Supporting Information for "The global overturning circulation and the importance of non-equilibrium effects in ECCOv4r3"

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Introduction

The supporting information contains one text section and 3 figures supporting the results presented in our main text. Text section S1 outlines the calculations used to derive the volume budget and water-mass transformations in the surface layer. Figure S1 shows the domain masks used to define the major ocean basins in our study. Figure S2 gives a schematic representation of the various terms in the volume-budget presented in Figure 2 of the main text. Figure S3 shows the surface layer transformations in the Southern Ocean and the North Atlantic.

S1. Calculation of Surface Layer Watermass Budgets in ECCOv4r3

Ultimately, any diapycnal transport in the surface layer must be balanced by buoyancy exchange with the atmosphere and/or sea ice and mixing. We perform a volume budget decomposition within the surface layer, which is analog to the interior volume budget decomposition described in the main text. Analog to the interior volume budget discussed in the main text, we assume that the volume transport at the base of the surface layer, ψ_{surf} (minus the transport across the Greenland-Iceland-Scotland (GIS) ridge system, Ψ_{GIS}, in the case of the North Atlantic), must be balanced by heat- and freshwater-driven surface transformations, $T_{surf} = T_{\Theta} + T_S$, isopycnal volume change within the surface mixed layer, $\frac{d}{dt}V_{surf}$, and horizontal and vertical mixing, T_{mix}:

$$\overline{\Delta\psi(\sigma_2, t)} = \overline{\frac{d}{dt}V_{surf}(\sigma_2, t)} + \overline{T_{surf}(\sigma_2, t)} + \overline{T_{mix}(\sigma_2, t)}, \tag{S.1}$$

where all terms are defined as positive towards higher buoyancy (lower density). Here $\Delta\psi = \psi_{GIS} - \psi_{surf}$ in the North Atlantic and $\Delta\psi = \psi_{surf}$ in the Southern Ocean. We compute $\frac{d}{dt}V_{surf}(\sigma_2, t)$ as in the main text, this time including only volume changes that occur within the surface layer. We compute diapycnal transport associated with heat- and freshwater-driven surface density forcing, T_{Θ} and T_S, as in Newsom, Bitz, Bryan, Abernathey, and Gent (2016):

$$\begin{aligned} T_{\Theta}(\sigma_2, t) &= -\frac{\partial}{\partial\sigma_2}\iint_{A_O(\sigma_2, y_1, y_2, t)} \frac{\alpha}{c_p} Q_{surf}(x, y, t)dA \\ T_S(\sigma_2, t) &= -\frac{\partial}{\partial\sigma_2}\iint_{A_O(\sigma_2, y_1, y_2, t)} \frac{\rho_0}{\rho_{fw}} \beta S_0 f_{fw}(x, y, t)dA \end{aligned} \tag{S.2}$$

where the integration area, $A_O(\sigma_2, y_1, y_2, t)$, is the outcropping region where the surface potential density is larger than σ_2 within the particular basin of interest (in this case the

Southern Ocean and the North Atlantic), Q_{surf} is the surface heat flux and f_{fw} is the surface freshwater flux. $\alpha = -\frac{1}{\sigma_2}\frac{\partial \sigma_2}{\partial \Theta}$ and $\beta = \frac{1}{\sigma_2}\frac{\partial \sigma_2}{\partial S}$ are the thermal expansion and haline contraction coefficients, respectively, $c_p = 3994$J/kg/K is the heat capacity of seawater, $\rho_0 = 1029.$kg/m^3 is the reference seawater density in ECCO, $\rho_{fw} = 1000.$kg/m^3 is the reference density of freshwater in ECCO, and $S_0 = 35$g/kg is a reference salinity. Here we define the heat- and freshwater-driven transformation rates, $T_\Theta(\sigma_2, t)$ and $T_S(\sigma_2, t)$, as positive for transport towards lower densities. In the North Atlantic, we calculate the rate of deep water inflow across the GIS ridge system, $\Psi_{GIS}(\sigma, t)$, by measuring the rate of meridional transport across the northern boundary of the integration area. We denote the effect of horizontal and vertical diabatic mixing within the surface layer as T_{mix}, and calculate it as the residual of the time-means of the other terms in equation (S1).

