Supplementary Information

1. The derivation of the topographic form stress.

In Masich et al. (2015)'s method, the topographic form stress signal is extracted from the total pressure field. Every ocean grid box adjacent to a bathymetric feature (for example, a seamount) and its pressure, P_t, is found at every model level. The pressure difference across each piece of bathymetry, calculated as that between the ocean grid adjacent to the eastern face of the seamount and the ocean grid adjacent to the western face, is then found (Figure S1 (a) and Equation S1 (1)):

$$\Delta P_t = P_t(x = x_E) - P_t(x = x_W) \qquad (1)$$

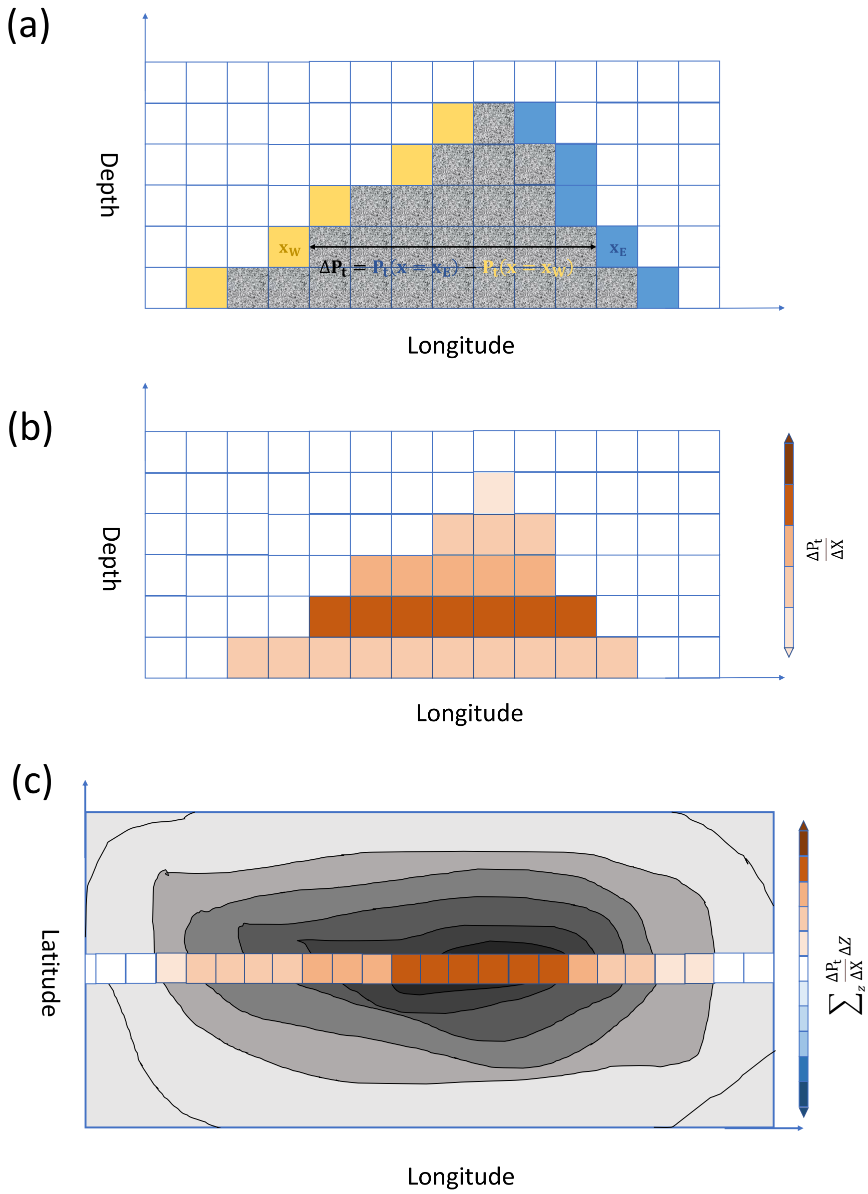

Figure S1: Assume that there is a submerged seamount. (a) A zonal slice of a seamount: white cells indicate sea water, grey cells indicate landmass. Grids in yellow are the grids adjacent to the western face of the seamount and grids in blue are the grids adjacent to the eastern face of the seamount. (b) The pressure difference is divided by the width of the seamount to give the pressure gradient /ΔX, which is assigned to every grid of the seamount in each vertical level. (c) Vertically integrated topographic form stress field across the seamount. This figure is adapted from Masich et al., 2015.

