Reply

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The problem of the appropriate lower boundary condition (LBC) for use in planetary wave models, such as ours (Chen and Trenberth 1988) is a complex one and the comment by da Silva (1989) touches on one important aspect. In the Chen–Trenberth model, we introduced, for the first time, the possibility that the flow could go around, rather than just over, high orography in a linear model. We showed that the extra eddy terms included in this case are the same size as the traditional term included in previous models. While part of that effect can be captured by using a linearized sigma (terrain-following) coordinate model (e.g. Hoskins and Karoly 1981; Nigam et al. 1988), other aspects can not. In particular, wave–wave interactions are present with the more complete LBC, and the flow that does go over the orography can be predominantly meridional, not zonal. This is the case for the Himalayas (Chen and Trenberth 1988; Trenberth and Chen 1988[1]), and as a result, the main net boundary induced upward motion occurs on the northern slope with downward motion to the south, rather than upward to the west and downward motion to the east, as for ω_z in the traditional formulation.

Trenberth and Chen (1988) have theoretically shown that the large-scale flow will prefer to go around those mountain complexes whose height is higher than a certain critical value which depends on the configuration and meridional extent of the mountain. High and zonally elongated orography, such as the Himalayas, tends to force the surface flow to go around. Other aspects of the LBC and the importance of omitted nonlinear terms are also discussed in much more detail in Trenberth and Chen (1988). In particular, we include further discussion of the pressure level from which the zonal wind should be taken in evaluating the orographic kinematic forcing. Da Silva attempts to derive a correction to the LBC due to the changes of pressure level as the mountain elevation changes. The actual LBC for a stationary state is given by

$$\omega_s = \mathbf{V}_s \cdot \nabla p_s, \tag{1}$$

where all these quantities are evaluated on the surface, $p = p_s$. The ω at $p = p_0 = 1000$ mb is

$$\omega_0 = \omega_s - \nabla \cdot \mathbf{V}_m \delta p,$$

where $\delta p = -\rho g(h - h_0)$, and the $\nabla \cdot \mathbf{V}_m$ is the mean divergence in the layer p_0 to p_s. Then, using (1),

$$\omega_0 = -\rho g \nabla \cdot [\mathbf{V}_m(h - h_0)], \tag{2}$$

where we have approximated the $\mathbf{V}_s$ in (1) with $\mathbf{V}_m$. This formula is similar to (10) of da Silva but the right hand side has $\mathbf{V}_m$ as the appropriate velocity and is evaluated in the middle of the mountain, not at $p = p_0$.

In the Chen–Trenberth model, we used the 850 mb winds for the computation of the LBC, to be applied at 1000 mb. We do not agree with da Silva that the wind at the bottom of the mountain (or 1000 mb) is appropriate, since the most appropriate wind would be the half-way point. Of course this varies from mountain to mountain, and no one pressure level is very satisfactory. With regard to da Silva's arguments in this regard, we point out that p_0 is an arbitrary reference level, not necessarily 1000 mb. We have carried out experiments in which the level of the wind used was varied and these showed that the resulting planetary wave pattern is not changed significantly, although the magnitude approximately increases or decreases linearly with the zonal wind speed. The latter varies from 4.4 m s^{-1} at 1000 mb to 9.8 m s^{-1} at 700 mb at the latitude of the Himalayan–Tibetan Plateau mountain complex. In da Silva's formulation, this effect would be included in the neglected term in his Eq. (8), and

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[1] This paper was "in press" at the time the comment was received.

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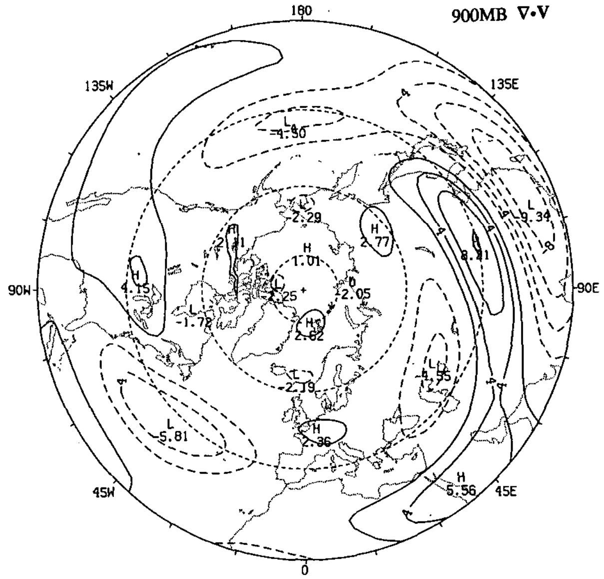

FIG. 1. Divergence at 900 mb for the orographically-forced planetary waves in the Chen–Trenberth model. The contour interval is 2×10^{-7} s^{-1}. Zero contours have been removed.

