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

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(I) Abstract

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. 1).

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 $\mathcal{M}$, 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 ν 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 $\mathcal{M} > 0$ and $\mathcal{M} \leq 0$; with and without wind forcing; with, without, and for two parameterizations of northern-boundary sinking that represent cooling external to and within the North Atlantic; for a wide range of ν and wind forcings (Box *VI*); and for different closures. Novel aspects of the model and solutions include the following: use of VLOM, which allows buoyancy forcing to be introduced realistically; the aforementioned closure, which allows V^* to be determined when layer 1 represents *both* the surface mixed layer and the depth of subsurface isopycnals; latitude y', where layer 1 outcrops in the SO, being *internally* determined rather than externally specified (Box *V*); and a boundary layer, based on Gill's (1968) solution, that smoothly connects the Southern- and Atlantic-Ocean responses across the latitude of the southern tip of South America (Box *IV*). Finally, some solutions in the set are comparable to solutions to idealized, ocean general circulation models (OGCMs); in these cases, our solutions provide insight into the underlying dynamics of the OGCM solutions, for example, pointing toward processes that may be involved in eddy saturation and compensation.

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(II) Ocean model

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

$$(\mathbf{V}_t) + f\mathbf{k} \times \mathbf{V} = -\nabla\mathcal{P} + \tau - \nu\mathbf{V}, \qquad (h_t) + \nabla \cdot \mathbf{V} = w,$$

where the available potential energy $\mathcal{P} \equiv g'h^2/2$, the reduced gravity $g' \equiv g\alpha[T^* - T_2]/\rho_o$, the thermal expansion coefficient $\alpha = 0.15$, $T^*(y)$ 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 $w = w_d + w_m + w_n$ represent interior diffusion (w_d), mixed-layer entrainment w_n that ensures that h is never less than a minimum value h_m, and cooling processes external to the domain in the North Atlantic. If the model is forced by sufficiently strong cooling in the SO ($g' = 0$), mass exchange between the layers also occurs by horizontal flow across the layer outcrop y_0.

Horizontal mixing: Rayleigh damping with damping coefficient ($\nu = 2 \times 10^{-6}\,\mathrm{s}^{-1}$) mimics GM-mixing with $\kappa_{GM} \sim \nu R_D^2$, where $R_D = \sqrt{g'h}/f$ is the deformation radius.

