Reply

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We welcome the comments of Reinhold (1989) on our paper, Cehelsky and Tung (1987, hereafter CT), and would like to take this opportunity to respond to the scientific issues he raised.

Reinhold does not dispute the finding of CT that, as resolution is increased, the degree of chaos (and hence the importance of the synoptic-scale transient waves) in the low-order model of Reinhold and Pierrehumbert (1982, hereafter referred to as RP) is visibly reduced and the qualitative behavior relating to weather regimes is drastically altered. The issues that are raised in Reinhold (1989) concern the appropriateness of the choice of parameters in CT, which are the same as those used in RP. Specifically, the parameters in question are (i) the surface damping rates, and (ii) the aspect ratio n. In addition, a third issue is raised on the need to use a more sophisticated method for regime identification than that adopted in CT.

An important issue that needs to be resolved concerns the role of the small scales. We attributed the difference in behavior concerning the degree of chaos between the high-order model and the low-order model mainly to the absence in the latter of a pathway of enstrophy cascade to the dissipated small scales. Spurious chaos can be created in a severely truncated model where energy and enstrophy undergo numerous reflections in the limited spectral domain and bounce around among the few retained modes. Reinhold suggests instead that retaining the higher modes is equivalent to increasing the surface damping rates on the large-scale waves retained in the low-order model, especially when the additional modes are baroclinically stable.

Reinhold reasons, using a linear stability diagram, that the effect of any additional modes retained by CT beyond the $(2x, 2y)$ level of RP can only act as a net energy loss to the system. This is because, according to him, for the particular value of $n = 1.3$, these higher modes all lie beyond the short-wave cutoff for baroclinic instability in the two-layer model. This leads to the conclusion in Reinhold (1989) that "more degrees of freedom in a periodic environment can easily lead to damping effects which overwhelm the increased interactions." The result that we presented in Figs. 6, 9 and 10 of CT shows that the opposite is true.

In that experiment, modes were added one by one beyond the $(2x, 2y)$ level of RP which lie to the short-wave (stable) side of the cutoff, according to Reinhold (1989). The degree of chaos was actually *increased,* through the added triad interactions. An additional experiment was performed in which these added modes were allowed to draw energy from the mean flow as before, but the triad interactions among the waves were artificially prohibited. The chaotic behavior of the large-scale waves returned to the level of RP. No visible sign of the "damping effect" caused by the addition of intermediate modes beyond the short-wave cutoff was found. Thus CT found, contrary to Reinhold, that the increased interactions overwhelm any supposed damping effects. This "destabilizing" effect was observed up to and until so many modes were retained that a cascading pathway to dissipated small scales was established. Then the degree of chaos in the large scales abruptly dropped. This result, which is ignored in Reinhold (1989), serves to further emphasize the point we made earlier; that it is the pathway to small scales that is important in reducing the degree of chaos, and not the supposed energy loss due to the baroclinically stable modes that are inevitably included.

In the case of Boville (1980) cited in Reinhold (1989), no additional experiment was performed to separate out the effects of the two mechanisms mentioned above (as was done in CT).

The arguments in Reinhold (1989) concerning the damping rates adopted by both models are based on the hypothesis that the effect of retaining more modes is equivalent to increasing the surface damping rates on the large-scale waves retained in the low-order model. This issue was examined in CT. Figures 11, 12 and 13 in CT showed that the effect of the high-order modes can be parameterized approximately by a scale-dependent "subgrid" diffusion that leaves the large-scale waves relatively untouched but severely damps

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the small-scale waves beyond $(4x, 4y)$, thereby completing the enstrophy-cascading pathway to the small scales. This effect cannot be mimicked in a low-order model simply by increasing the values of Ekman, Newtonian and interfacial damping rates.

While it is true that the values adopted by CT and RP for surface damping rates are generally too high, they are nevertheless not so high as to suppress the nonlinear process responsible for producing chaos. It therefore was appropriate for CT to use such a model to examine the effect of truncation on the degree to which the intermediate and small scales contribute to the chaotic behavior of the large scales. Nevertheless, as a model for the atmosphere, a more realistic (lower) range of damping parameters is probably more appropriate. There is, however, a technical difficulty involved in performing the kind of convergence experiments in CT using low damping rates: Lowering the damping rates drastically increases the number of modes that need to be retained before convergence can be established. Based on what we have learned from CT, we know that the convergence of a high-order model can be sped up by the application of a subgrid diffusion to modes beyond a sufficiently high level of truncation [say $(7x, 7y)$]. Using this device, a series of calculations have been carried out in different parameter regimes. A typical example is described here briefly. The details will be given in Cehelsky and Tung (1989, Part III), a sequel to CT (which is Part II).

A 6-day surface damping time (vs 1-day in CT and RP) and a 10-day Newtonian cooling time are used. The ad hoc interfacial friction is removed, and a more realistic value for radiative driving ($\theta_A^* = 0.08$) is adopted. As expected, the traveling wave component in the large scale wave, which was severely damped in the high damping case of CT, now becomes very strong and visually dominates the time-dependent behavior of the large scale waves. "Persistent anomaly" involving the quasi-stationary waves occasionally appears in the flow field. There is only one such persistent quasi-stationary state, and it occurs in the same location in the fourth quadrant in the $\psi_K - \psi_L$ phase diagram, as in CT. The main difference between the high damping case of CT and the present one is that the periods of "persistent anomaly" do no occur all the time (as in CT), but only occasionally, more akin to the observed "blocking" situation in the atmosphere. This and other experiments we have done suggest to us that the qualitative results of a high order model with "realistic" damping rates on the large-scale waves cannot be reproduced by a low-order model with higher damping rates, contrary to the implication in Reinhold.

Concerning the problem of identifying weather regimes mentioned by Reinhold, more sophisticated analysis methods are probably needed in some ambiguous case to extract some evidence for multiple regime behavior. However, in the case of CT, there is no need to use a more sophisticated "statistical-dynamic analysis" for regime identification: There is simply no reasonable way for one to see more than one regime in the converged solution presented in Fig. 10f of CT.

Apart from these technical issues, there appears to be an underlying philosophical disagreement expressed by Reinhold. We agree with him that low-order models may be an excellent tool that can be used profitably to present and illustrate one's "conceptual model." However, because truncation levels are mostly arbitrary and model results are often extremely sensitive to the exact truncation level chosen, low-order models cannot also be used to deduce from first principles that the proposed conceptual model is a correct representation of reality. In CT, an additional conceptual model was proposed which is different from that of RP. While stressing that we have not proven (nor do we intend to prove) that multiple weather regimes do not exist, CT proposed that perhaps the manifestations of multiple weather regimes could alternatively be caused by changes in "external conditions."

This proposed mechanism was not meant as a replacement for the nonlinear "internal" mechanism suggested by RP. Both "internal" and "external" mechanisms may conceivably be involved in producing the observed variability of the extratropical atmosphere. The result of CT does suggest, however, that the degree of importance of synoptic-scale waves in organizing the large-scale flow found in the model of RP is largely a result of truncation. By retaining the destabilizing effects of the intermediate scale waves while excluding the mechanism of cascading pathway to small scales, the dominating importance of the synoptic-scale wave in inducing significant variability in the large-scale waves may have been overestimated in the low-order model of RP.

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