2.5 THE EQUILIBRATION OF SHORT CHARNEY WAVES: IMPLICATIONS FOR PV HOMOGENIZATION

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1. INTRODUCTION

Baroclinic adjustment theories postulate that baroclinic instability equilibrates in the Earth's atmosphere by smoothing the PV gradients in the interior and the temperature gradients at the surface. It has been previously suggested in the literature (e.g., Lindzen, 1993) that the temperature gradients at the surface are not as well mixed as the interior PV gradients, which is often attributed to surface thermal damping (Swanson and Pierrehumbert, 1997).

However, full PV homogenization is only observed in the extratropical troposphere in a narrow interior region around 700 hPa. Considered in an integral sense, the interior tropospheric PV gradient is in fact as poorly mixed as the boundary PV gradient. This is consistent with the fact that observed tropospheric shears are comparable to the critical shear of a two layer model of tropospheric depth (Stone, 1978).

In the Boussinesq-Charney problem, the Held (1978) scale, defined as: (symbols have standard meaning)

$$h = \frac{1}{\beta}\frac{f_0^2}{N^2}\frac{dU}{dz},$$

gives the depth over which the integrated interior PV gradient balances the delta function PV gradient at the ground. In this work we have studied how short Charney waves (i.e., waves with penetration depths smaller than, or of the order of, h) equilibrate.

2. LINEAR ANALYSIS

For a linear growing mode, the PV diffusivity:

$$\kappa = -\frac{\overline{v'q'}}{\bar{q}_y} = \frac{kc_i}{2}|\eta'|^2$$

is bounded away from the steering level but can be very large at that height as c_i decreases (Zurita and Lindzen, 2001). Hence, waves with penetration depths smaller than the Held scale can only satisfy the kinematic condition $\int_0^\infty \overline{vq}dz = 0$ (including the surface heat flux but neglecting the eddy momentum flux) through a large PV flux at the steering level. We have tested whether these modes could be neutralized when the PV gradient is smoothed out locally in a neighborhood of the steering level.

First, we have used an analytical model with an idealized interior PV gradient of the form:

$$\bar{q}_y = \alpha(U-c)^2$$

which vanishes at the steering level alone. The substitution of this expression in the vertical structure equation eliminates the singularity at the steering level. It can then be shown that neutral eigenvalue solutions exist for this case.

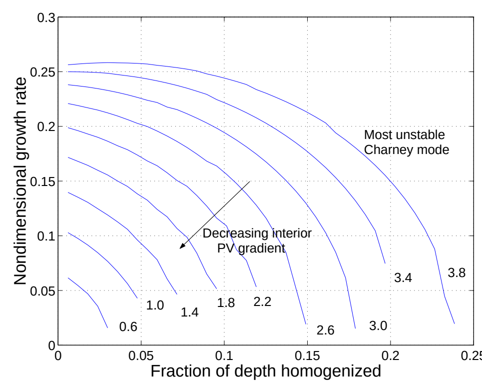

Figure 1: *Growth rate as a function of the thickness of the homogenized region around the steering level.*

This result has been confirmed numerically using a linear quasigeostrophic model. We calculated the growth rates of a modified Charney problem in which the interior PV gradient equals β everywhere except for a finite region around the steering level where it vanishes. The results are shown in figure 1 where the growth rate is plotted as a function of the thickness of the homogenized region surrounding the steering level. The different curves correspond to different ratios of the interior and boundary PV gradients, with the rightmost curve corresponding to the most unstable mode in the Charney problem.

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This suggests that short baroclinic waves can equilibrate by mixing PV across a localized region, even when the Charney-Stern condition is violated.

3. QUASILINEAR EQUILIBRATION

We have tested whether short Charney waves can equilibrate by reducing the local PV gradient at the steering level. This is plausible in view of the linear considerations of the previous section. Also, dynamical mixing is expected to be more efficient in the vicinity of the steering level. We have used for our study a 50 level nonlinear quasigeostrophic beta-plane channel model forced by Newtonian cooling. The depth of the unstable modes is limited by the channel length, the jet width after equilibration, and the static stability (fixed). The ratio between the interior and boundary PV gradients (i.e., the dimensionless mode depth) is varied by changing β.