(III) Forcing and domain

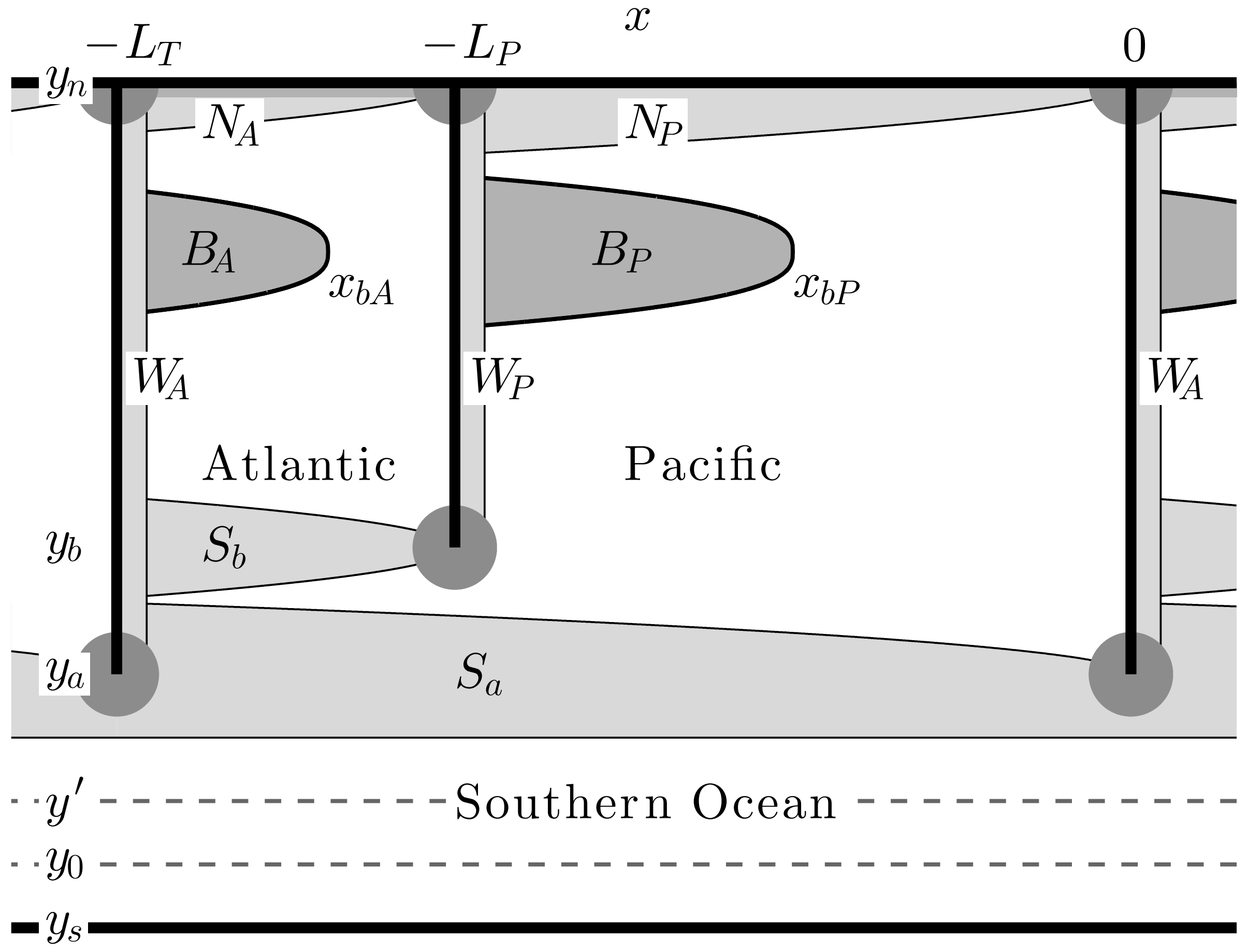

Fig. 1: Schematic plot of of the model domain, illustrating the idealized Atlantic, Pacific and Southern Oceans and boundary layers linking the different regions.

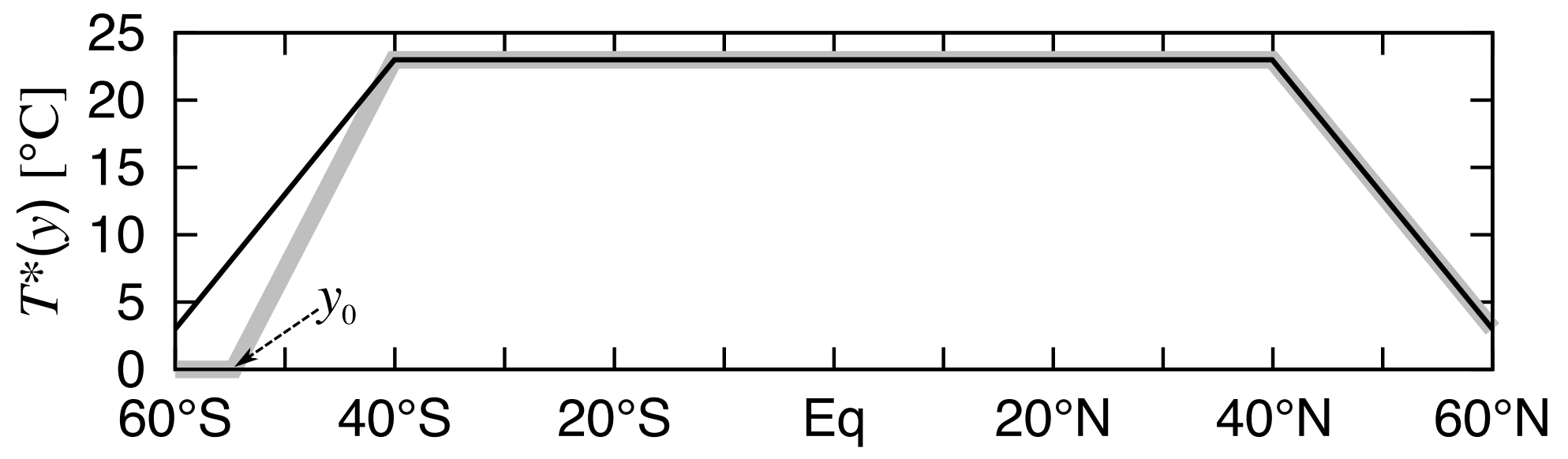

Fig. 2: Prescribed meridional layer-1 temperature profiles without ($g' > 0$, black curve) and with ($g' = 0$, gray curve) outcrop in the SO.

