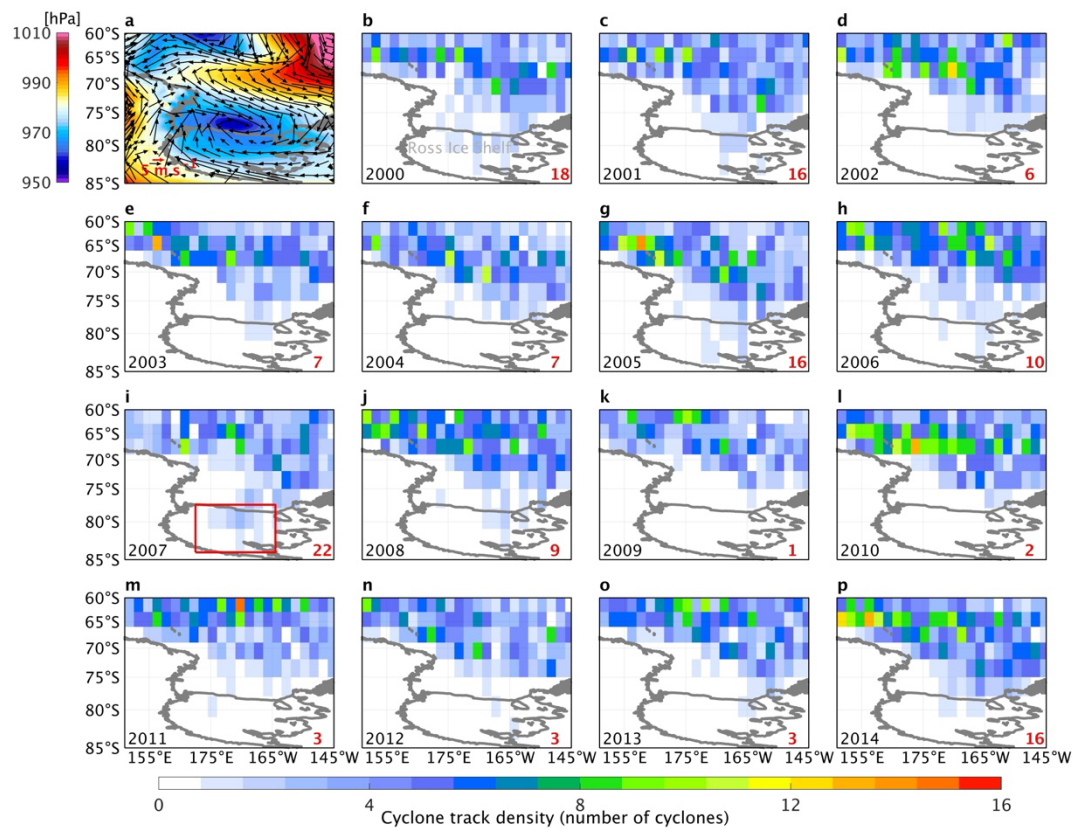
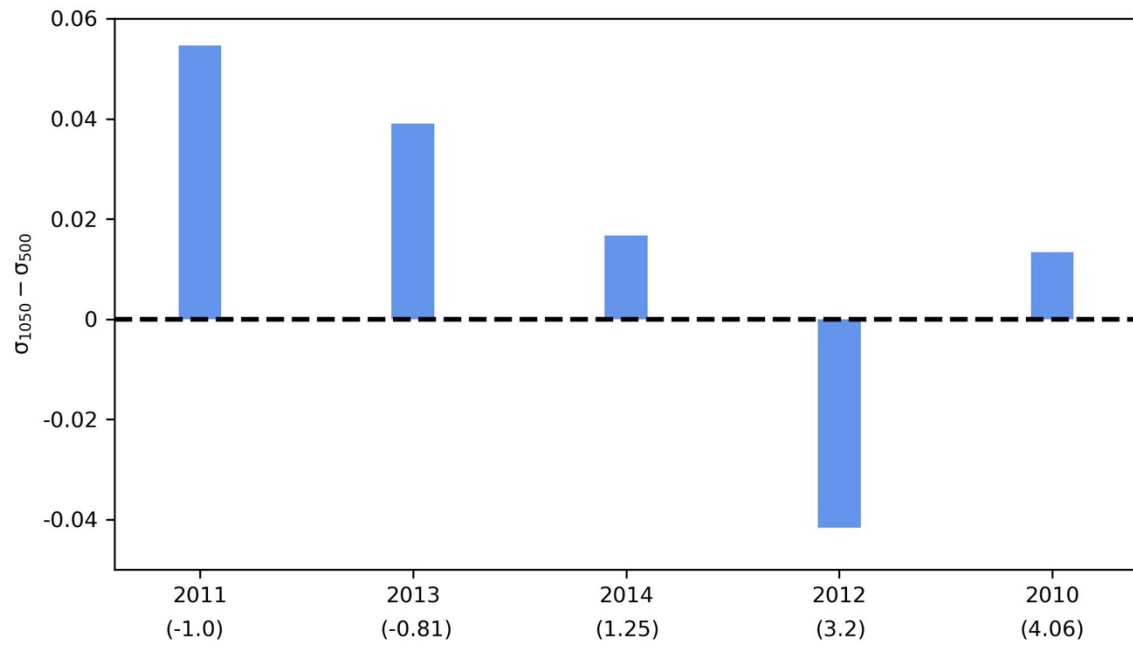
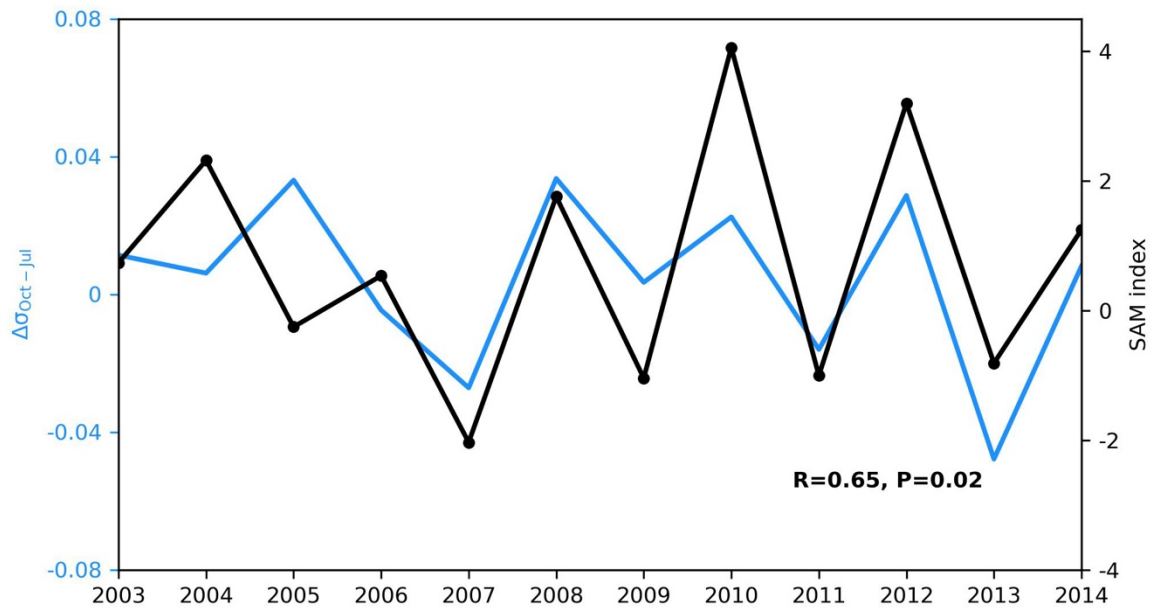




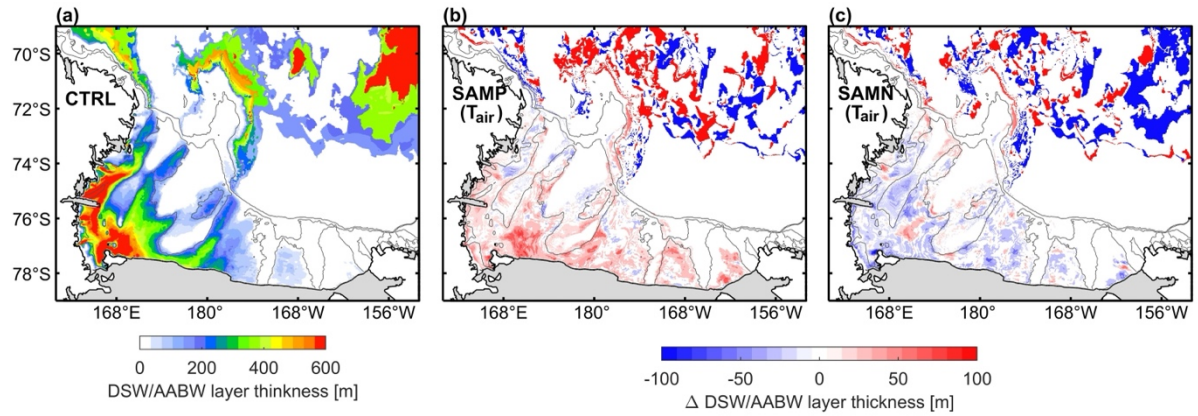
Supplementary Fig. 1 | Cyclone track density in winters of 2000–2014 over the Ross Sea. a, Spatial distributions of sea level pressure (colored shading) and 10-m wind vectors (black arrow) for a typical cyclone occurring on 22 June 