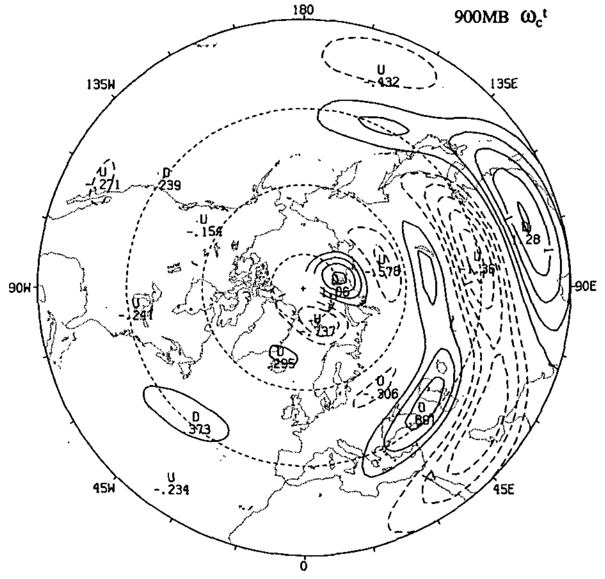

FIG. 2. The correction term, $\omega_c^t = -\rho g \nabla \cdot [\mathbf{V}_d h]$, calculated at 900 mb. The contour interval is 0.25×10^{-4} mb s^{-1}. Zero contours have been removed.

while small, it is in fact just as important as the other suggested correction terms.

The Chen–Trenberth model used the linear balance equations, in the manner suggested by Lorenz (1960). Consequently, we used only the rotational wind for evaluating the kinematic LBC. Thus, there are no spurious mass sources or sinks through the lower boundary, and our ω_e and ω_b also have zero horizontal area average. Consequently, the correction term[2] using da Silva's methodology applied to our model should be

$$\omega_c^t = -\rho g \nabla \cdot [\mathbf{V}_d h], \tag{3}$$

not his (12). In accord with geostrophic theory, one would expect from scaling arguments that this term would be of order Ro, the Rossby number, times the terms we have included, and it is therefore not consistent to include it in our model. We have confirmed this by using the results of orographically forced planetary waves from Chen and Trenberth (1988) to evaluate ω_c^t a posteriori at 900 mb. Note that this is the lowest full level of the model and is where surface drag is applied.

Figure 1 shows the 900 mb divergence, and reveals divergence and convergence centers on both flanks of the Himalayas. The term $h\nabla \cdot \mathbf{V}_d$ (da Silva's ω_c) is significant only for the local Himalayan area where the mountain height is greater than 1500 m. Since the corresponding divergent winds have magnitude of only 0.5 m s^{-1}, the value of da Silva's ω_c is small. Figure 2 shows that the magnitudes of ω_c^t are at least a factor of six smaller than either ω_e or ω_z. In addition, because ω_c^t is of such small scale and of importance only in the vicinity of Himalayas, the resulting planetary waves would be trapped vertically within the troposphere and of little consequence. Accordingly, the extra correction term suggested by da Silva is definitely not the same order of magnitude as the ω_e term and does not affect our conclusions concerning the relative importance of the orographic and thermal waves.

The issue of the mathematical inconsistency of our LBC has been dealt with in Trenberth and Chen (1988) and, as we point out, some small inconsistency is to be preferred in order to obtain a much more accurate solution. By including the wave-coupled LBC, our model incorporates the effect of forcing the main flow to follow the surface contours of a steep mountain. Therefore, local cancellation between the imposed zonal mean wind and the resulting eddy winds on constant p surfaces near mountains such as the Himalayas and Greenland[3] indeed occurs. It is doubtful, therefore, whether the divergent eddy wind, with magnitude of 0.5 m s^{-1}, could play a decisive role in cancelling the rotational zonal mean wind (whose magnitude, as given above, is about 5 m s^{-1}).

To conclude, while it seems that ω_c^t might have some impact on the forced planetary waves, it is of secondary importance compared with ω_e and the imposed ω_z. In fact, it is about the same order of magnitude as other neglected nonlinear terms, (e.g., the wave heat flux di-

[2] The superscript t (= total) is used to distinguish our (3) from da Silva's (12).

[3] For an interesting discussion of the observed evidence for the flow to go around Greenland, see Scorer (1988).

vergence), discussed in Trenberth and Chen (1988). It would be, however, of interest and more consistent to consider $\omega_c^{\,t}$ in a future model in which all other missing terms are included. But perhaps a better solution would be use of a sigma-coordinate model in which the nonlinear terms and the missing effects associated with orography are also incorporated, possibly in an iterative manner. Such a model does not yet exist.

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