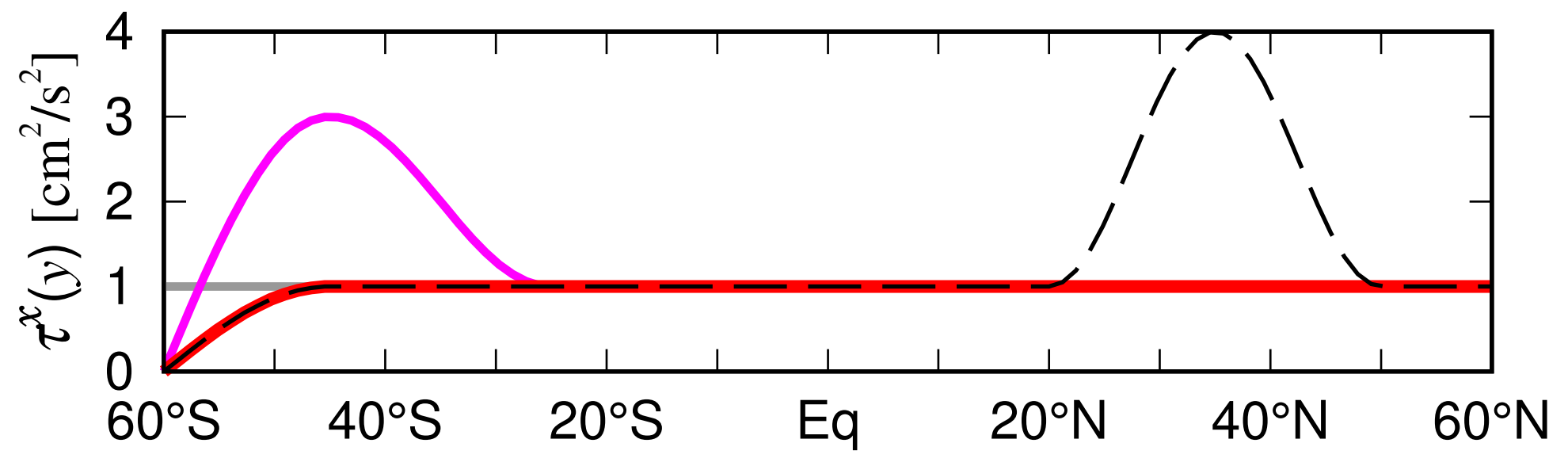

Fig. 3: Meridional profiles of zonal wind stress.

(IV) SO boundary layer

Solutions in the Atlantic (and Pacific) are obtained by integration along characteristics, and 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. 8d).