2007. **b–p,** Cyclone track densities (number of cyclone tracks per 3°×3° sector) during winters of 2000–2014 based on the ERA5 product. The number of cyclones centered over the central Ross Ice (within the red box in **i**) is labeled in the lower left corner of each panel.



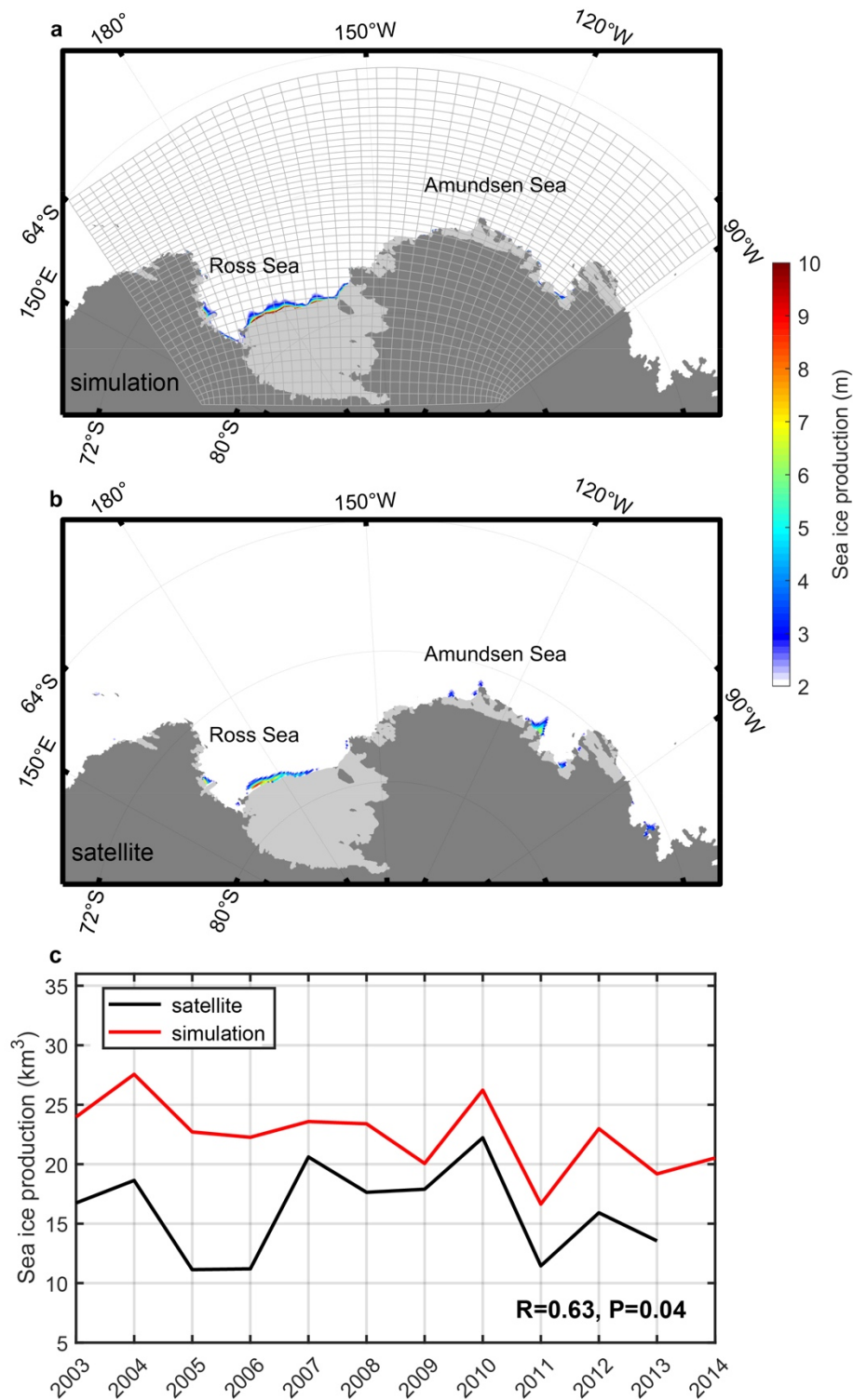
Supplementary Fig. 2 | Relation between ocean stratification in the Terra Nova Bay polynya and