5.1 DIAGNOSTICS OF VERTICALLY INTEGRATED FLUXES OF ENERGY

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1. INTRODUCTION

We have made detailed computations of the vertically integrated heat, energy and moisture budgets using the reanalyses from National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) (referred to as NCEP) and European Centre for Medium Range Weather Forecasts (ECMWF). 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 ERA-40 ECMWF reanalysis being at T159 resolution and 60 levels, there is 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. They are on a 2.5°grid (equivalent to T63 resolution) at 17 levels. In addition, we have developed a postprocessor to recreate a pressure level archive at much higher vertical resolution. Diagnostics can be compared with the complete results and evaluated to determine the effects of vertical interpolation to the pressure levels and degraded horizontal and vertical resolution on the results.

The results may have implications not only for diagnostic computations but also for modeling and analyses. Comments are made on the utility of sigma (terrain-following) (as in the NCEP model), hybrid (as in the ECMWF model) and pressure coordinates. Sigma coordinates are those where the surface pressure level is the first level, and all other levels are normalized by the surface pressure. Hybrid coordinates are similar at the bottom of the atmosphere but transition to pressure levels in the stratosphere, somewhere near to 100 mb. Consequently there are issues relating to the interpolation from one vertical coordinate to another, and how to define time averages when the surface pressure and thus the coordinate system is varying in time.

We focus on the energy budget as a key diagnostic. We have compared NCEP and ECMWF reanalyses in full model coordinate configurations. We have also compared the full model results with those from the different official pressure level archives and with our own higher resolution pressure-level archive.

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2. A PATHOLOGICAL PROBLEM WITH THE NCEP REANALYSES

We focus on the divergence of the vertically integrated atmospheric energy transports as the primary quantity of interest and we use January 1989 to illustrate the results. The full model integrations for NCEP and ECMWF are regarded as the "truth" in each case, although each differ by amounts that can exceed ± 100 W m^{-2} (Trenberth et al. 2001a).

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 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.

The problems turn out to be most pronounced across the Andes, but are also present over other topographic features. The problems are standing waves with mostly a two delta vertical wavelength in the topmost five or so levels, which for NCEP are at σ = 0.0027, 0.0101, 0.0183, 0.0288 and 0.0418 and which therefore are close to 2.7, 10, 18, 29 and 42 mb. These spurious waves are most pronounced in the summer stratospheric easterlies in the divergence of the wind, $\nabla\cdot\mathbf{v}$, and almost entirely from the $\frac{\partial u}{\partial x}$ term.

To reveal the vertical structure and the extent of these pathologies, Fig. 1 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 increasing with height. South of the equator on the 10 mb surface, the easterlies vary from a prevailing value of ∼35 m s^{-1} to 40 m s^{-1} just east of the Andes and 30 m s^{-1} just west of the Andes. 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).

The spurious structures in the NCEP reanalyses are aligned exactly with the topography and thus the σ levels themselves, 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. We conclude that this is a problem with the σ coordinate system in combination with the upper boundary, and how that is handled in the model.

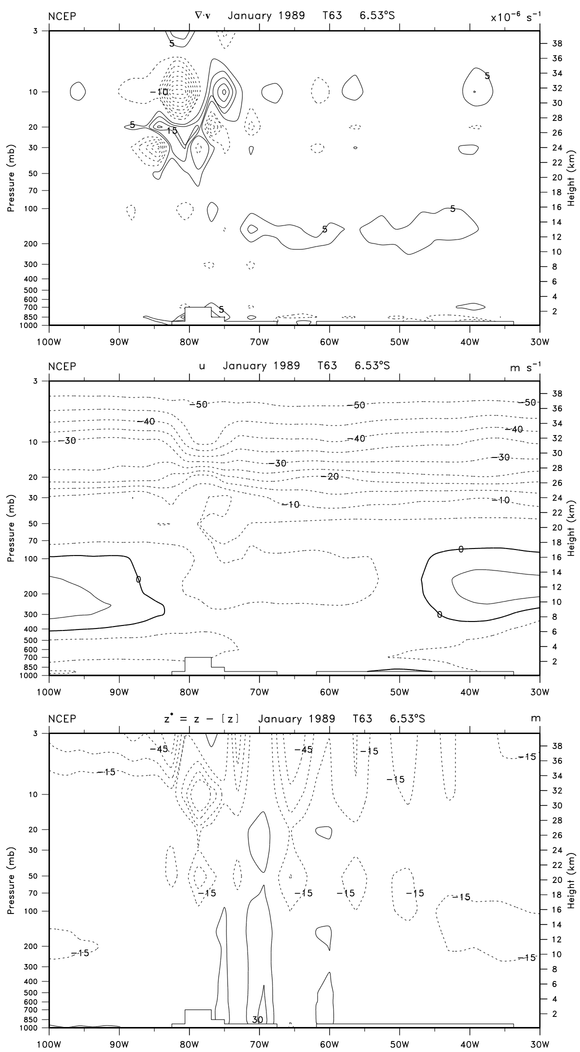

Fig. 1. From NCEP for January 1989, height-longitude cross sections at about 6.5°S across the Andes of $\nabla\cdot\mathbf{v}$, contour interval 5 $\times 10^{-6}$ s^{-1} (zero contour omitted); u, contour interval 5 m s^{-1}; and $z-[z]$, contour interval 15 gpm.

Several recommendations follow. Firstly, it seems highly desirable to switch to hybrid vertical coordinates and avoid sigma coordinates in the stratosphere. Secondly, 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. Thirdly, 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.

3. SOME RESULTS RELEVANT TO ENERGY BUDGETS

We have computed the various energy components including sensible heat, potential energy, and their sum, the dry static energy, as well as kinetic energy and latent energy. Contributions from the two components of the dry static energy have very large contributions that tend to cancel, so that their sum is about a third of the individual terms. The cancellation arises from the dry adiabatic lapse rate combined with the opposite values of divergence in the upper and lower troposphere (because of conservation of mass). Thus temperatures are large in the lower troposphere where geopotential height is small, while temperatures are low in the upper troposphere, where geopotential height is large, and they are related through a relatively constant potential temperature. This cancellation requires very strict adherence to the hydrostatic relationship between temperature and geopotential in finite differences or else discrepancies arise. This was a source of problems in earlier budget computations where geopotential and temperature were processed separately, especially in computing zonal means from radiosonde observations. It can also be a source of problems in pressure level archives: only one quantity should be interpolated and the other derived in the new coordinate system.

There is also a strong positive correlation between the moist component of the energy divergence and that of the sensible heat, because all of the moisture is at low levels, and the low level divergence field operates on both boundary layer moisture and sensible heat. Hence there is also a strong cancellation between the moist component and the dry static energy divergences which arises from vertical gradients of the moist static energy and the saturated adiabatic lapse rate.

Although not demonstrated here, we found clear evidence that the standard pressure level archive is far too coarse in terms of vertical resolution to resolve the surface and boundary layer adequately. On the other hand, for many purposes, the model coordinate is not suitable and the number of levels is more than required. We suggest that a suitable future pressure archive should contain the following 27 levels below 10 mb rather than the current 17: $p = 1000$, 975, 950, 925, 900, 875, 850, 800, 750, 700, 650, 600, 550, 500, 450, 400, 350, 300, 250, 200, 150, 100, 70, 50, 30, 20 and 10 mb. This increases the resolution to 25 mb below 850 mb, 50 mb through the main troposphere, and includes the 20 mb level in the stratosphere.

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Reference

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