Final report for: Warm Bias and Parameterization of Boundary Upwelling in Ocean Models - DE-SC0001962 DOE (416441/25245A)

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Executive Summary:

It has been demonstrated that Eastern Boundary Currents (EBC) are a baroclinic intensification of the interior circulation of the ocean due to the emergence of mesoscale eddies in response to the sharp buoyancy gradients driven by the wind-stress and the thermal surface forcing. The eddies accomplish the heat and salt transport necessary to insure that the subsurface flow is adiabatic, compensating for the heat and salt transport effected by the mean currents. The EBC thus generated occurs on a cross-shore scale of order 20-100 km, and thus this scale needs to be resolved in climate models in order to capture the meridional transport by the EBC. Our result indicate that changes in the near shore currents on the oceanic eastern boundaries are linked not just to local forcing, such as coastal changes in the winds, but depend on the basin-wide circulation as well.

Approach:

Our original hypothesis was that eastern boundary dynamics is part of the large-scale overtuning circulation and it is governed by adiabatic conservation of buoyancy: indeed that has been successfully demonstrated. In this context, we were able to derive "effective boundary conditions", that parametrize the effect of tracers' transport in narrow up/downwelling layers near the coast. These "effective boundary conditions" conserve mass and total tracers, and we hypothesized that they could be used in climate models to remedy the systematic warm-bias in sea-surface temperature caused by poor resolution of upwelling layers (cf. publications 1 and 2 below).

We also performed and analyzed high-resolution computations to evaluate the accuracy of the "effective boundary conditions", using the following model.

Model description:

The model employed is the ocean-only MITgcm (versions checkpoint62b, 62k, and 63a) configured as a closed basin which comprises one and one quarter hemispheres. The overall dimensions of the domain are 2400km $\times$ 6500km $\times$ 2000m, with four fifths of the domain in the Northern Hemisphere. The horizontal resolution is 5.4 km in the interior, and the horizontal grid is stretched over the 125km nearest to the boundaries, with maximum resolution of 1km at the boundary. There are 20 unequally spaced levels in the vertical, with vertical spacing increasing with depth ranging from 12m at the surface to 225m at the bottom. Hence the grid is given by 520 $\times$ 1272 $\times$ 20 points.

There is no salt and the buoyancy, b, is determined by temperature, θ only, through the linear equation of state $b = g\alpha\theta$, with $g\alpha = 2 \times 10^{-3}$m s^{-2} K^{-1}. Forcing is applied at the surface in the form of wind-stress, $\tau(y)$, in the zonal direction, x, and rapid relaxation to a prescribed temperature profile, $T^\star(y)$. Both τ and the relaxation to $T^\star$ are applied in the top level of the domain, and they