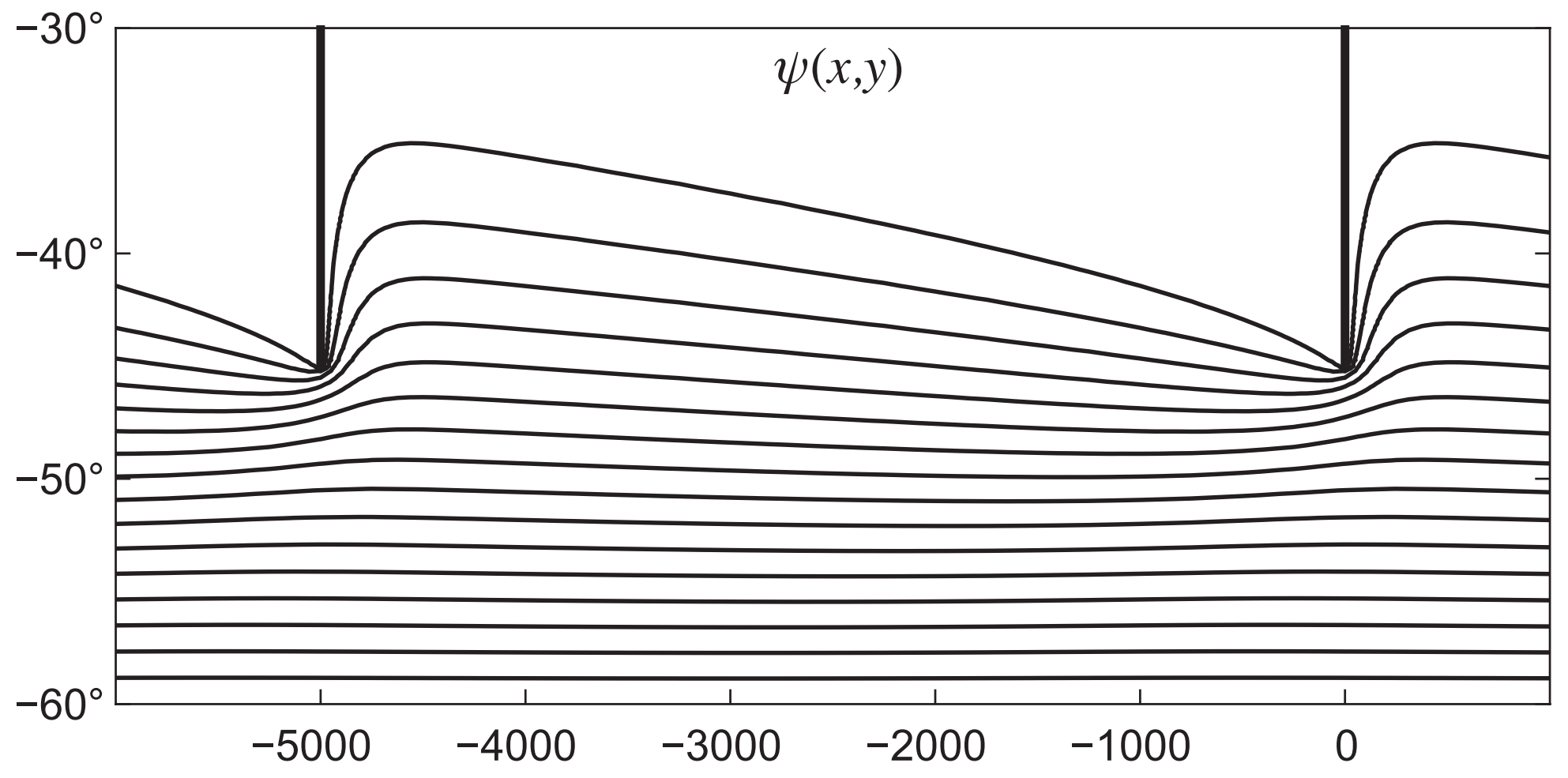

Fig. 4: Streamfunction in analytic sol. without outcrop, $\mathcal{M} = 0$, constant τ^x, and Atlantic only as in Gill (1968).

