NOTES AND CORRESPONDENCE

A Comparison of Winds from the STRATAN Data Assimilation System to Balanced Wind Estimates*

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5 March 1993 and 6 December 1993

ABSTRACT

Winds derived from a stratospheric and tropospheric data assimilation system (STRATAN) are compared with balance winds derived from National Meteorological Center/Climate Analysis Center (NMC/CAC) heights. At middle latitudes in the lower stratosphere, the results show that STRATAN winds are comparable to the balance winds. In addition STRATAN winds provide useful horizontal divergence analyses, and hence, vertical velocity fields. More generally, the STRATAN winds are useful in a more extended domain than the balanced winds. In particular, they are useful in the Tropics and the upper stratosphere where the balanced winds fail. The assimilation also captures the quasi-biennial oscillation, but does not do a good job of representing tropical waves.

1. Introduction

Winds determine to a large extent the distribution of ozone and other trace gases in the middle atmosphere. Even in photochemically controlled regions, winds influence trace gas distributions by advection of constituents into different chemical environments and through the advection of temperature. Since winds are not routinely measured in the middle atmosphere, some method of obtaining winds from the available data is necessary if the relationships between the dynamics and composition of the middle atmosphere are to be studied. One tool that is now being used to determine winds is data assimilation.

A global data assimilation system combines a general circulation model (GCM) with analyzed data fields in such a way that, while the data keeps the model close to reality, the GCM ensures that the analyzed data fields are consistent in space and time. The use of a GCM in the data assimilation cycle also augments the data by providing analyses for unmeasured variables (such as middle atmospheric winds and vertical velocities) and by advecting information from data-rich to data-poor regions. While most current data assimilation systems focus on the troposphere, this paper reports on the data assimilation system developed at the Goddard Laboratory for Atmospheres (NASA/GLA) called STRATAN (short for stratospheric analysis), which extends from the surface to the top of the mesopause.

We have elected to compare the STRATAN winds to winds derived from one of the best stratospheric wind analysis methods, the balance winds as developed by Randel (1987). The balance wind method begins with geostrophic winds as determined from satellite measurements of the temperature field. These geostrophic winds are then corrected for flow curvature by iterating the nonlinear advection terms in the horizontal momentum equations. While geostrophic winds have significant errors in the stratosphere (Boville 1987), Randel showed that the balance winds gave good estimates of the wind fields and planetary wave fluxes. There are limitations to the balance winds; however, they cannot be calculated near the equator, and they do not provide accurate horizontal divergence fields. Both of these missing features are important for wind analyses intended as input to global transport models.

2. Description of wind analyses

The data assimilation system, STRATAN, produces global wind fields four times daily on a 4° latitude by

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* Contribution Number 74 of the Stratospheric General Circulation with Chemistry Project.

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5° longitude grid from the surface up to 0.4 hPa (Rood et al. 1989; 1990; 1991; Steenrod et al. 1992). The GCM used in STRATAN is a gridpoint model with up to 46 vertical levels, and includes radiative transfer, moist convective adjustment, and an explicit boundary layer. The GCM output is used as a first guess for a multivariate statistical data analyses, done on 18 standard pressure levels, using all available data.

The balance wind analyses were derived from the National Meteorological Center (NMC) height analyses. The NMC analyses are briefly described in Nagatani et al. (1990) and Newman et al. (1990). It is important to distinguish between the different sources for the NMC tropospheric and stratospheric analyses: tropospheric NMC analyses come from the NMC Global Data Assimilation System (GDAS), while stratospheric NMC analyses are from the NMC Climate Analysis Center (CAC) and are produced not by data assimilation but by the method of successive corrections (Cressman 1959). These analyses are commonly referred to as the NMC analyses in the stratospheric community, but here will be referred to as the NMC/CAC analyses to distinguish them from other analyses produced and distributed by the NMC.