The pressure gradient is then calculated as the pressure difference divided by the width of the bathymetric feature (see Figure S1 (b) and Equation S1 (2)):

$$\frac{\Delta P_t}{\Delta X} = \frac{P_t(X=X_E) - P_t(X=X_W)}{X_E - X_W} \quad (2)$$

The vertically and zonally integral then gives the total topographic form stress signal, as shown in Equation S1 (3):

$$-\oint_x \int_{-H}^{\eta} \frac{\partial p}{\partial x}\, dz\, dx = \sum_x \sum_{-H}^{\eta} \frac{\Delta P_t}{\Delta X} \Delta z\, \Delta x = \sum_x \sum_{-H}^{\eta} \Delta P_t \Delta z \quad (3)$$

2. Uncertainty of the method calculating topographic form stress

The method calculates the topographic form stress by taking the vertical and zonal integral of pressure gradient (east-minus-west), between the fluid cell adjacent to the eastern face of the bathymetric features and the fluid cell adjacent to the western face (Masich et al., 2015).

The ocean model uses partial vertical cells, for a better representation of the bathymetry. This means that, vertically, a fraction of each grid box is ocean, and the rest is land. To simplify the calculation, we treat all partial cells as land and select the adjacent ocean cell to extract the pressure of this face. This simplification results in an uncertainty in the calculation of the total topographic form stress due to the neglect of pressure change in partial ocean cells. We provide an example to show how this uncertainty occurs and estimate its magnitude (Figure S2).

We extract some partial cells with longitudes from -44.1250°E to -42.8750°E, latitude as 83.3750°S, depth as 298.3048 m. At each grid box, L_i is the fraction of the level thickness that is ocean, P_i is the pressure at the center of the grid box, i is the index of the grid box. For this section of the domain for 1500_max_53°S case, the extracted Li's and P_i's are:

L_1=0.3122, P_1=-32.7140 N m^{-2}; L_2=0.5305, P_2=-32.7111 N m^{-2}; L_3= 0.7643, P_3=-32.7143 N m^{-2}; L_4= 0.9608, P_4=-32.7182 N m^{-2}; L_5=1, P_5=-32.7196 N m^{-2}.

Taking into account the pressure pushing on each partial cell wall, the pressure on the land (longitude from -44.1250°E to -42.8750°E, latitude as 83.3750°S, depth as 298.3048 m), P_b, could be calculated as

$$P_b=P_1*L_1+P_2*(L_2-L_1)+P_3*(L_3-L_2)+P_4*(L_4-L_3)+P_5*(L_5-L_4)\approx-32.7145 \text{ N m}^{-2}$$

In the method of estimating topographic form stress, we select the P_5 as the fluid pressure on the land on the eastern side. The difference rate between P_b and P5 is (P5-P_b)/ $P_b\approx$ 0.0156%.