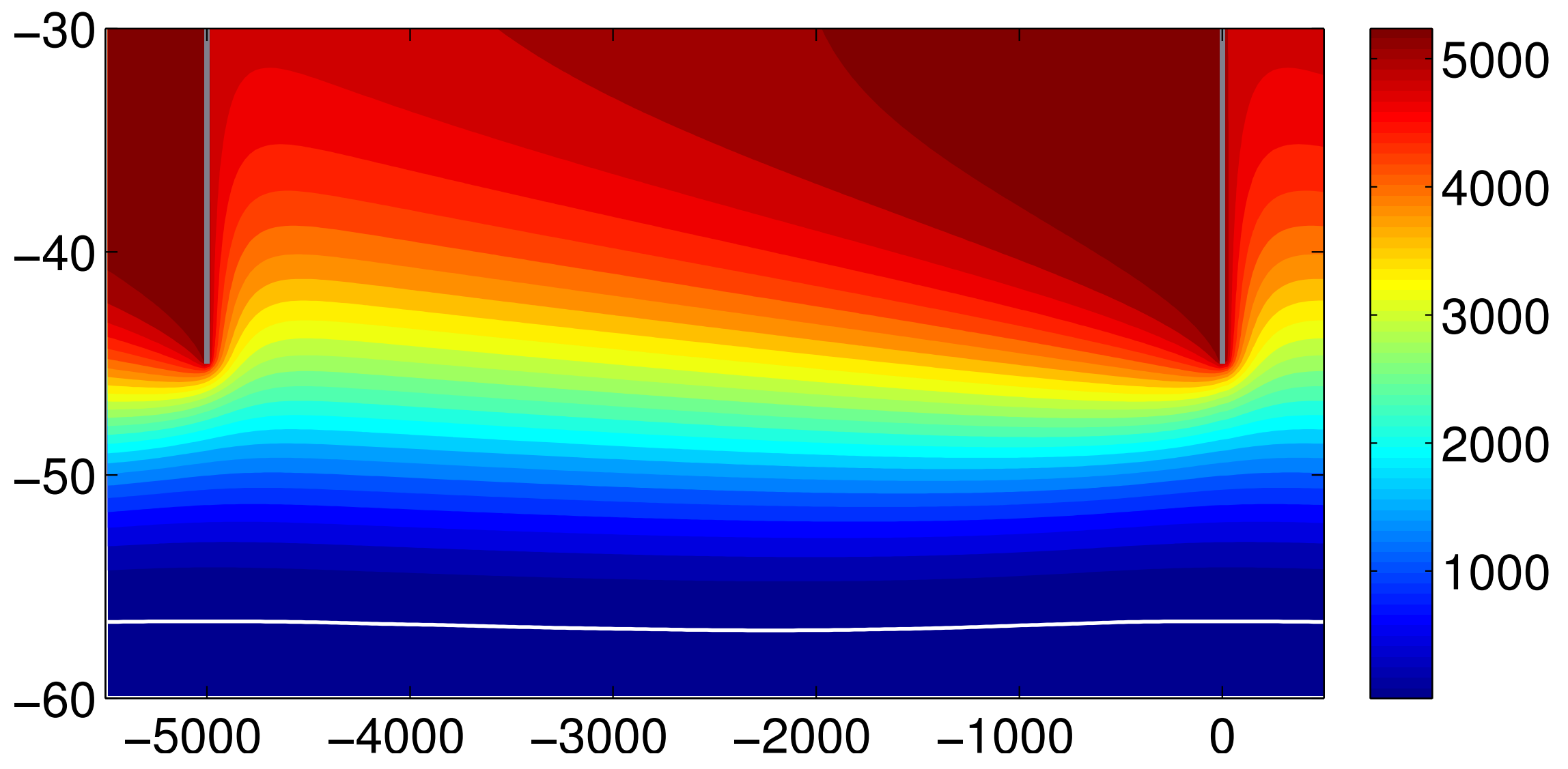

Fig. 5: Map of $\mathcal{P}$ from numerical model with $g' > 0$, τ^x given by red curve in Fig. 3, and without a Pacific Ocean.

(V) SO stratification

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)