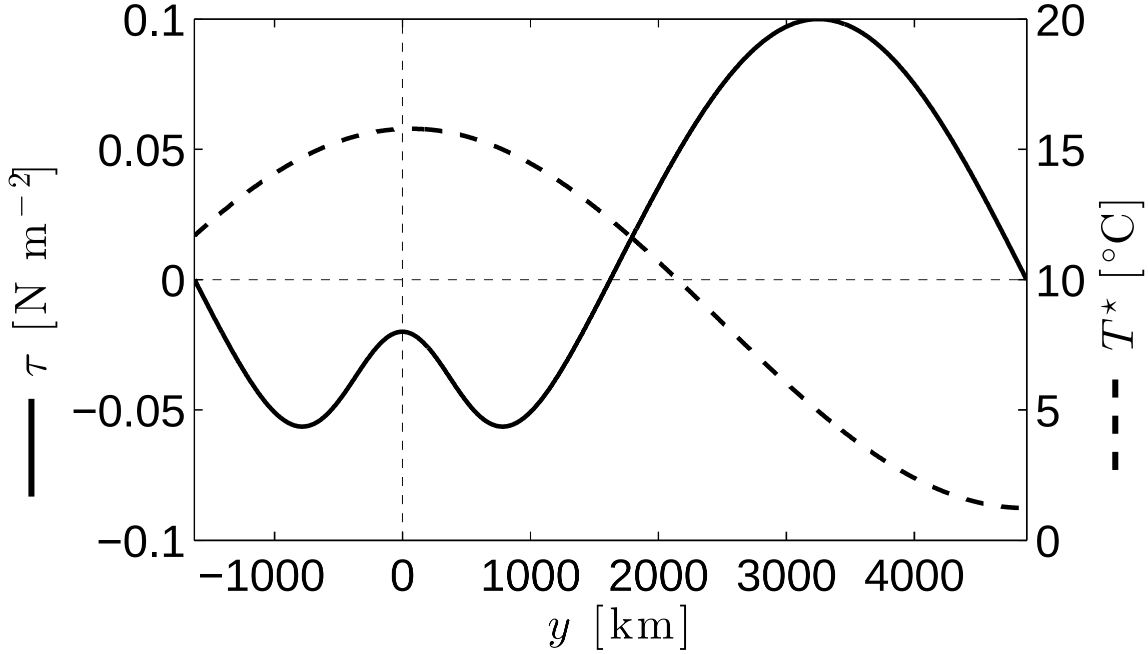

Figure 1: The zonal component of the wind-stress, τ, (solid line) and the relaxation temperature, $T^\star$, (dashed line) as a function of y.

are functions of latitude, y, only. There is no wind-stress in the north-south direction. The profiles of surface buoyancy and east-west wind-stress are shown in figure 1. The boundary conditions on the solid walls are no-normal-flow and no-slip. The lateral viscosity is $\nu = 12\text{m}^2\text{s}^{-1}$ and the fourth-order hyperviscosity $\nu_4 = 9 \times 10^7\text{m}^4\text{s}^{-1}$. The vertical visosity is $\nu_v = 3 \times 10^{-4}\text{m}^2\text{s}^{-1}$ and the diffusivity is $\kappa = 4 \times 10^{-5}\text{m}^2\text{s}^{-1}$. The model is in cartesian coordinates, on a β-plane, with $\beta = 2 \times 10^{-11}\text{m}^{-1}\,\text{s}^{-1}$.

The MITgcm solves the primitive equations, and we used it both in hydrostatic and non-hydrostatic mode. The computations were performed at NERSC on Hopper and Franklin computers, using 1056 CPU's per run. The initial run was spun up for about 800 years and the analyes were performed on the final 200 years. On Franklin, the performance was of 12 wall clock hours/model year (13k core-hours/model year) in non-hydrostatic mode and 3 wall clock hours/model year (3k core-hours/model year) in hydrostatic mode.

Accomplishments:

A novel set of diagnostics based on the "thickness weighted average" formulation was used to analyze the model's result. This approach allows to calculate the transport of buoyancy and momentum, including the eddy-transport component, without any approximation. Through these diagnostics, the adiabatic nature of the sub-surface component of the EBC has been clearly documented, and the characteristics of the EBC, its scales, and dynamics have been clearly explained. In particular it has been shown that the near-shore eddy-fluxes have a cross-shore component which drives a pressure gradient which maintains the baroclinic meridional mean currents. These currents are naturally *poleward* at the surface and *equatorward* at depth in the subtropics and subppolar regions and in the opposite direction in the tropics/equatorial region.

The analysis of high-resolution computations was focused on the dynamics of eastern boundary current. It has revealed that the cross-shore scale of EBC is the baroclinic deformation radius, ranging from 20km in the subpolar regions to 100km in the tropics. Furthermore, the vertical scale of the EBC is directly proportional to the strength of the eddy flux of buoyancy in the vicinity of the eastern boundary (details provided in publication 3 below). Our results lead to the conclusion that it is essential to resolve the mesoscale fields in the vicinity of the eastern boundarues in order to calculate the vertical and horizontal transports of heat, salt and nutrients that accompany these currents.

Published work:

1. Cessi, P. and C. L. Wolfe, 2009: Eddy-Driven Buoyancy Gradients on Eastern Boundaries and Their Role in the Thermocline. J. Phys. Oceanogr., 39, 1595-1614.

2. Cessi, P., C.L. Wolfe, and B. C. Ludka, 2010: Eastern-boundary contribution to the meridional overturning circulation. J. Phys. Oceanogr., 40, 2075-2090.

3. Cessi, P. and C.L. Wolfe, 2012: Adiabatic Eastern boundary currents (submitted to J. Phys. Oceanogr.).

Conference presentations:

Eddy-balanced buoyancy gradients on Eastern boundaries and the MOC. Ocean Sciences conference (ASLO) 2010, Portland, Oregon.

Eastern-boundary contribution to the Residual and Meridional Overturning Circulations. Conference in Mathematical Geophysics (CMG-IUGG) 2010, Pisa, Italy.

