NOTES AND CORRESPONDENCE

Comments on "On the Subtropical Edge of the Stratospheric Surf Zone"

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Polvani et al. (1995, hereafter PWP) discuss the interaction of nonlinear wave breaking and thermal forcing in the stratosphere using a shallow water model. Despite using an identical formulation to that of Juckes (1989, hereafter J) they make no attempt to compare the results, limiting themselves to the assertion that previous work in the area is unclear. This note reviews the conclusions of J and their relevance to PWP.

Both papers are concerned with the dynamics of wave breaking, using the insight obtained from theoretical and observational work (McIntyre and Palmer 1983 and references) that showed that this process leads to quasi-horizontal mixing of potential vorticity on isentropic surfaces. Juckes and McIntyre (1987) investigated this process with a nondivergent barotropic model; J and PWP take the modeling a step further by using the shallow water equations and including a linear relaxation on the layer thickness to represent radiative forcing of the flow. As explained in J, the resulting thickness equation is the same as that obtained in an isentropic description of three-dimensional flow with Newtonian cooling. Salby et al. (1990a) use a model similar to the shallow water equations but with a more complex mass equation that allows a more direct comparison with the three-dimensional flow that these models are intended to imitate.

The wave breaking creates sharp potential vorticity gradients around the polar vortex, as suggested by McIntyre and Palmer (1983). Interestingly, in the experiments reported by both J and PWP the maximum in the potential vorticity within the vortex exceeds the maximum that would occur in the absence of wave breaking. In purely conservative flow localized mixing can create enhanced gradients but cannot induce such an increase in the maximum value, implying that nonconservative processes must be involved. Juckes (1989) analyzes the effect of the diabatic forcing on the zonal mean potential vorticity equation. The enhanced potential vorticity values can be interpreted in terms of the layer thickness, which is near its equilibrium value within the isolated polar vortex. The wave breaking leads to values thicker (i.e., warmer) than equilibrium in the surf zone and, hence, enhanced gradients across the boundary of the vortex. This structure implies enhanced potential vorticity values poleward of the vortex boundary.

The nonlinear dynamics and the Lagrangian structure of the flow are essential parts of the problem, but comparison with data is greatly facilitated by considering well-defined averaged quantities, although any averaging process will of course throw out some useful information. A number of authors have employed empirical diffusion coefficients, that is, the ratio between the meridional eddy flux and the meridional gradient. As expected on theoretical grounds, this quantity is not a pure measure of the dynamics but also depends on the nature of the quantity used to define the flux and gradient. Nevertheless, the empirical diffusion coefficients clearly show the confined region of wave breaking in midlatitudes. Juckes (1989) and Salby et al. (1990b) show that the transport deduced in the shallow water model is consistent with this broad range of studies, including three-dimensional simulations, analysis of observed quasigeostrophic potential vorticity, and two-dimensional models of the zonal mean flow and tracer distributions (see references cited in the above papers). PWP find a transport rate from the Tropics into the surf zone of 1%–2% of the hemispheric area per 10 days. Converted into more conventional units this is 3–6 ($\times 10^6$ m^2 s^{-1}), which is in the upper range of values previously estimated for transport rates in the surf zone. It would be interesting to see a comparison between the new Lagrangian diagnostics used here and the Eulerian results widely reported in the literature. The "one-sidedness" reported in PWP, for instance, is clearly related to the localization of the mixing that is seen from the Eulerian point of view: material displaced into the region of strong mixing undergoes large meridional displacements, while material displaced

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into regions of weak mixing tends to remain near the boundary.

PWP show the dependence of the extent of wave breaking on forcing amplitude and also discuss the propagation of the disturbance into the Southern Hemisphere. They suggest that strong shear acts to limit wave propagation, but there does not seem to be any theoretical basis for this suggestion. In J, the meridional extent of wave breaking shows a clear temporal dependence (Fig. 12 of J). In the initial flow, which includes moderate tropical easterlies, traveling wave-1 disturbances propagate into the Southern Hemisphere. In the course of the integration the tropical easterlies become stronger. This is a shortcoming of the model formulation: in the absence of unrealistically large relative vorticity values, there is no mechanism within the model to balance the easterly forcing generated by the dissipation of Rossby waves in the Tropics. In midlatitudes this forcing is balanced by the Coriolis torque associated with a mean meridional circulation, but this mechanism is absent at the equator. The model used by PWP is no different in this respect, so the tropical flow is likely to have the same defect. The accelerating easterlies eventually create a critical line for the traveling waves and this prevents further propagation into the Southern Hemisphere. In reality the variations in the zonal wind in the Tropics are dominated by the quasi-biennial oscillation, whose influence on the extent of the surf zone has been the subject of much research (e.g., O'Sullivan and Salby 1990 and references). The effectiveness of critical lines in confining wave activity in strongly nonlinear flows has been clearly illustrated by the observational study of Randel and Held (1991).

The transport barrier formed by the edge of the polar vortex is well documented and readily reproduced in barotropic models. A number of observational studies (reviewed in Holton et al. 1995) suggest that there is a second barrier to meridional transport at the southern edge of the surf zone. The results of J show a sharp reduction in the mixing intensity between 30°N and 10°N, but no clear intensification of the potential vorticity gradients comparable with that which is observed around the polar vortex. PWP, however, using an identical model, do find a strong potential vorticity gradient localized at the southern limit of the surf zone. Both sets of experiments show a spiral band of steep gradients extending from the Tropics across the surf zone to the polar vortex. This feature appears to be a robust response to forcing at zonal wavenumber one. Given the shortcomings of the model in the Tropics, noted above, the implications of these results for transport out of the Tropics are unclear.

In conclusion the shallow water model has shown that nonlinear dynamics associated with Rossby wave breaking coupled with a very simple representation of the radiative forcing can reproduce the main dynamical and transport related characteristics of the extratropical winter stratospheric. This does not, of course, rule out the possible importance of omitted details of the radiative forcing, but serves to clarify the nature of the dynamical processes. In the Tropics, on the other hand, the model is missing an essential momentum forcing and so cannot yield much information about the nature of the potential vorticity distribution. The value of the Lagrangian transport calculations would be greatly enhanced if their relation to previous work was discussed.

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