SAM. Stratification is indicated by the difference in potential density at 1050 m and 500 m ($\sigma_{1050} - \sigma_{500}$), which is averaged over the period of mid-July to mid-October in years when mooring data were available at both the bottom and middle depths. Years are arranged in the order of increasing austral-winter SAM index (labeled at the x-axis below each year).



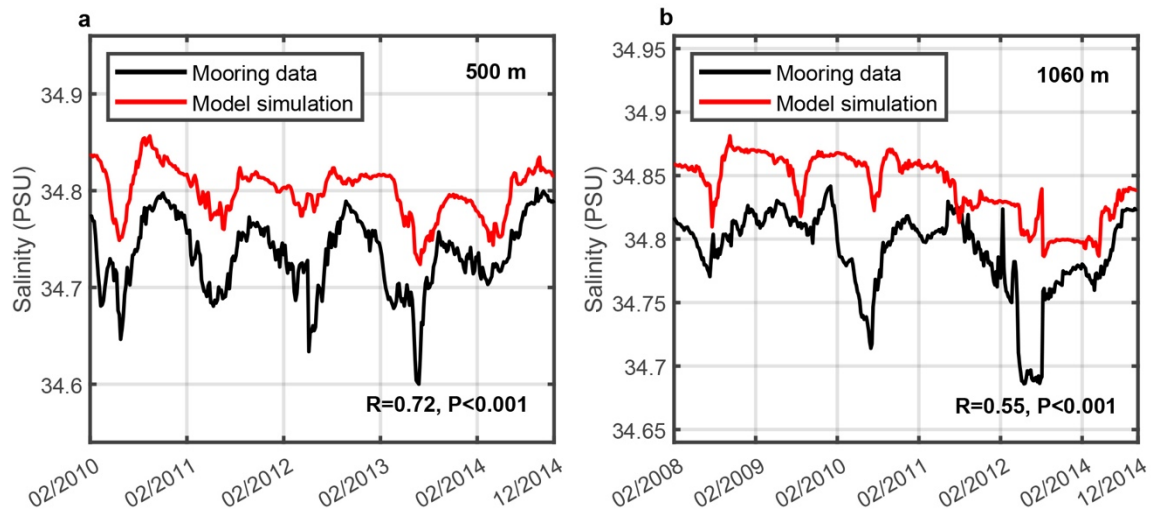
Supplementary Fig. 3 | Relation between potential density change at bottom in the Terra Nova Bay polynya from model simulations and SAM. Time series of potential density change from mid-July to mid-October at 1050 m in the Terra Nova Bay polynya from model simulations and the austral-winter SAM index for 2003–2014. The correlation coefficient (R) and p-value (P) between the two time series are provided.