The numerical implementation of the surface transformation terms follow that used by Abernathey et al. (2016) and is evaluated by discretizing σ_2 into evenly spaced bins at $\Delta\sigma_2 = 0.02$kg/m^{-3} spacing. Equations (S2) are then evaluated numerically as

$$\begin{aligned} T_\Theta(\sigma_2, t) &= \frac{1}{\Delta\sigma_2}\sum_{i=1}^{N_x}\sum_{j=1}^{N_y} A_{c_{ij}} \frac{\alpha}{c_p}\ Q_{surf}\ \delta(\sigma_2 - \sigma_2') \\ T_S(\sigma_2, t) &= \frac{1}{\Delta\sigma_2}\sum_{i=1}^{N_x}\sum_{j=1}^{N_y} A_{c_{ij}} \frac{\rho_0}{\rho_{fw}}\beta S_0\ f_{fw}\ \delta(\sigma_2 - \sigma_2') \end{aligned} \tag{S.3}$$

where A_c is the horizontal area of each grid cell and N_x and N_y are the zonal and meridional extents of the model domain. The discrete delta function, $\delta(\sigma_2 - \sigma_2')$, is defined as

$$\delta(\sigma_2 - \sigma_2') = \begin{cases} 1 & \text{if } (\sigma_2 - \Delta\sigma_2/2) <= \sigma_2' < (\sigma_2 + \Delta\sigma_2/2) \\ 0 & \text{else} \end{cases} \tag{S.4}$$

References

Abernathey, R. P., Cerovecki, I., Holland, P. R., Newsom, E., Mazloff, M., & Talley, L. D. (2016). Water-mass transformation by sea ice in the upper branch of the southern ocean overturning. *Nature Geoscience*, *9*, 596–601. doi: 10.1038/NGEO2749

Newsom, E. R., Bitz, C. M., Bryan, F. O., Abernathey, R., & Gent, P. R. (2016). Southern Ocean Deep Circulation and Heat Uptake in a High-Resolution Climate Model. *Journal of Climate*, *29*(7), 2597-2619. doi: 10.1175/JCLI-D-15-0513.1