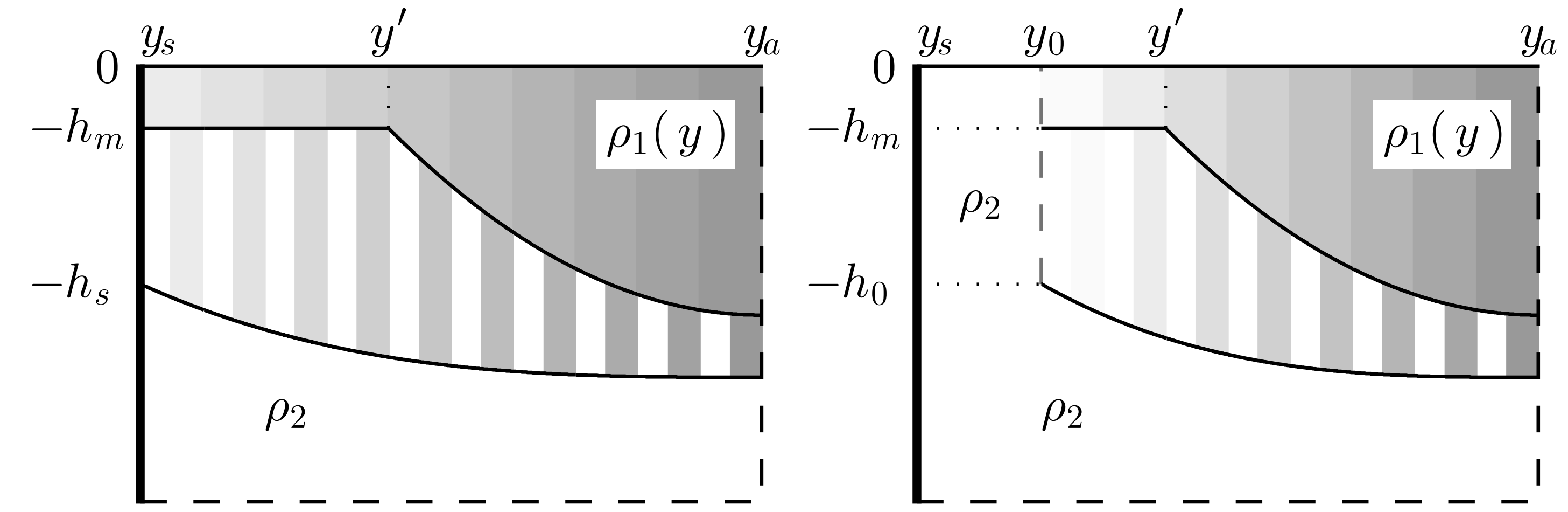

Fig. 6: Schematics of SO stratification with $g' > 0$ (left) and $g' = 0$ (right panel).

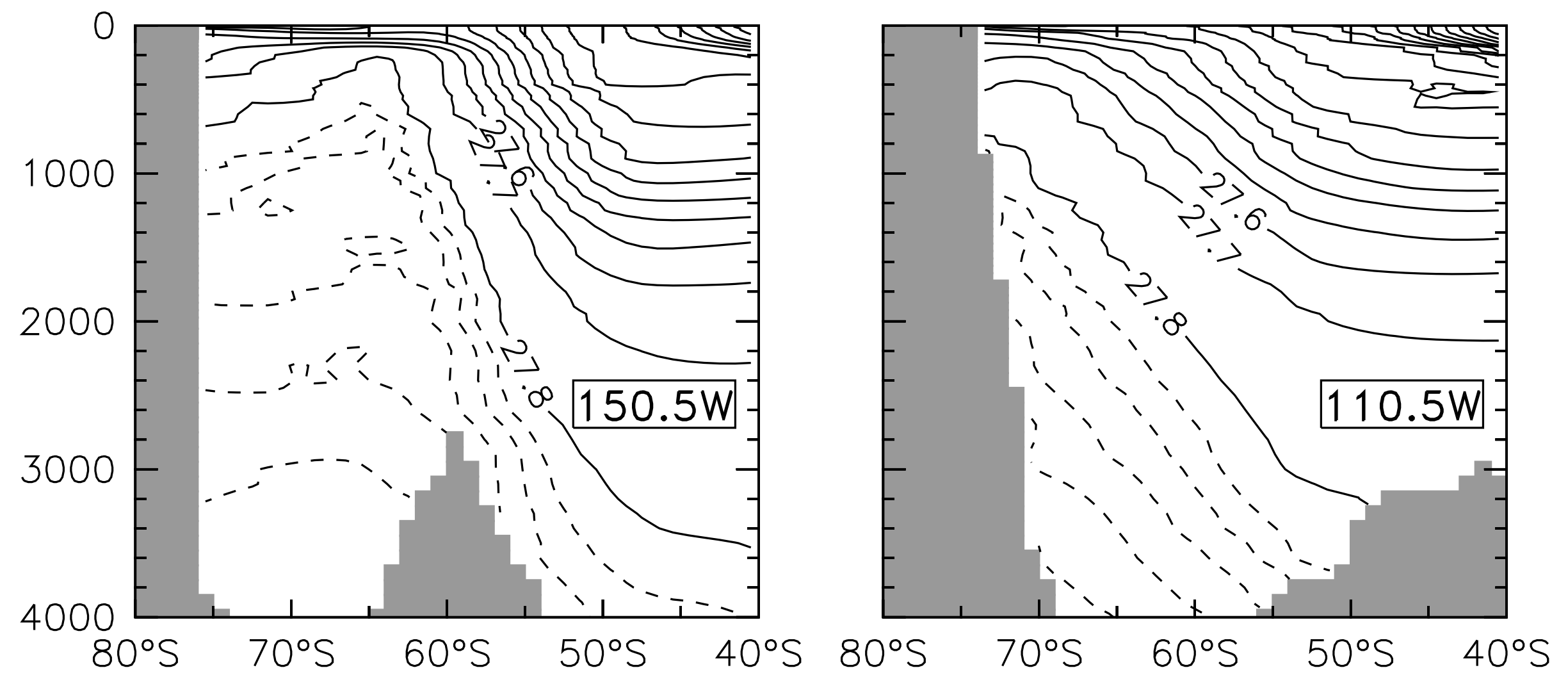

Fig. 7: SO stratification from WOA 2013, climatologic October above 1500 m, and annual mean below.