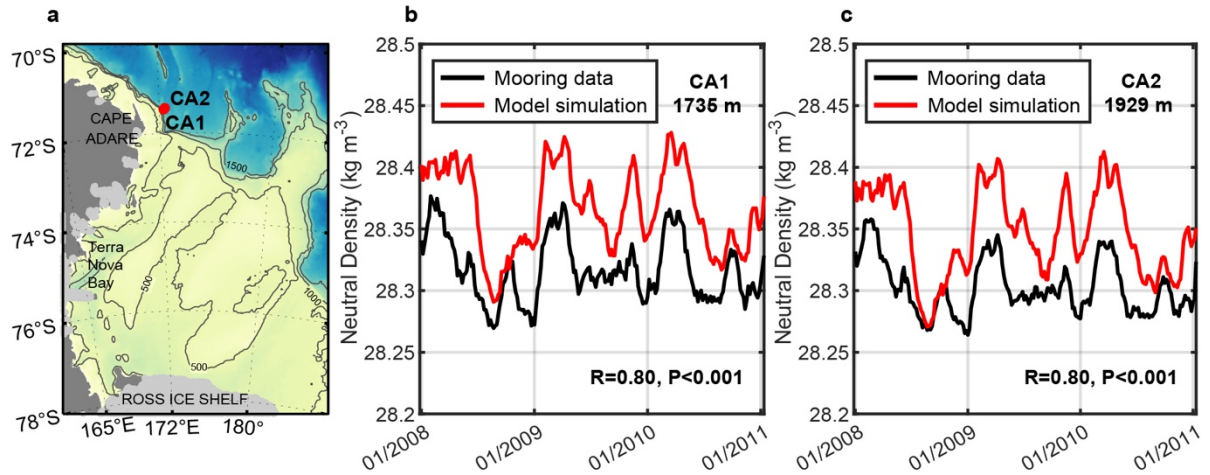
Supplementary Fig. 4 | Results from sensitivity experiments for surface air temperature perturbations related to SAM changes. a, DSW/AABW thickness in the CTRL simulation. **b,** Changes in DSW/AABW thickness in the SAMP (T_{air}) compared to CTRL. **c,** Changes in DSW/AABW thickness in the SAMN (T_{air}) compared to CTRL.



Supplementary Fig. 5 | Grid and sea ice production simulation of the coupled ocean-sea ice-ice shelf model. **a**, Model grid and the simulated cumulative sea ice production (unit: m) in June–August averaged over 2003–2014. **b**, Cumulative sea ice production in June–August averaged over 2003–2010 from satellite estimates. **c**, Time series of cumulative sea ice production (unit: km³) averaged over the Terra Nova Bay polynya from the model simulation and satellite estimate. The correlation coefficient (R) and p-value (P) between the two time series are provided.



Supplementary Fig. 6 | Validation of the simulated salinity from the numerical model in the Terra Nova Bay polynya. a, Time series of 5-day-average salinity at 500 m from the model and observations at the mooring location in the polynya. **b,** Same as (a) but for salinity at 1050 m. The correlation coefficients (R) and p-values (P) are provided.



Supplementary Fig. 7 | Validation of the modelled neutral density in the slope area of the western Ross Sea. b, Time series of 5-day-average neutral density at 1735 m from the model and observations at the location of mooring CA1 deployed in the U.S. CALM program. **c,** Same as (a) but for neutral density at 1929 m at the CA2 mooring location. The correlation coefficients (R) and p-values (P) are provided.