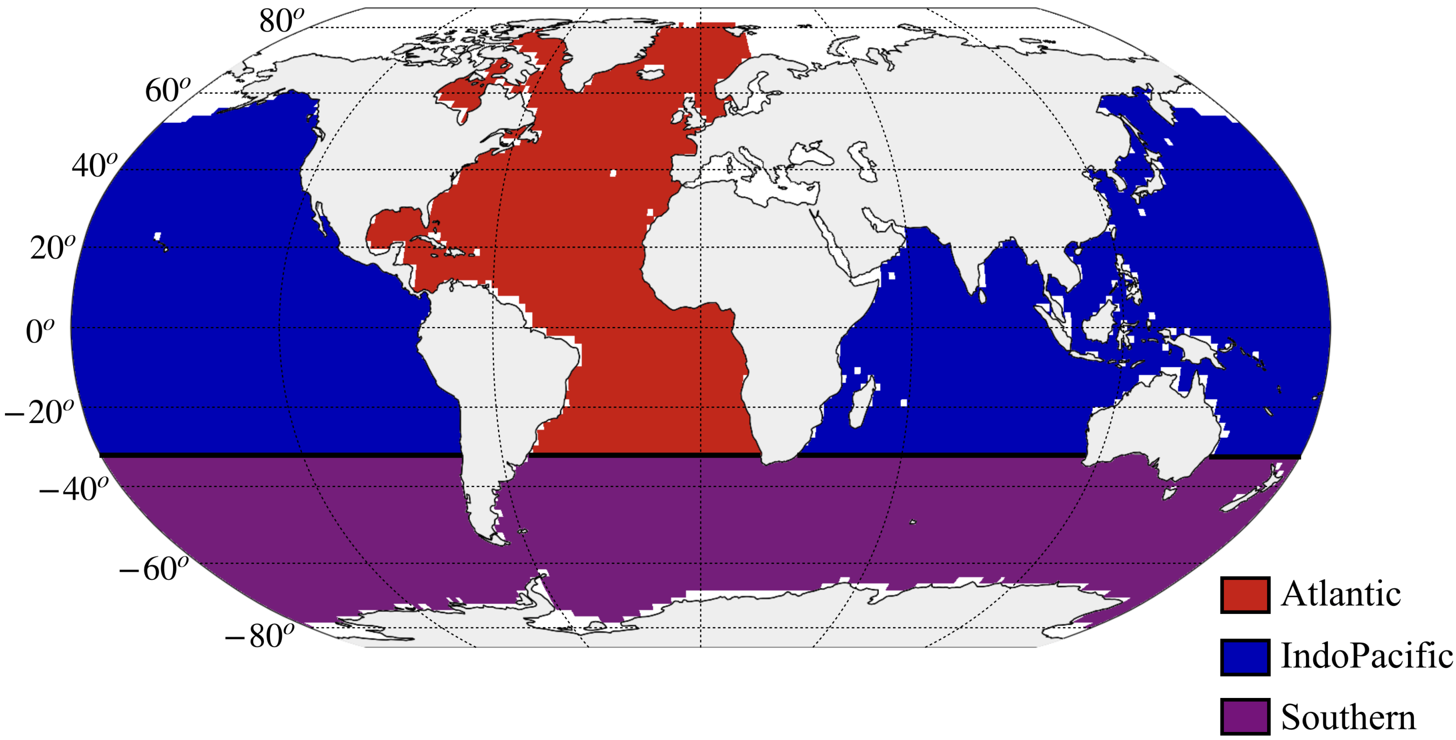

Figure S1. Basin masks used for subdividing the global ocean. The Atlantic basin (red) extends from 32^oS north into the Norwegian and Greenland seas. The Indo-Pacific basins (blue) are considered together and extend from 32^oS to the Aleutians in the North. The Southern Ocean (purple) is bounded in the north at 32^oS and extends to the coast of Antarctica.

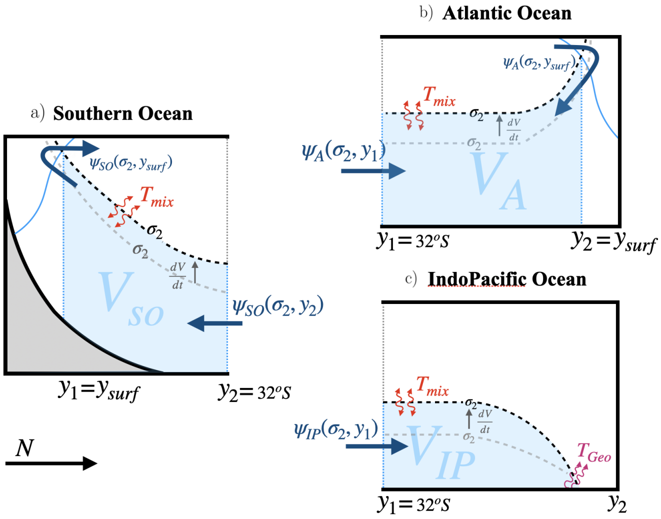

Figure S2. Schematic of the water-mass-transformation framework used in this study, applied to the Atlantic (subscript A), Indo-Pacific (subscript IP), and Southern Ocean (subscript SO). Black dashed lines indicate an isopycnal surface of density σ_2. Transports into and out of isopycnal volumes are indicated by arrows, with dark blue indicating advective flux ($\psi(\sigma_2, y)$), red diffusive flux (T_{mix}), grey apparent flux balanced by volume change (dV/dt), and purple transport balancing geothermal heating (T_{Geo}). Latitudes defining the southern and northern meridional bounds of the ocean basins are given by dotted blue lines and labeled y_1 and y_2, respectively, and the latitude where the isopycnal intersects with the surface layer is given by y_{surf}. The bottom of the surface layer is indicated by solid blue lines.

