A steady-state, variable-density, 2-layer ocean model (VLOM, Box II) is used to investigate basic dynamics of the Atlantic meridional overturning circulation (AMOC) and Southern Ocean (SO). The domain consists of idealized (rectangular) representations of the Atlantic, Southern, and Pacific Oceans (Fig. I).

Analytic solutions and integral constraints: Solutions are obtained both numerically and analytically. The analytic approach splits fields into interior and boundary-layer parts, from which a coupled set of integral constraints (similar to Gnanadesikan, 1999) can be derived. The set allows properties of the circulation (upwelling-driven transport out of the SO, downwelling transport in the North Atlantic, transport of the Antarctic Circumpolar Current) and stratification (Atlantic thermocline depth, and the latitudes, and the layer outcrop in the SO) to be evaluated in terms of model forcings (Southern-Ocean wind strength and buoyancy flux Figs. 2 & 3), processes (eddy mixing $\nu$ and transports $V$ in the SO, northern sinking, upwelling within the Atlantic Subpolar Gyre), and to the presence of the Pacific Ocean.

Key results: A hierarchy of solutions is reported in which forcings and processes are individually introduced. The complete solution set includes a wide variety of solution types: with $g' > 0$, gray curves with $g' = 0$, and wind forcings $\tau_x$ (Fig. IV), processes (eddy mixing $\nu$ and transports $V$ in the SO, northern sinking, upwelling within the Atlantic Subpolar Gyre), and to the presence of the Pacific Ocean.

Dynamics of the AMOC and SO in an ocean model of intermediate complexity, Progress in Oceanography

Equations of motion: For horizontal transports $V$ and layer thickness $h$ in the surface layer we solve equations

$$ \nabla \cdot (hV) + f k V = - \nabla T + g \rho h, $$

where the available potential energy $\mathcal{E} = g h h' \rho$, the thermal expansion coefficient $\beta = 0.15$, $T'$ and $T_2$ are the surface and deep layer temperatures, and the wind stress $\tau = (\tau_x, \tau_y)$.  

Diapycnal processes: The three parts of the across-layer-interface velocity $w = w_x + w_y + w_z$ represent interior diffusion ($w_x$), mixed-layer entrainment ($w_y$), and bottom Ekman pumping ($w_z$) that ensures that $h$ is never less than a minimum value $h_{min}$.

Horizontal mixing: Rayleigh damping with damping coefficient $\alpha = 2 \times 10^{-6} \text{s}^{-1}$ mimics GM-mixing with $\alpha_{GM} \sim R_0^2$, where $R_0 = \sqrt{75} f$ is the deformation radius.

Solutions in the Atlantic (and Pacific) are obtained by integration along characteristic, and the SO response is zonally uniform. Based on Gill’s (1968) solution, these regions are smoothly joined through a boundary layer. This boundary layer carries a significant part of the ACC transport (Fig. VIII).

Three possible $h$-structures in the SO: 1. Outcrop at an internally determined latitude $y'$ 2. No outcrop ($g' = 0$, left panel) 3. Outcrop forced by buoyancy forcing ($g' = 0$, right panel).

Fig. 2: Prescribed meridional layer-1 temperature profiles without ($g' = 0$, black curve) and with ($g' = 0$, gray curve) outcrop in the SO.

Fig. 3: Meridional profiles of zonal wind stress.

Fig. 4: Streamfunction in analytic sol. without outcrop, $M = 0$, constant $\tau'$, and Atlantic only as in Gill (1968).

Fig. 5: Map of the $\mathcal{E}$ from numerical model with $g' > 0$, red curve given by red curve in Fig. 3, and without a Pacific Ocean.

Fig. 6: Schematics of SO stratification with $g' > 0$ (left) and $g' = 0$ (right panel).

Fig. 7: SO stratification from WOA 2013, climatologic October above 1500 m, and annual mean below.

Fig. 8: MOC properties as a function of $\tau_y$ the amplitude of wind forcing at the Drake passage latitude (pink curve in Fig. 3), in solutions without Pacific. Black curves (×) show analytic (numerical) results with $g' = 0$, gray curves with $g' = 0$ (cf. Fig. 2). Variable $\hat{y}$ denotes the SO outcrop (a), $\hat{h}$ the layer depth at $\hat{y}$ (b), $\lambda$ the overturning strength (c), $\Phi$ the ACC transport through the Drake passage, and $\delta$ the transport associated with the zonally independent SO sol. (d). Ekman and eddy transports at $\hat{y}$ together combine to $\Phi$ (e), and $P_P$ is the eastern-boundary $\mathcal{E}$ in the Atlantic, and $P_S$ the $\mathcal{E}$ at the Drake Passage associated with the zonally independent solution (f).