In all cases, a good agreement was found, both at equilibration and during the time evolution, between the region of homogenized PV and the position of the steering level. Figure 2 corresponds to the case with $\beta = 1.3 \times 10^{-11} m^{-1} s^{-1}$ and no surface damping. As can be seen, PV is well mixed below the initial steering level, including the negative PV delta function at the ground. Figure 2 also shows that this mixing is linked to the drop of the steering level throughout the model troposphere as the wave equilibrates.

Zurita and Lindzen (2001) have discussed in detail the main factors affecting the position of the steering level. From a strict linear point of view, the phase speed of short waves (i.e., waves seeing little interior PV gradient) should be more sensitive to the magnitude of the negative boundary PV gradient than to the integrated interior PV gradient. This suggests that the phase speed should decrease as the wave reduces the temperature gradient. However, in all cases examined, the phase speed was actually found to vary little or even increase slightly. This arises because the Doppler shift associated with the enhanced wind speeds tends to compensate this effect. Nevertheless, note that the steering level still drops because of the increase in the mean winds down to the surface (see lower panel of figure 2).

Additional experiments with Rayleigh damping have confirmed that the containment of the steering level when the surface wind is damped is essential for partial PV homogenization in our model. This is true even for “longer” waves (i.e., with higher β), as long as surface friction is strong enough. For example, figure 3 shows a case with $\beta = 3.0 \times 10^{-11} m^{-1} s^{-1}$ and Rayleigh damping of time scale 1 day.

4. CONCLUSION

The main points of this paper are the following:

1) In an integral sense, the interior tropospheric PV gradient is as poorly mixed as the surface temperature gradient.
2) Baroclinic waves can equilibrate by mixing PV across a neighborhood of the steering level alone, even in the presence of interior and boundary PV gradients of opposite sign. The Charney-Stern condition is only a necessary condition for instability.
3) The extent of PV mixing required for neutrality increases with the ratio between the interior and boundary PV gradients.
4) During the quasilinear equilibration, the steering level of a mode drops as the surface wind is enhanced by the momentum fluxes. Equilibration by localized PV mixing thus requires enough surface friction to contain the steering level.

It is interesting to note that the meridional wavenumber imposed by the midlatitude jet (like the static stability, also a product of the equilibration) limits the depth over which the eddy PV fluxes can extend. As a result, for typical values of β and the vertical wind shear, a substantial part of the baroclinic spectrum is short in the sense defined above. We suggest that the equilibration of these modes may explain the observed partial homogenization of the tropospheric PV gradients.