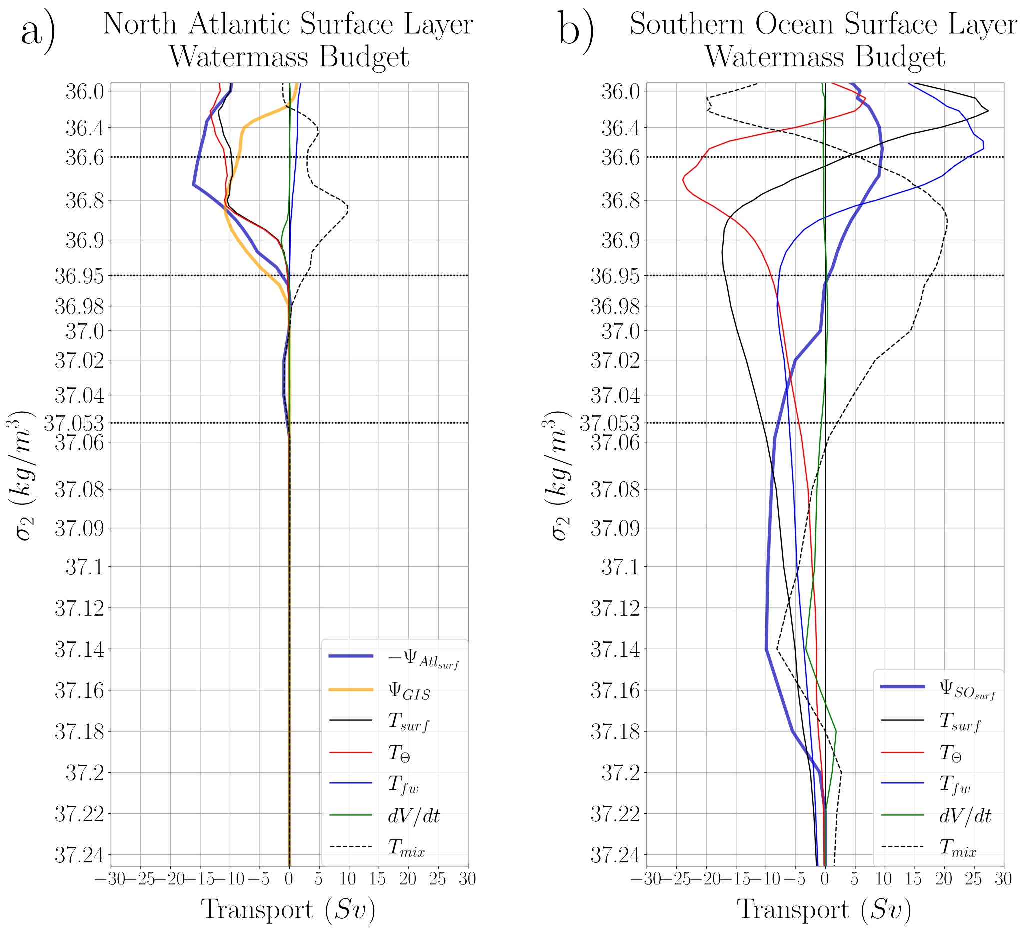

Figure S3. Water-mass-transformation decompositions in the surface layers of the North Atlantic (**a**) and Southern Ocean (**b**) high latitudes. All terms are defined positive for transformations towards higher buoyancy (lower density). Shown are the total surface transformation rate, T_{surf}, (thin, solid black) and its heat-driven, T_{Θ}, (thin, solid red) and freshwater-driven, T_{fw}, (thin, solid blue) components, as well as contributions from isopycnal volume change within the surface layer, dV/dt, (thin, solid green). Dense water inflow across the Greenland-Iceland-Scotland (GIS) ridge system, Ψ_{GIS}, is included in (**a**) (thick, solid orange). Stream function values at the bottom of the surface layer (thick, solid blue) are shown in the North Atlantic, $-\Psi_{Atl_{surf}}$, and the Southern Ocean, $\Psi_{SO_{surf}}$. Note the sign of stream function values in the North Atlantic is flipped such that negative values denote transport towards higher density. Any contributions from surface-layer mixing are calculated as a residual, T_{mix}, (dashed, black).

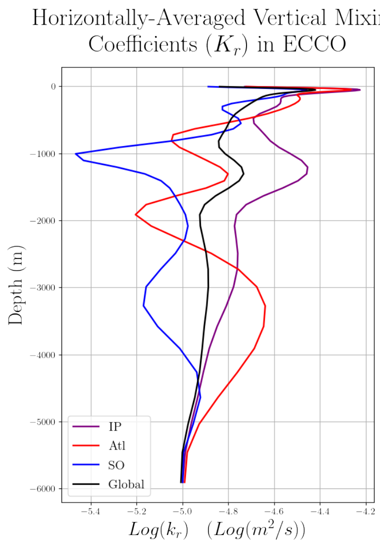

Figure S4. Vertical diffusivities k_r (m^2/s) in ECCOv4r3 horizontally averaged over the major ocean basins. Notice that these are the "background" diffusivities optimized by the inversion, and do not include mixing parameterized via the GGL scheme (diagnostics for which are not available). The averages presented are area-weighted horizontal averages, and masked using the same spatial mask as in Figure S1. Colored lines refer to the Indo-Pacific (purple), Atlantic (red), and Southern Ocean (blue). The black line gives the global average.