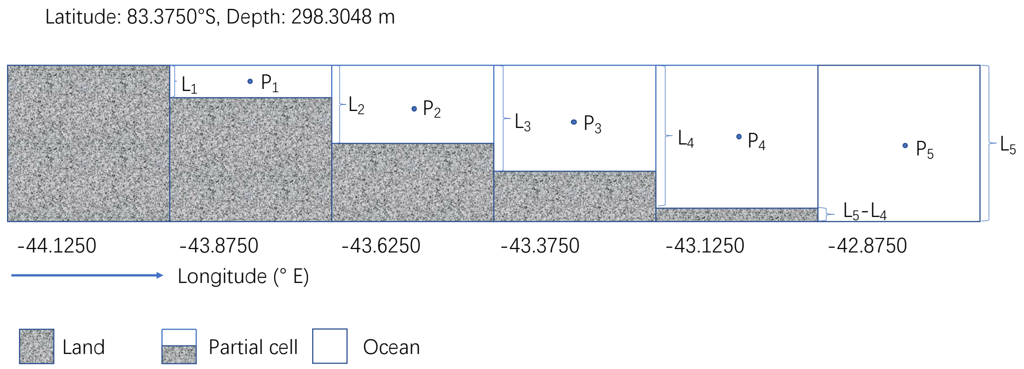

Figure S2: Some model grid boxes that include land, partial cells, and ocean with longitude from -44.1250°E to -42.8750°E, latitude as 83.3750°S, depth as 298.3048 m. L_i is the fraction of the level thickness that is ocean, P_i is the pressure at the center of the grid box, i is the index of the grid box.

3. The reconstructed paleo-bathymetry used in the simulation

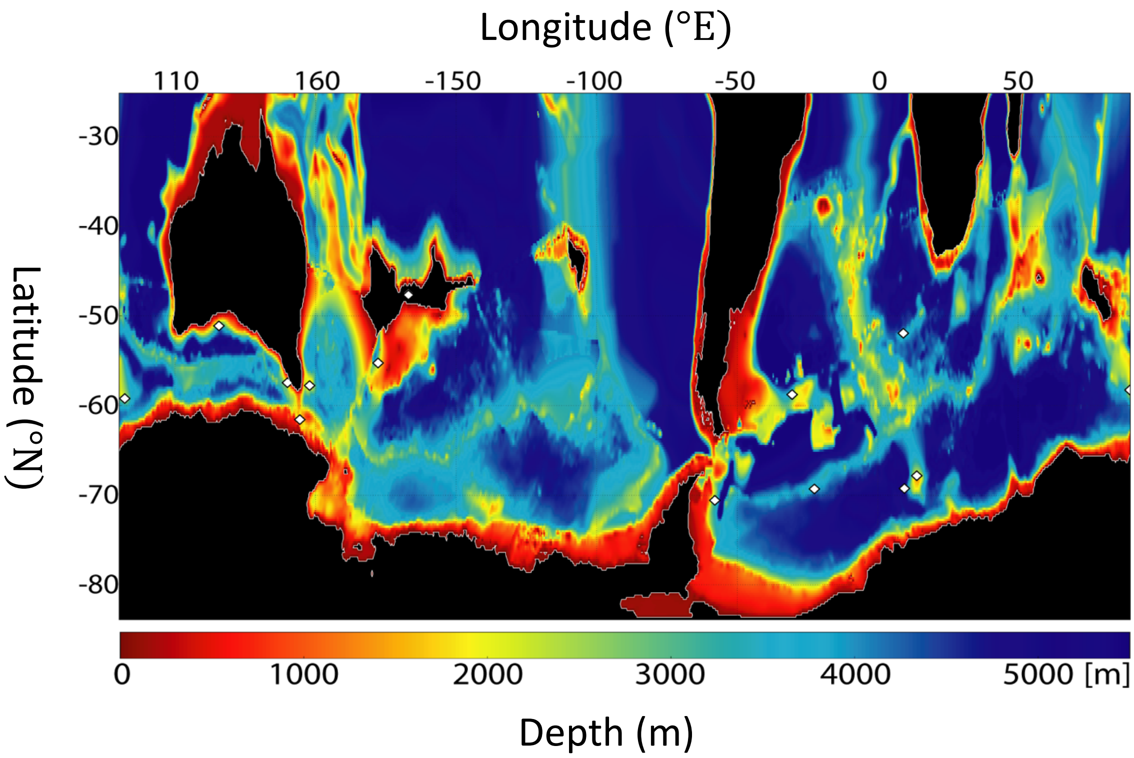

Figure S3: High-resolution (0.25°) reconstructed bathymetry of the late Eocene Southern Ocean.