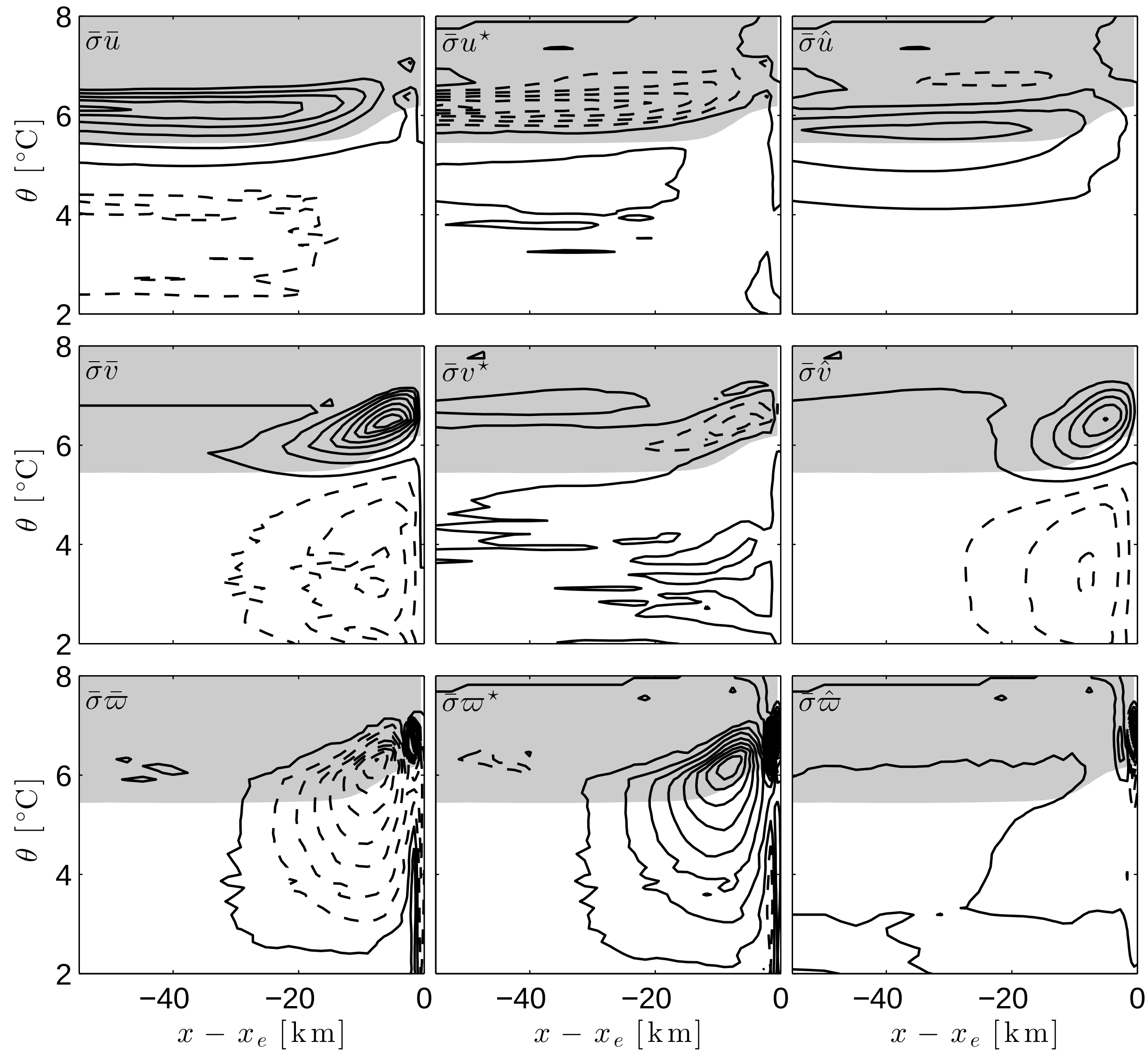

Figure 2: The three components of the thickness weighted velocity at $y = 3000$km (in the subtropics) are shown as a function of cross-shore distance from the eastern boundary and temperature. On the top is the zonal component, in the middle is the meridional component, and on the bottom is the diapycnal component. The rightmost column shows the totalthickness weighted velocity, the leftmost and central columns additionally show the contributions of the residual transport from the time mean and eddy components respectively. The contour intervals are 300ms, 2000ms, and $2 \times 10^{-5}\text{ms}^{-1}$ for the upper, middle, and lower panels, respectively; negative contours are dashed.