A Pathological Problem with NCEP Reanalyses in the Stratosphere

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ABSTRACT

A pathological problem has been discovered in the NCEP reanalyses in the stratosphere. It is manifested most strongly as a two-delta vertical wave in the divergence of the wind field above steep topography especially where the wind increases with altitude in the stratosphere. It is present primarily above 50 mb at the topmost four levels in the NCEP model used for data assimilation and appears to be directly related to the use of the sigma (terrain following) coordinate system and the upper boundary condition in the assimilating model. Recommendations suggested for addressing the problem include switching to a hybrid coordinate system that transitions to a pressure coordinate in the stratosphere, and with a damping upper boundary condition. Certain climate diagnostics are greatly impacted by these pathologies.

1. Introduction

During the course of research into the energy budget using reanalyses from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR; referred to as NCEP; Kalnay et al. 1996) and the European Centre for Medium-Range Weather Forecasts (ECMWF; Gibson et al. 1997) we came across a curious phenomenon in the NCEP reanalyses that is a major source of some problems. The problem is manifested mostly in the upper four or so levels of the NCEP reanalyses in model coordinates and seems to be directly caused by the use of sigma coordinates in the assimilating model.

The sigma coordinate is one where pressure p is normalized by the surface pressure p_s (Fig. 1), so that $\sigma = p/p_s$, and hence it is a terrain-following coordinate. At NCEP, this coordinate is used all the way to the top of the model, and so even at 10 mb there is a distinctive perturbation on the model coordinate surface, reflecting the change at the surface. The $\sigma = 0.0101$ surface, which is the second model level from the top, varies from about 10 to 6 mb, and thus ranges from about 31 to 34.5 km in altitude. Hence the altitude distances are not small and wind shears can be substantial. With σ levels, vertical interpolation is necessary to get to and from pressure levels where data are given. How these wind shears are handled in the analysis, in the absence of wind information (because the main data are broad-layer radiances) and in the presence of such a distorted surface is a key issue. A closely related issue is the upper boundary condition in the model.

At ECMWF, in contrast, a hybrid vertical coordinate is used in the assimilating model. This coordinate begins as a σ coordinate at the surface but transitions to a pure pressure coordinate at about 100 mb, and thus the stratospheric layers are not distorted by surface topography. The very name ''stratosphere'' comes from its highly stratified nature and thus it seems desirable to build this into a model as much as possible. In the stratosphere in the reanalysis model used for the 15-yr reanalysis from 1979 to 1993 ECMWF Reanalysis Project (ERA-15) the model levels are at 10, 30, 50, and 70 mb and so there is no issue in interpolation to the standard pressure levels. Nevertheless, some early operational problems were encountered at ECMWF at the model top (10 mb) with the formation of long-lasting spurious vortices in the operational analyses (Trenberth 1992). This problem was cured on 14 December 1988 with a change in the model upper boundary condition. In general, for models with a top about 10 mb, a highly diffusive damping is included to ensure that waves are not reflected from the model top, for example in the NCAR Community Climate Model version 3 (CCM3) model, which also has a hybrid vertical coordinate (Kiehl et al. 1996). What is done in the NCEP model is not known to us.

The problems we expose here are most pronounced across the Andes, but are also present over other topographic features and seem to be largest where the horizontal gradients are greatest. Thus they occur where the distortion in the sigma coordinate from horizontal

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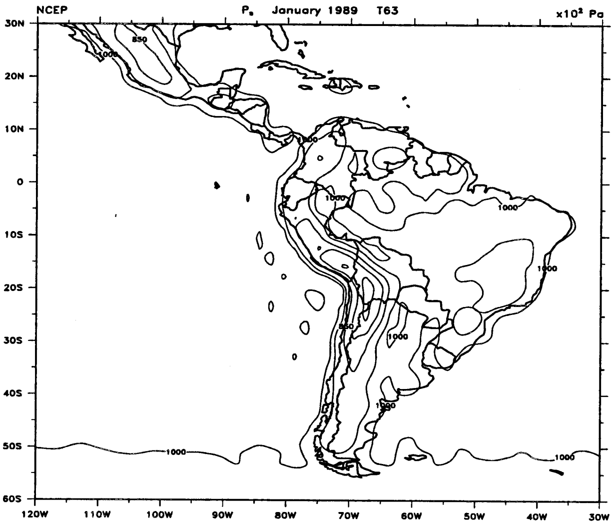

