# Reply

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## Introduction

Juckes raises several points, which we will attempt to address in turn. It might be helpful to begin with an overview of the main point of our paper (Polvani et al. 1995, hereinafter PWP).

Following the observational diagnostic work of McIntyre and Palmer (1983) and the modeling studies of Juckes and McIntyre (1987) and others, we have come to understand the formation of a sharp poleward "edge" to the stratospheric surf zones as a direct consequence of the termination at those edges of the breaking of quasi-stationary Rossby waves. As McIntyre (1990) speculated, it seemed likely that there should be some similar kind of edge in the subtropics since it is well known that quasi-stationary waves cannot propagate deep into tropical easterlies. Given the now overwhelming evidence that such an edge—manifested most clearly in sharp gradients in trace gases and volcanic aerosols (Grant et al. 1996, and references therein)—really does exist in the subtropical stratosphere, it was our intention to clarify the underlying dynamics.

What we found was, at first sight, surprising. In some circumstances a sharp subtropical edge formed in the model, in others it did not. In the latter cases, even though the topographic forcing was (after a brief initial adjustment) stationary, wave breaking was occurring throughout the tropical easterlies. (As Juckes notes, the model dynamics ensure the development of tropical easterlies, even if they are not present initially.) What was happening—this point was emphasized in PWP, but seems not to have been appreciated by Juckes in his comment—is that breaking of quasi-stationary waves within the surf zone produces secondary, transient waves, which are then able to propagate into, and break within, the easterlies. In cases in which a sharp edge did form, these waves were still present, but did not break in the Tropics. Similar behavior has recently been found in a three-dimensional model by O'Sullivan and Chen (1996).

## Dependence on the wind profile

The appearance of the transients complicates theoretical analysis of the dynamics of edge formation. Breaking of small-amplitude waves will concentrate around the critical line where the mean zonal wind $\bar{u} = c$, the wave's phase speed. Although stratospheric planetary wave amplitudes are far from small, the extent of the surf zone is still likely to be determined by the location of the critical points where the total flow is stationary with respect to the wave (e.g., Polvani and Plumb 1992). One therefore expects that the primary, stationary wave will be sensitive to the mean wind and, in particular, that breaking will not extend deep into the tropical easterlies. This is consistent with what we found in PWP: the subtropical edge of the main surf zone—the strongly turbulent region dominated by breaking of the stationary wave—was located a little equatorward of the transition from westerlies to easterlies in the mean flow.

That, however, was not the main issue in PWP. Rather, we were concerned with the sharpness of the subtropical edge and its efficiency as a barrier to transport. While the location of this edge may have been determined by the primary, stationary wave, it was, as noted above, the breaking of the secondary transients that determined the edge sharpness. For such waves, $\bar{u} - c$ is not simply a function of the local winds since $c$ (or the range of its values) is likely to be sensitive to

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the winds in the midlatitude region where the waves are generated. Consider, for example, adding a solid body rotation to one of our experiments. If the transients are free modes [cf. the generation of free modes on the vortex edge in the experiments of Polvani and Plumb (1992)], their phase speeds will simply be shifted by the solid body rotation and their Doppler-shifted phase speeds will thus be unchanged; therefore, the whole problem will simply be translated by the solid body rotation and the tropical behavior will be unaffected, despite the shift in the tropical winds. Thus, there is a theoretical expectation that transient wave breaking in the Tropics will depend not primarily on the tropical winds, but on the wind *difference* (i.e., the gross shear) between midlatitudes and Tropics. (We do not mean to imply that it is the *local* shear at the subtropical edge that is crucial.) So, while we have no rigorous theoretical analysis to give, we dispute Juckes' claim that the link between edge sharpness and subtropical shear has no theoretical basis. Incidentally, the calculations in Juckes (1989) were fundamentally different from ours in this respect, as the transients in that case appear to have been generated externally by the pulsating forcing, and thus their phase speeds would have no sensitivity to the midlatitude winds.

In our numerical experiments (only some of which were described in PWP) we certainly found empirical evidence to support our statement that the edge sharpness depends on the shear and not on the strength *per se* of the tropical easterlies. Figures 1 and 2 illustrate results from experiments described in PWP. The case labeled "Fig. 9" (corresponding to that shown in Fig. 9 of PWP) includes thermal relaxation and develops a sharp subtropical edge. The three cases labeled "Fig. 12" are adiabatic experiments, with different values of subtropical shear. Of the latter three, cases 12-1 and 12-2 have tropical winds similar to those of case 9 (cf. Fig. 1b), but the subtropical edges that develop (cf. Fig. 2) in those experiments are very diffuse and wave breaking extends well beyond the main surf zone in both cases. Only in case 12-3, with subtropical shear comparable to that of case 9 (but with much stronger tropical easterly winds), does a similarly sharp edge form.