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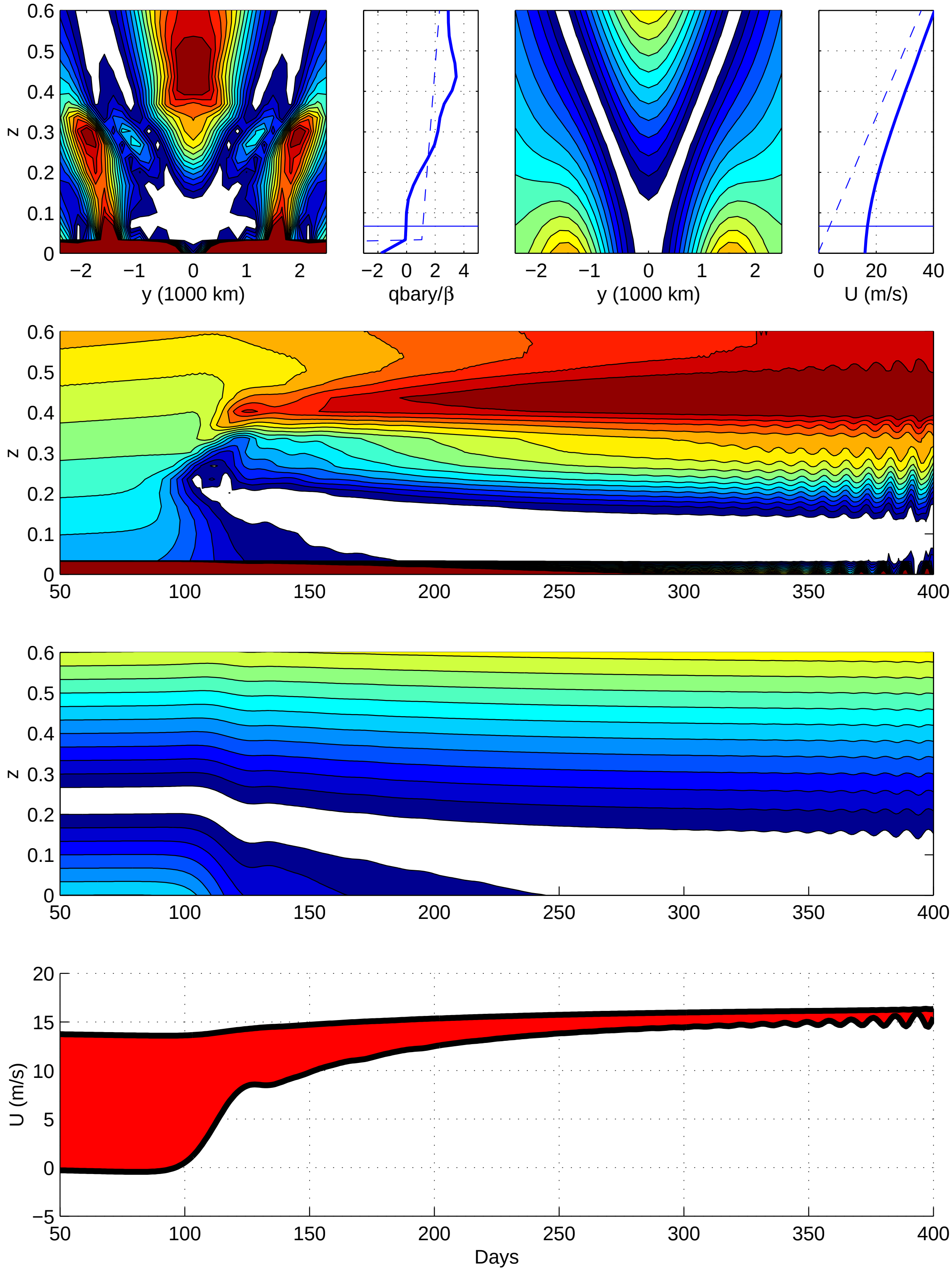

Figure 2: *Upper panels: Time-mean absolute values of* $|\frac{\bar{q}_y}{\beta}|$ *and* $|U - c|$ *and their respective profiles (dashed for radiative equilibrium) at the center of the channel for* $\beta = 1.3 \times 10^{-11}\ m^{-1}s^{-1}$ *and no surface damping. The horizontal lines emphasize the position of the steering level. Non-shaded areas have smaller magnitude than the corresponding contour unit (.2 for* $|\frac{\bar{q}_y}{\beta}|$ *and 2 m/s for* $|U - c|$*). Medium panels: time series of* $|\frac{\bar{q}_y}{\beta}|$ *and* $|U - c|$*, same definitions apply. Lower panel: time series of phase speed (upper line) and surface wind (lower line); note that the shaded area is related to the height of the steering level.*