FIG. 1. The p_s field in the South American sector from NCEP at T63 resolution. Contours are 1000, 950, 850, 750, and 650 mb.

is greatest. The problems are standing waves with mostly a two-delta vertical wavelength in the topmost five or so levels, which for NCEP are at $\sigma = 0.0027$, 0.0101, 0.0183, 0.0288, and 0.0418 and that therefore are close to 2.7, 10, 18, 29, and 42 mb. "Two delta" waves are locked to a numerical grid with values of opposite sign at adjacent grid points, and commonly arise from numerical approximations. These spurious waves are mainly present when the wind is increasing with height in these layers in both easterlies and westerlies. They are most pronounced in the summer stratospheric easterlies in the divergence of the wind, $\nabla \cdot \mathbf{v}$, and almost entirely from the $\partial u/\partial x$ term.

In the following, we briefly describe how we came upon this problem and tracked it down, then we go on to describe and document the nature of the problem and recommendations for fixing it.

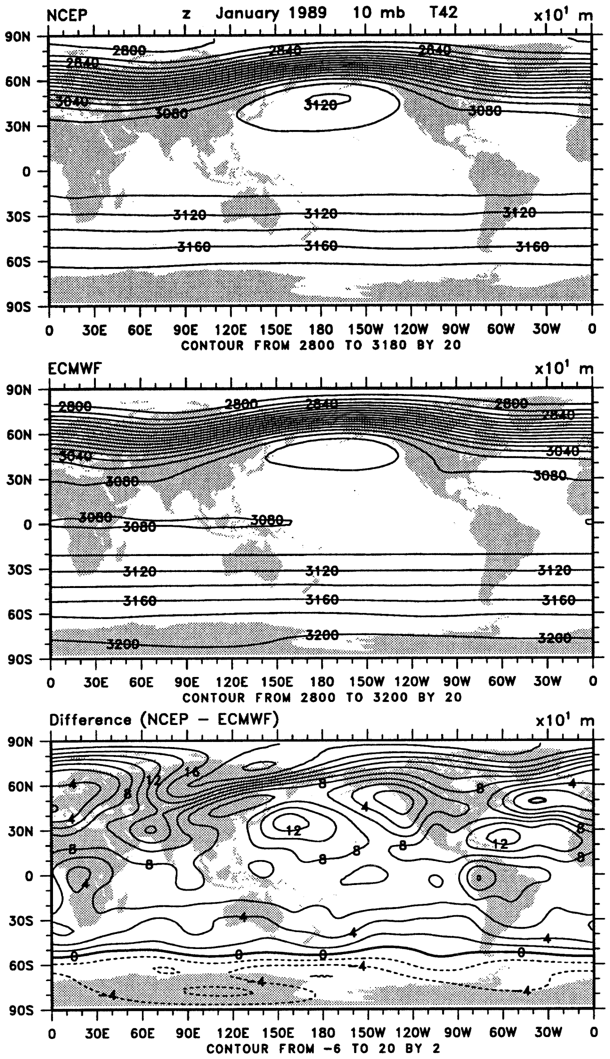

FIG. 2. The z field as archived by NCEP and ECMWF at 10 mb for Jan 1989 and their difference, at T42 resolution. The contour interval is 20 dam in the top two panels and 2 dam in the bottom.

2. Encountering the problem

We have made detailed computations of the vertically integrated heat, energy, and moisture budgets using the reanalyses and compared the results from NCEP and ECMWF (Trenberth et al. 2001). The full-resolution data four-times daily on model coordinates (T62, 28 levels for NCEP and T106, 31 levels for ECMWF) were used to obtain the best accuracy possible and this required processing of 3.1 Terabytes of data. With prospects of the future ECMWF reanalysis being at T159 resolution and 60 levels, there is a lot of interest in how well the results can be replicated with the pressure level analyses, as they are more readily available and constitute a much smaller processing task because they are on a 2.5° grid at 17 levels.

We have therefore attempted to replicate the results from the full model levels with those from the pressure levels, as this is a necessary condition before we can break down the vertically integrated transports into the contributions by layers. To explore the sources of errors, we have developed a postprocessor of the model-level data to recreate the pressure-level archive, and thus we have developed the capability to create a pressure-level archive at much higher vertical resolution. In particular, we created a set of analyses at 3 mb, just below the $\sigma = 0.0027$ model level, chosen so that no extrapolation of values would be involved.