Further evidence that the shear, and not the strength of the tropical winds, is the controlling factor in the sharpness of the tropical edge can be seen in the numerical calculations of Chen (1996), who performed a series of calculations differing only in the initial zonal wind profile, as in PWP. Although this is not stated in the paper, cases with stronger shear, but the same zonal wind at 30°N, produce a sharper tropical edge [e.g., Fig. 7 of Chen (1996)].

## Quantification of the transport

We chose to quantify transport across the subtropical edge in terms of the area transport rate. Juckes suggests we should have determined an effective diffusivity to permit comparison with other estimates. We do not understand this suggestion, for several reasons.

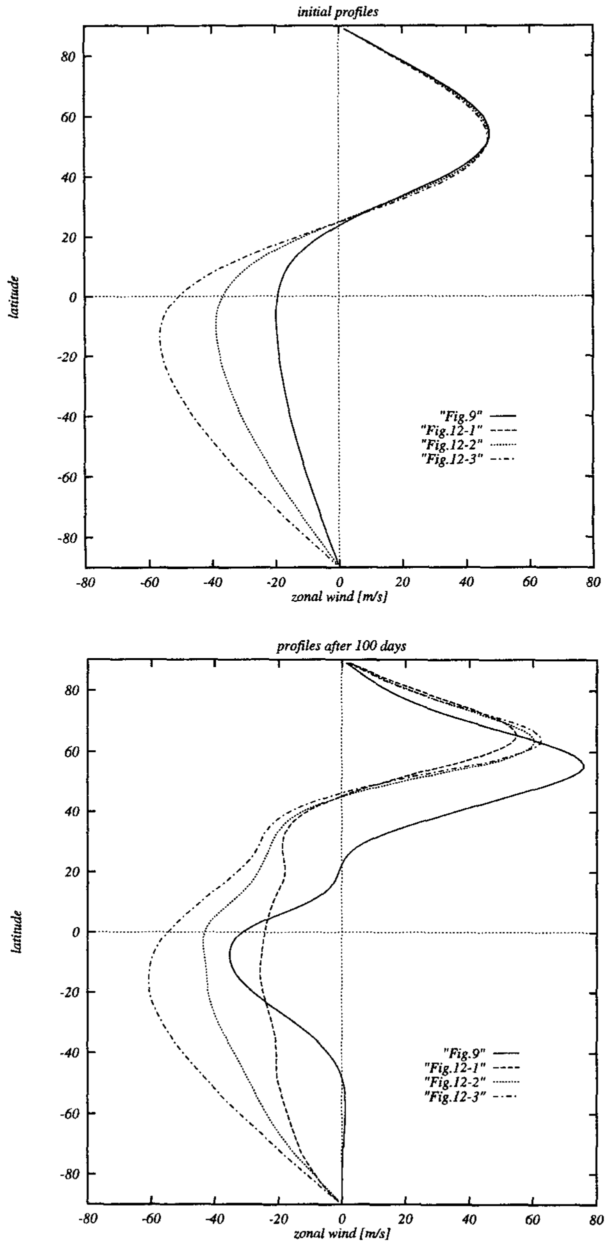

FIG. 1. (a) The initial zonal wind profiles for the cases presented in Figs. 9 and 12 of PWP. The case labeled "Fig. 9" includes relaxation to the equilibrium layer thickness given in Fig. 7 of PWP; the cases labeled "Figs. 12-1 to 3" are adiabatic with increasing shear in the Tropics. The initial conditions for cases "Fig. 9" and "Fig. 12-1" are identical. (b) The zonally averaged wind profiles after 100 days for the same four cases.

There has in the past 20 years or so been a strong interest in determining effective diffusivities to meet the practical demands of two-dimensional (zonally av-