4. Temperature gradient across the circumpolar belt (from New Zealand to Antarctic)

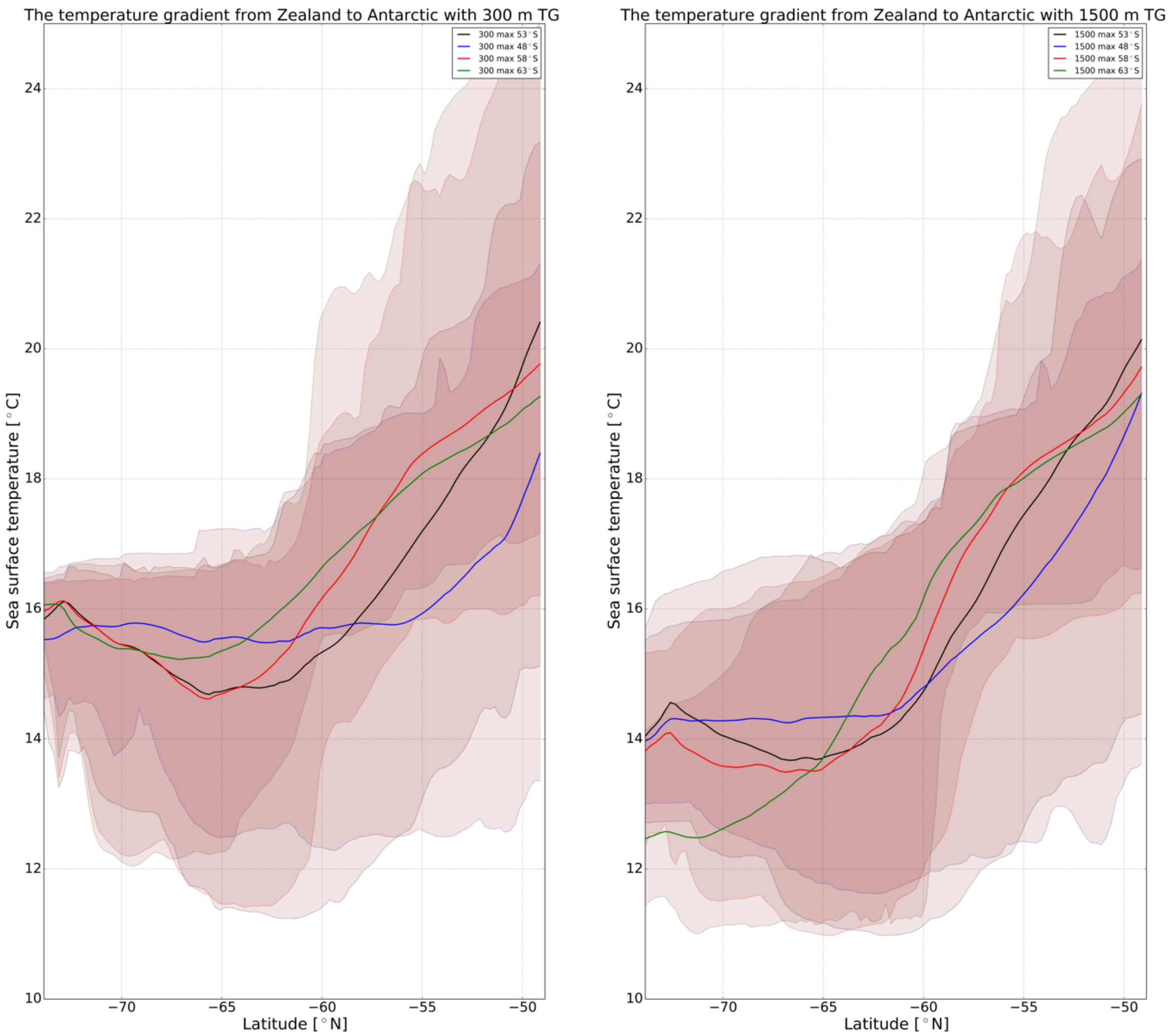

Figure S4: Annual mean sea surface temperature gradient from New Zealand to Antarctic coast (at 100 m depth) with two Tasmania Gateway depths (left: 300 m and right: 1500 m) and four wind stresses (different color solid curves). Shading shows the range of values for sea surface temperature.