We had much greater difficulty in replicating the energy budget results with the NCEP pressure archive than from ECMWF, and differences were well in excess of 100 W m^{-2}. Further we traced those differences to the upper layers of the stratosphere and primarily to the term involving the divergence of potential energy, $\nabla \cdot \mathbf{v}\Phi$. While it might be thought that terms in the upper

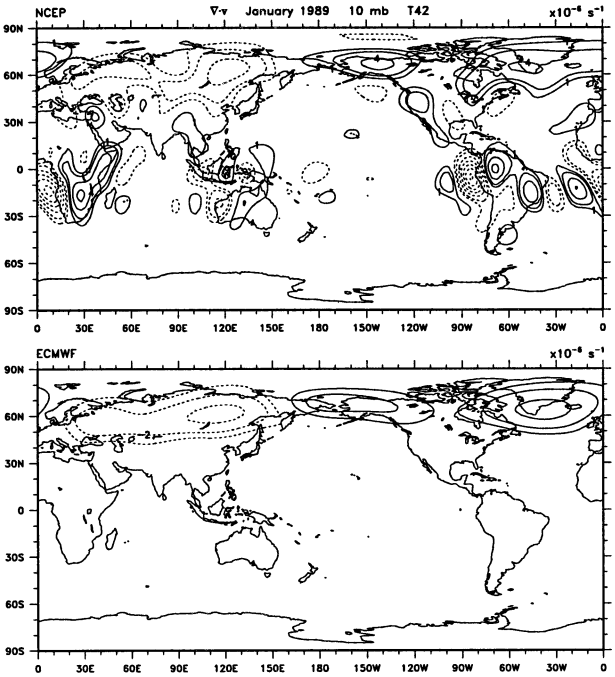

FIG. 3. Divergence $\nabla \cdot \mathbf{v}$ at 10 mb from NCEP and ECMWF for Jan 1989 at T42 resolution. The contours are ± 1, 2, 4, 6, 8, 10, and 12×10^{-6} s^{-1} and negative values are dashed.

stratosphere would be negligible in an energy budget because the mass weighting is quite small, the geopotential and potential energy become very large, and so this term can be substantial provided that ageostrophic winds are present. This last point proved to be the key difference between the ECMWF and NCEP reanalyses at these upper levels, and ultimately we traced the main NCEP problem to the divergent winds above 50 mb.

3. Documenting the NCEP problems

We examined results for the entire reanalyses archives and the results shown here for January 1989 are typical. The analyses are processed using spectral transform techniques on a T63 grid. The original T62 grid for NCEP reanalyses is the same in the east–west dimension but the T63 grid involves changes with latitude and addition of an extra mode that can lead to some ringing effects, but these are not a factor in this analysis, as the flow in the stratosphere is zonal. The 2.5° grid of the pressure level analyses is also processed on a T63 grid, which is able to retain all the information at that resolution. Some fields are truncated at T42 for clarity of presentation.

We first present the z field as archived by ECMWF and NCEP at 10 mb (Fig. 2), and while they appear quite similar overall, the differences are substantial and range up to 20 decameters (dam). There are gradients over South America and elsewhere that seem to be associated with surface topography. Figure 3 presents the