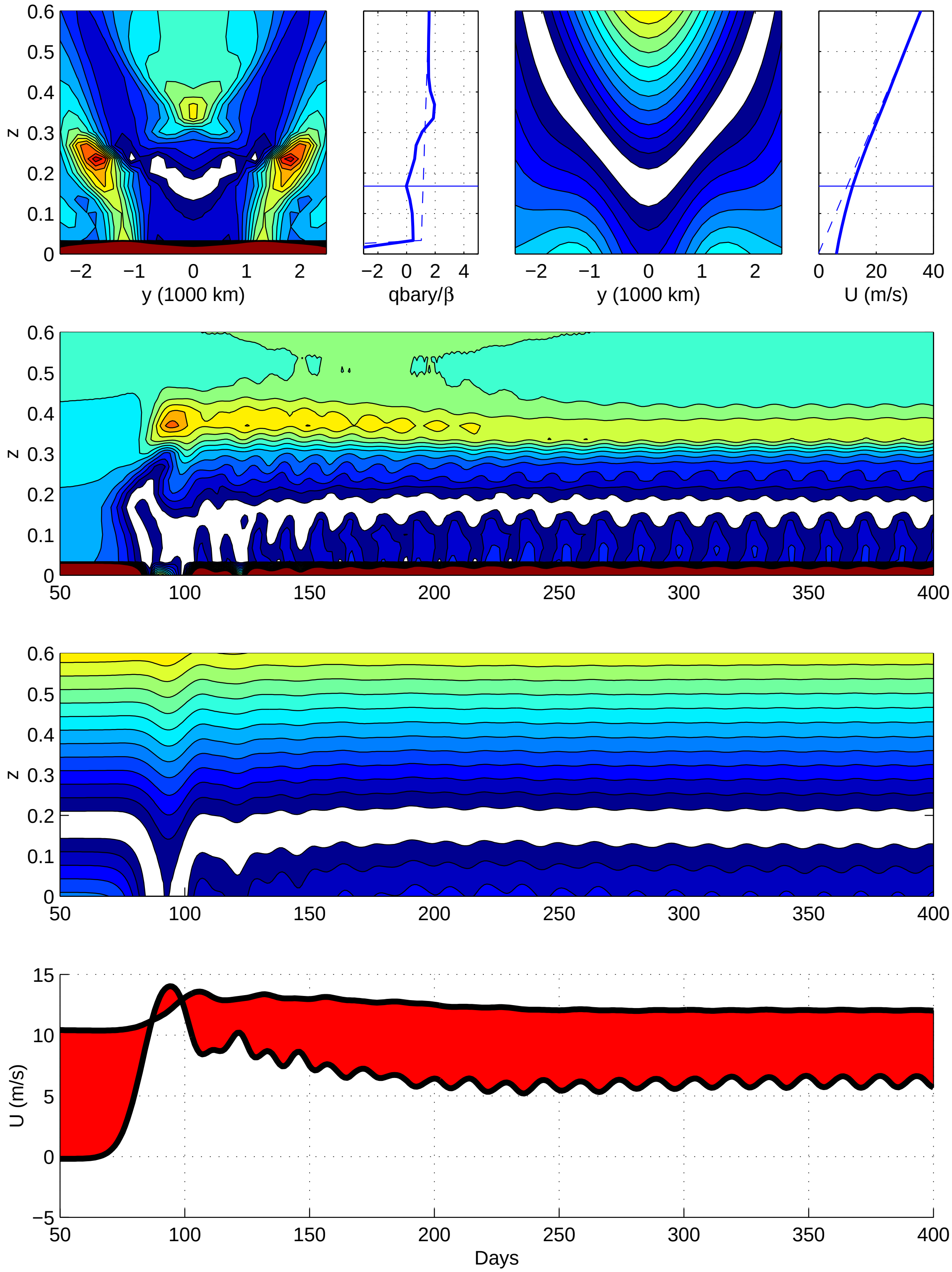

Figure 3: *As figure 2, but for the case with* $\beta = 3.0 \times 10^{-11}\ m^{-1}s^{-1}$ *and Rayleigh damping of time scale 1 day at the lowest resolved level.*