5. The calculation of the T_b and T_{tw}

The "bottom flow" and "thermal wind" components are given by:

$$T_b = H_b \int U_b \, dy \qquad (1)$$

$$T_{tw} = T_{total} - T_b \qquad (2)$$

Above two equations are referring to equations (4) and (5) in the Munday et al. (2015). There is a difference in calculating the zonal bottom flow velocity U_b. By looking at hydrographic sections of the local bathymetry and U velocity for the TG and DP, respectively, we select a model level (e.g. Figure S5; model level 32; H_b), below which the current velocities are nearly homogenous, and above the level the velocities show strong horizontal and vertical gradient. Then we use a vertical average of zonal velocity below that model level as the U_b.

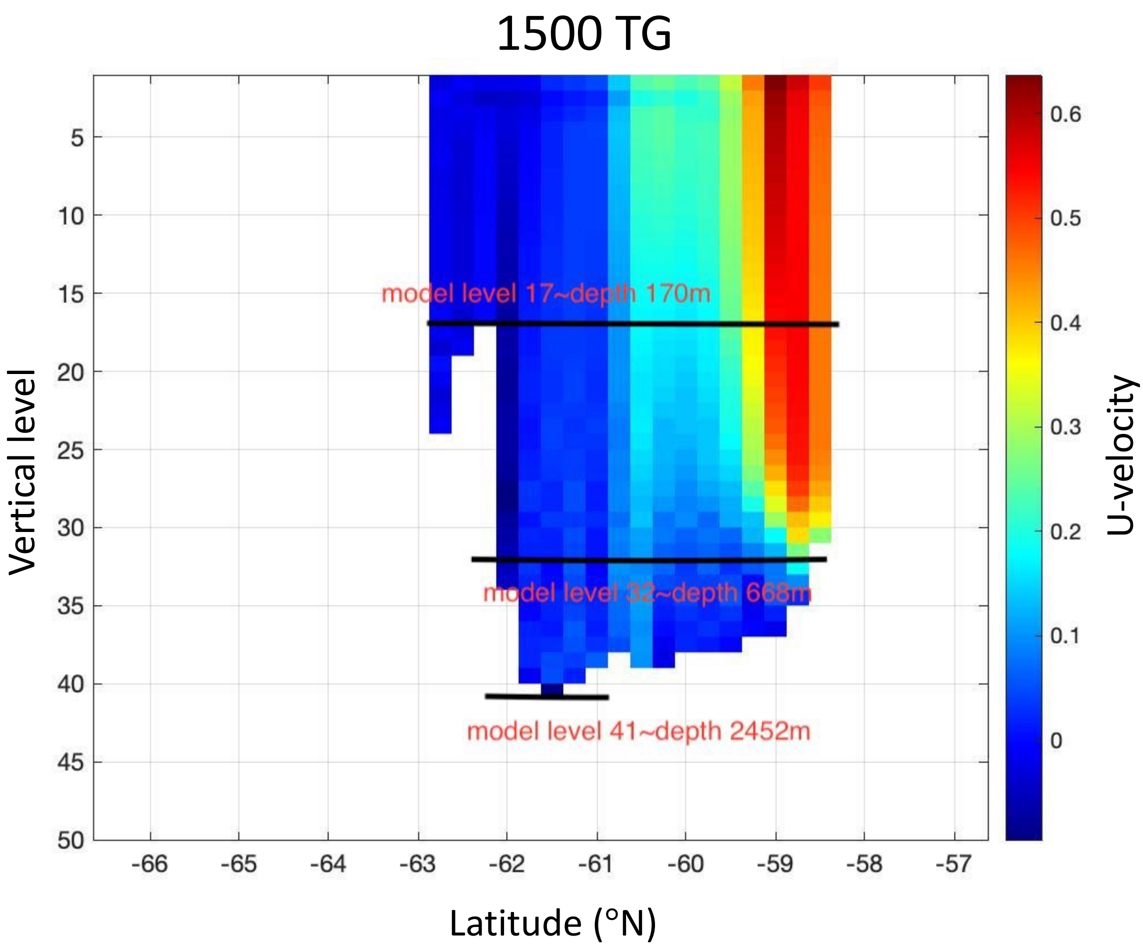

Figure S5: Hydrographic sections of the zonal velocities through the 1500 m TG. The vertical level is the uneven model level. Black lines show some unique levels and the corresponding depths