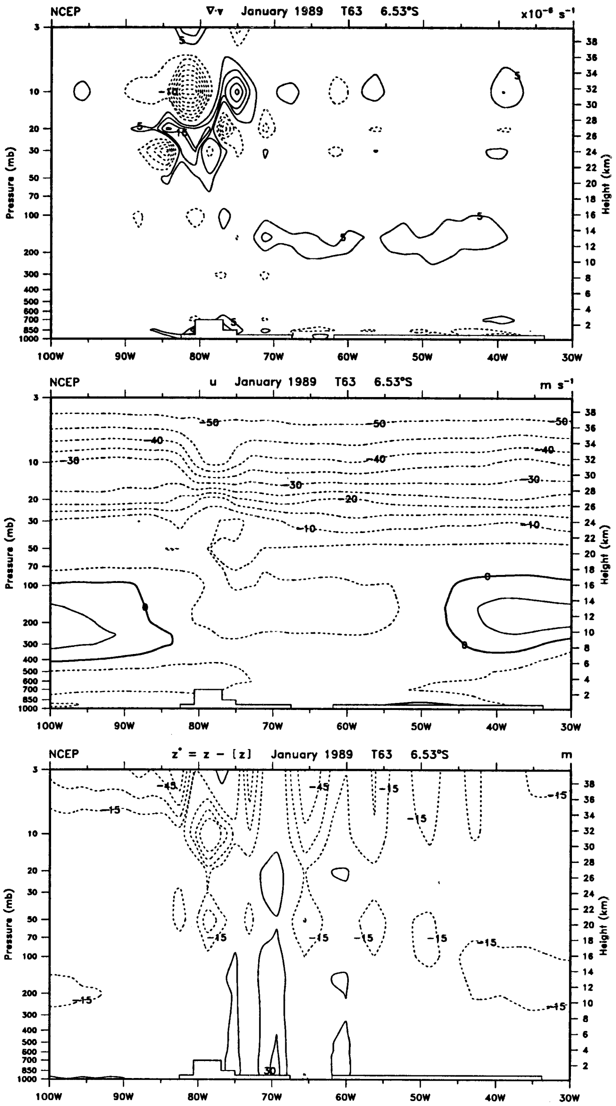

FIG. 4. From NCEP for Jan 1989, height–longitude cross sections at about 6.5°S across the Andes of $\nabla \cdot \mathbf{v}$, contour interval 5×10^{-6} s^{-1} (zero contour omitted); u, contour interval 5 m s^{-1}; and $z - [z]$, contour interval 15 gpm.

divergence $\nabla \cdot \mathbf{v}$ computed from the archived velocity values from NCEP and ECMWF at 10 mb (note the uneven contours). Immediately the structures across South America to Africa in the NCEP reanalyses stand out, with magnitudes of divergence well in excess of 10^{-5} s^{-1}; a factor of 5 or more greater than elsewhere and in the ECMWF results.

To further examine the vertical structure and the extent of these pathologies, Fig. 4 shows cross sections of several fields across the Andes. It shows that the stratospheric divergence field has a lack of coherence in the vertical and instead a $2\Delta\sigma$ structure exists, with strongest signature at the second level but reversing in sign at the top and third level. The structure is clearly seen in the u field and note that the easterlies are in-