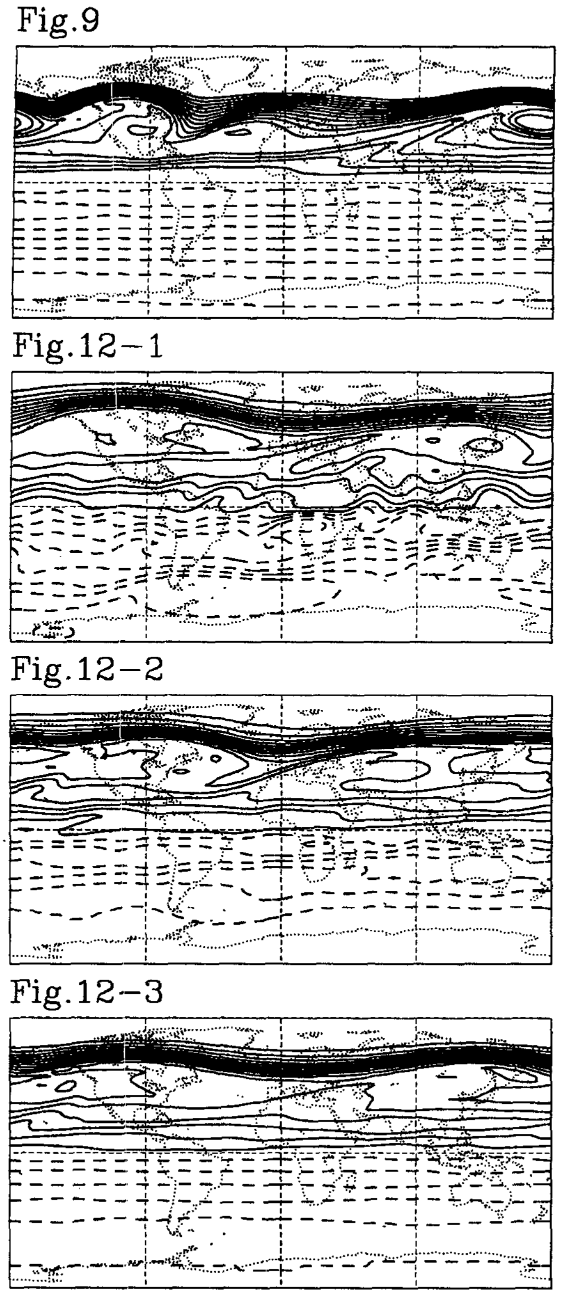

FIG. 2. The potential vorticity field for the four cases of Fig. 1. The case with diabatic relaxation "Fig. 9" is a lot more similar to case "Fig. 12-3," which has a strong wind shear in the Tropics, than to cases "Fig. 12-1" and "Fig. 12-2," which have weaker shear.

eraged) chemical transport models. In practice, this approach seems capable of reproducing the mean transport reasonably well (Plumb and Mahlman 1987; Juckes 1989). However, from a theoretical point of view, it is well known that representing turbulent transport by diffusion can be justified formally only under assumptions known to be false in the stratospheric surf zones. In general, therefore, we do not believe this approach offers a sound basis for making comparisons.

More to the point, however, it is not transport *within* the turbulent surf zone that we were addressing in PWP, but the transport *into* the surf zone by entrainment across the subtropical edge. It is not conventional to characterize entrainment by a diffusivity, since diffusion is an ill-defined concept under such circumstances, the mean gradient being ill-defined at the edge. We do not understand how Juckes converted our transport rate into a diffusivity. Moreover, comparison of our subtropical transport rate with earlier estimates of surf zone transport rates is misleading because these are quite different, and not necessarily related, quantities. It is quite possible, for example, to have vigorous mixing within the surf zone without any transport across its edges [e.g., see Fig. 13 of Polvani and Plumb (1992)].

In many areas of fluid dynamics, transport across the edge of a turbulent region is expressed in terms of an entrainment velocity. The area transport rate is an alternative way of expressing this quantity. (For the record, our result of 1%–2% of the hemispheric area per 10 days corresponds to an entrainment velocity of 8–15 cm $s^{-1}$.) Quantifying the transport in this way is not new, as Juckes claims; it has been widely used to express stratospheric transport rates across the poleward and subtropical edge of the surf zone, estimated from global analyses or models (Dahlberg and Bowman 1994; Manney et al. 1994; Plumb et al. 1994; Waugh et al. 1994; Norton and Chipperfield 1995; Waugh 1996). We chose to express our transport rates in this form to facilitate comparison with such estimates.

## Can a shallow water model capture the dynamics of the subtropical edge?

We do not dispute Juckes' suggestion that the model is unrealistic in the Tropics, a point explicitly noted in PWP. However, we do disagree with what we think is his implication that the model differs from the atmosphere in the way in which the tropical stratosphere responds to midlatitude Rossby waves—the very existence of the quasi-biennial oscillation (QBO), for example, is indicative of the inability of the equatorial atmosphere to resist stress.

Of course, as noted in PWP, the presence of the QBO is one of the reasons why none of our numerical experiments can be seen as representing reality. The point of our experiments was to identify the dynamical *mechanisms* involved in the formation of the subtropical edge and to identify how the properties of the edge might depend on stratospheric conditions, such as tropical winds. Given the dominance of the QBO and the strong evidence of modulation of tropical transport by the QBO (e.g., Trepte and Hitchman 1992), this is a matter of some importance to our understanding of stratospheric transport. The recent three-dimensional modeling study of O'Sullivan and Chen (1996) indicates that the mechanisms discussed in PWP may indeed be very relevant to the interaction of the tropical QBO with the midlatitude stratosphere.

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