(VI) Example: Impact of SO winds

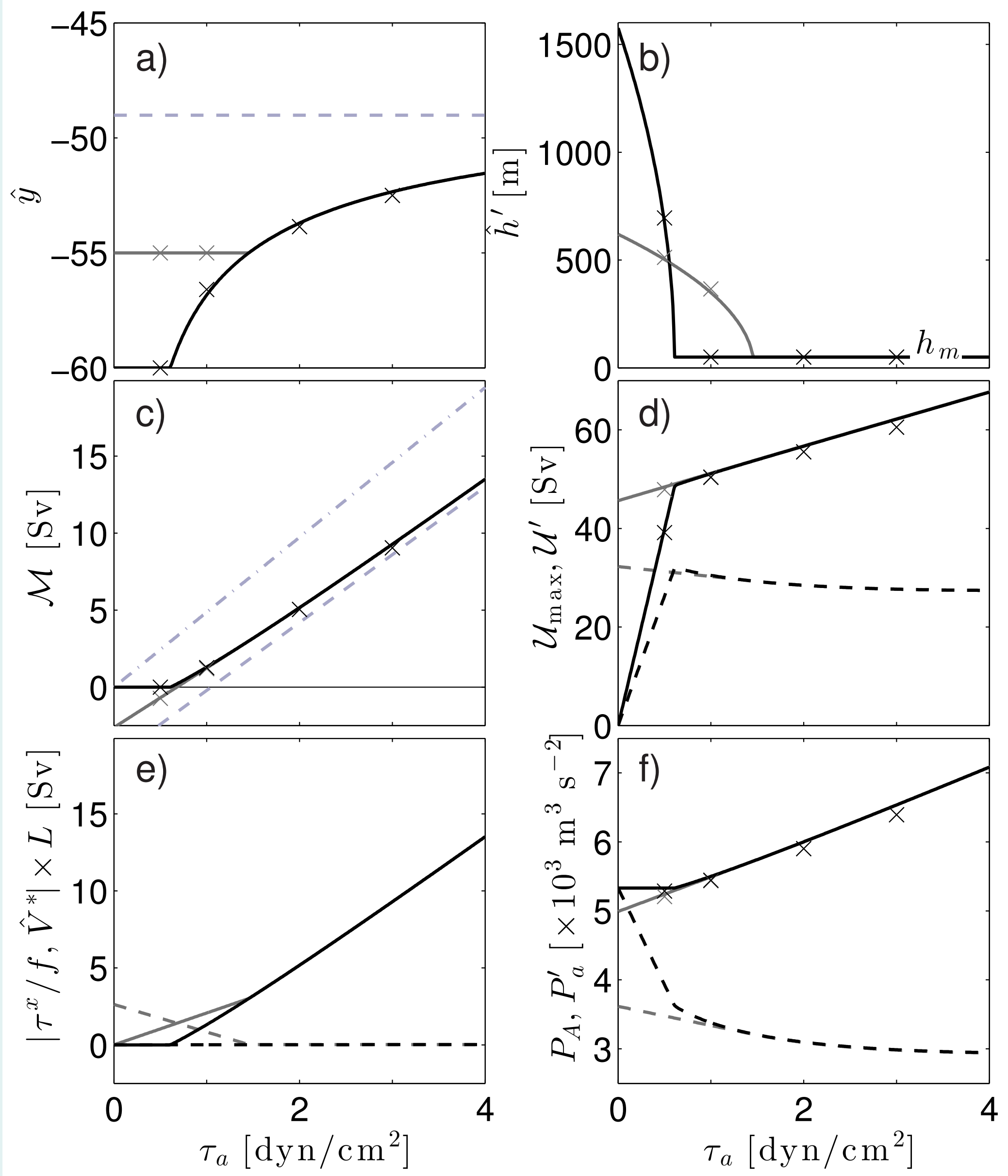

Fig. 8: MOC properties as a function of τ_a, the amplitude of wind forcing at the Drake passage latitude (pink curve in Fig. 3), in solutions without Pacific. Black curves (×) show analytic (numerical) results with $g' > 0$, gray curves with $g' = 0$ (cf. Fig. 2). Variable $\hat{y}$ denotes the SO outcrop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

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