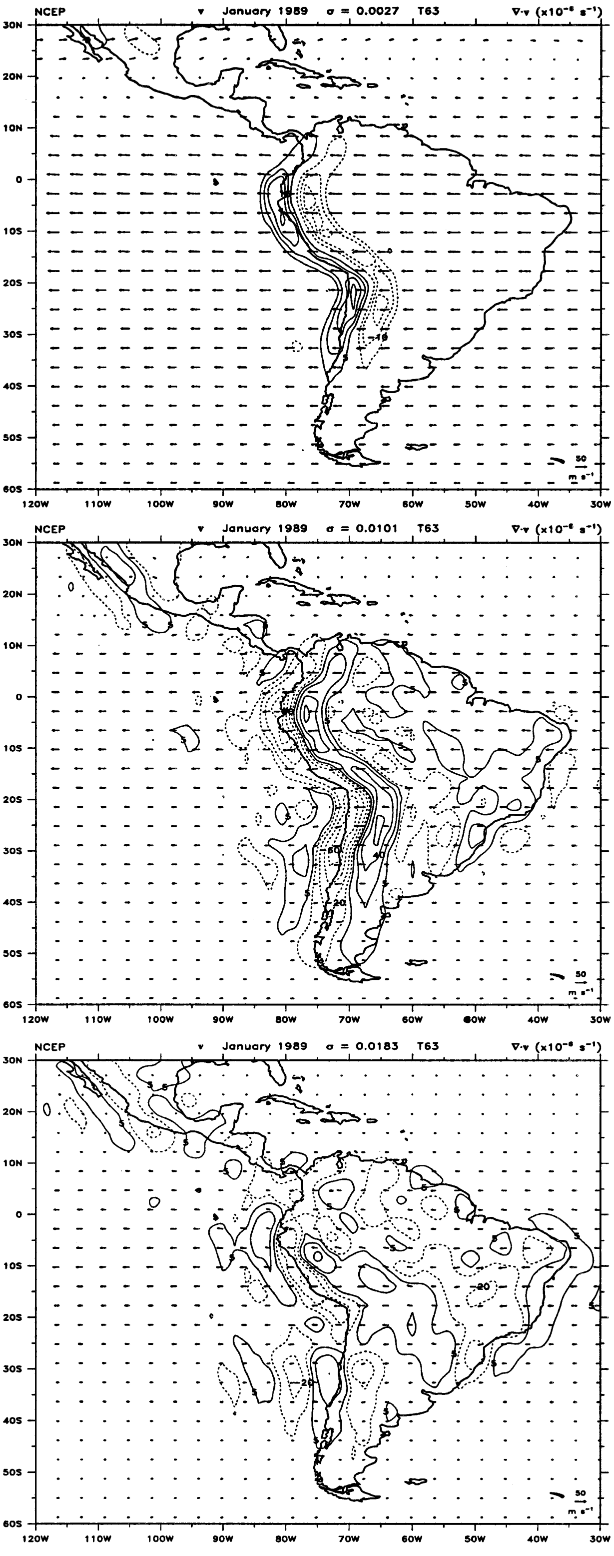

FIG. 5. From NCEP for Jan 1989, $\nabla \cdot \mathbf{v}$ on $\sigma = 0.0027$ (top), 0.0101, 0.0183 (bottom) surfaces and the **v** field in the South American sector. Divergence contours are ± 5, 20, 40, and $60 \times 10^{-6}\ \mathrm{s}^{-1}$ except the top panel has extra ± 10 and 15 contours. The wind (m s^{-1}) is indicated at lower right.

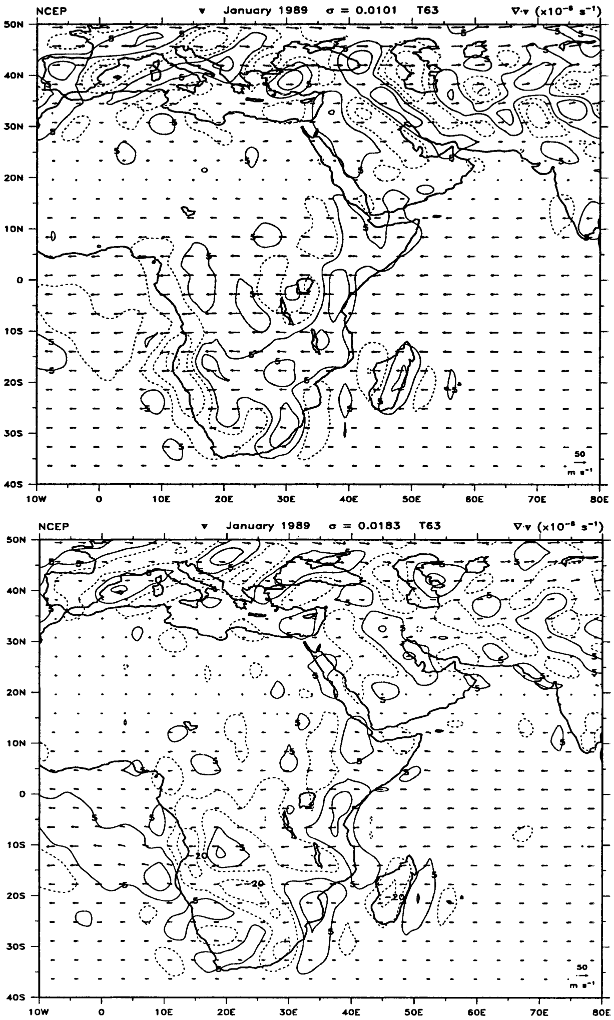

FIG. 6. From NCEP for Jan 1989, $\nabla \cdot \mathbf{v}$ on $\sigma = 0.0101$ (top) and 0.0183 (bottom) surfaces and the **v** field in the African sector. Divergence contours are ± 5, 20, and $40 \times 10^{-6}\ \mathrm{s}^{-1}$. The wind (m s^{-1}) is indicated at lower right.

creasing with height. There are also related structures in the geopotential height field, shown as departures from the zonal mean to remove the vertical gradients, and vertical motions (not shown).

Note that east of the Andes in Fig. 4, low-level convergence is compensated by upper-tropospheric divergence as part of the monsoon circulation over the Amazon. These real divergence values are about as large as expected in nature for monthly means and indicate how extremely large the spurious values are above 50 mb.

To focus on and examine where the 10-mb results originate from, Fig. 5 presents $\nabla \cdot \mathbf{v}$ and **v** at the three uppermost model levels in the South American sector. In the Southern Hemisphere in January, almost straight easterlies prevail and the divergence comes from the variations in the easterlies. Just south of the equator on the 10-mb surface, the easterlies vary from a prevailing value of approximately 35 m s^{-1} to 40 m s^{-1} just east of the Andes, and 30 m s^{-1} just west of the Andes. The structure is present along the whole extent of the Andes. Similar fluctuations are present across South Africa although concentrated along coastal regions and across Madagascar where the topographic gradients are greatest (Fig. 6; note only the second and third levels are presented).

In regions where the wind increases with height, the curvature of the σ surfaces means that winds on a σ surface increase as the mountain is approached and decrease as we move away. That is, on σ surfaces there should be divergence on the upslope and convergence on the downslope simply because of the vertical wind shear. In contrast in Fig. 5, the reverse is seen at the topmost level and, although the expected pattern is seen at the second level, it is much stronger than justified by the wind shear, so that the same signature appears on the 10 mb surface after interpolation. Nevertheless, it is easy to see how the vertical interpolation matters.

In July (not shown) the structure is also present and is again strongest across the Andes but this time only south of 25°S and embedded in westerlies that are increasing with height. A smaller signature like that in January occurs in the easterlies north of the equator over the northern Andes. In between the zonal winds are weak.

Aside from Africa and South America, smaller signatures of the reversal in sign of divergence at these three levels can also be seen near the Mexican highlands (Fig. 5), across southern Europe and extending to the Himalaya/Tibetan Plateau (Fig. 6), and with smaller but unmistakable signatures elsewhere, such as along the east and west coasts of Australia and over New Guinea (Fig. 3). Of note is the diminished signal over the Rockies and some other mountainous areas. In some areas this is related to the absence of much flow orthogonal to the mountains in the stratosphere, but it may also be that there is less problem as long as the mountains are adequately smooth.

4. Conclusions

The spurious structures in the NCEP reanalyses are aligned exactly with the topography and thus the σ levels themselves (cf. Figs. 1 and 5), and have largest amplitude where the topographic gradients are very large and the magnitude of the u field increases with height in the top layers.

It is clear that this is a problem with the σ coordinate system in combination with the upper boundary, and how that is handled in the model. Other contributing factors may include the following: (i) the σ coordinate is not orthogonal to the east–west (x) and north–south (y) coordinates and the less quasi-horizontal it is, the greater the potential for truncation errors. This fact is independent of resolution. (ii) There are potentially large numerical errors in computing the pressure gradient term in the model equations that arise from large horizontal and vertical gradients on σ surfaces that result in a small residual from two large terms. (iii) Harmonic or biharmonic diffusion is often used to control spurious waves, but this operator is not simple to apply in σ coordinates and a correction term is needed (e.g., Kiehl et al. 1996). (iv) Observations in these regions in the stratosphere are scarce and most likely come from radiance/temperature data, which do not help define the velocity field in low latitudes, where the problems seem worst. Making use of observations requires interpolations back and forth between pressure and sigma surfaces. How these data are assimilated on model surfaces may contribute to spurious vertical motions. (v) The evidence suggests a key role for the model-level topography in the stratosphere because the waves are not connected to the topography through the troposphere. Therefore it is apparent that flow over the stratospheric model-level topography creates gravity waves that are reflected from the model top and thus become standing waves. Some atmospheric models have a diffusive top layer to trap upward-propagating waves to prevent this kind of behavior. (vi) Many models include a gravity wave drag parameterization that is typically tied to orography and attempts to include real drag effects of unresolved gravity waves on the flow where the gravity waves break. It is possible that a parameterization might contribute to the structures in the analyses in some implementations.

Several recommendations follow. First, it seems highly desirable to switch to hybrid vertical coordinates and avoid sigma coordinates in the stratosphere. Second, more attention should be given to the smoothness of the topography that is represented in σ coordinates. Of course there is a conflict over how to properly represent the ''knife edge'' topography like the Andes that provides a very effective blocking barrier. Third, an upper boundary condition that is diffusive should be implemented for computational reasons, and this is most simply done in hybrid coordinates. Finally, any diagnostics (including Eliassen–Palm fluxes) or other use of the NCEP reanalyses above about 50 mb will be corrupted in mountainous regions, and thus the reanalyses should be used with great caution.

As a final note, these results were communicated to NCEP who have examined the operational model, which runs at T170 and 42 levels, for January 2001 for some of the same fields. They find ''less evidence of the problems'' (most likely from the increased vertical levels). However, they now ''smooth their orography and have plans to introduce hybrid coordinates and a diffusive upper boundary condition'' (G. White, 25 June 2001, personal communication).

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