This paper examines winds for January and February 1989 and concentrates mainly on the Northern Hemisphere stratosphere. January 1989 was extraordinarily cold (Nagatani et al. 1990), with a wave-1 minor warming (Steenrod et al. 1992), while in February 1989 a major sudden stratospheric warming occurred. As described by Newman et al. (1990) and Fairlie et al. (1990), this major warming split the polar vortex and led to a reversal of the lower-stratospheric 80°–50°N temperature gradient that lasted for the rest of the winter season. The comparisons shown here are for January zonal mean wind fields, during the mainly zonal flow in January, and for 19 February wind fields, at the time of the major warming.

3. Results

a. January 1989 averages

Figure 1 shows the STRATAN and NMC/CAC balance zonal mean zonal wind components for January 1989. The tropospheric and stratospheric jets produced by STRATAN and NMC/CAC balance winds are in good agreement, with the STRATAN jet being slightly stronger and more confined in latitude than the NMC/CAC analysis (Fig. 1c). In addition, the January 1989 STRATAN winds are slightly stronger at 30°N than the NMC/CAC winds. The balance winds are of limited use in the Tropics, since the balance wind calculation becomes unstable where the meridional shear of the zonal wind is nearly equal to the Coriolis parameter, and this condition is often met at and equatorward of 20°. In contrast, the STRATAN winds give true global coverage. There are large differences between the two wind estimates in the Tropics. The STRATAN equatorial winds in the middle atmosphere show a weak closed westerly region (at 50 hPa) with easterlies above. This agrees with the expected pattern of the quasi-biennial oscillation (QBO) in which the equatorial westerlies are being replaced by descending easterlies in January 1989.

Figure 2 compares the zonal averaged meridional wind component for the STRATAN and NMC/CAC balance analyses for January 1989. The STRATAN analysis shows a Hadley circulation and the two-cell stratospheric Eulerian circulation. The Hadley circulation is not expected in the balance winds because the balance winds are based on iterations of the horizontal momentum equations about a geostrophic state and do not include the radiative forcing that drives the Hadley cell. The balance winds do, however, give a somewhat weaker version of the middle atmosphere two-cell Eulerian circulation, and this suggests that the two-cell Eulerian circulation arises in part from an adjustment to a balanced wind state.

A comparison of the January 1992 momentum flux for the STRATAN wind analysis and the NMC/CAC balance wind analysis is made in Fig. 3. Figure 3a gives the STRATAN wind analysis momentum flux, while Fig. 3b shows the difference field between the STRATAN and balance wind momentum fluxes. The STRATAN wind analysis momentum flux above 10 hPa is as much as 40% larger than the NMC/CAC balance wind momentum flux; however, the latitude of the maximum poleward momentum flux is about the same in the two analyses. The correct placement of the momentum flux maximum is a positive feature of using the balanced winds over the geostrophic winds (Randel 1987). Here it is seen that the STRATAN momentum fluxes agree with the balance winds in the latitudinal placement of the poleward momentum flux.

Figure 4 compares zonally asymmetric features in the zonal wind component at 10 hPa for January 1989. The 10-hPa level was chosen as being representative of the kind of differences seen at other levels. Figure 4a shows the STRATAN zonal wind component, while Fig. 4b shows the difference between the STRATAN and NMC/CAC balance zonal winds. The largest differences are located in three regions near 30°N: northern Africa, northern India, and off the east coast of Japan. The differences in these three regions cause the differences in the zonal averages at 30°N seen in Fig. 1c. These differences have been traced back to differences in the height fields between the STRATAN heights and the NMC/CAC heights in these regions. These differences at and above the tropospheric jet are consistent features of the analysis.

There are also differences in the jet region near 60°N that can be seen in Fig. 4b. These take the form of a lumpy wave 6 structure in the jet region. This structure is mainly in the NMC/CAC balance wind analysis, and has been traced back to the NMC/CAC height analysis. Appar-

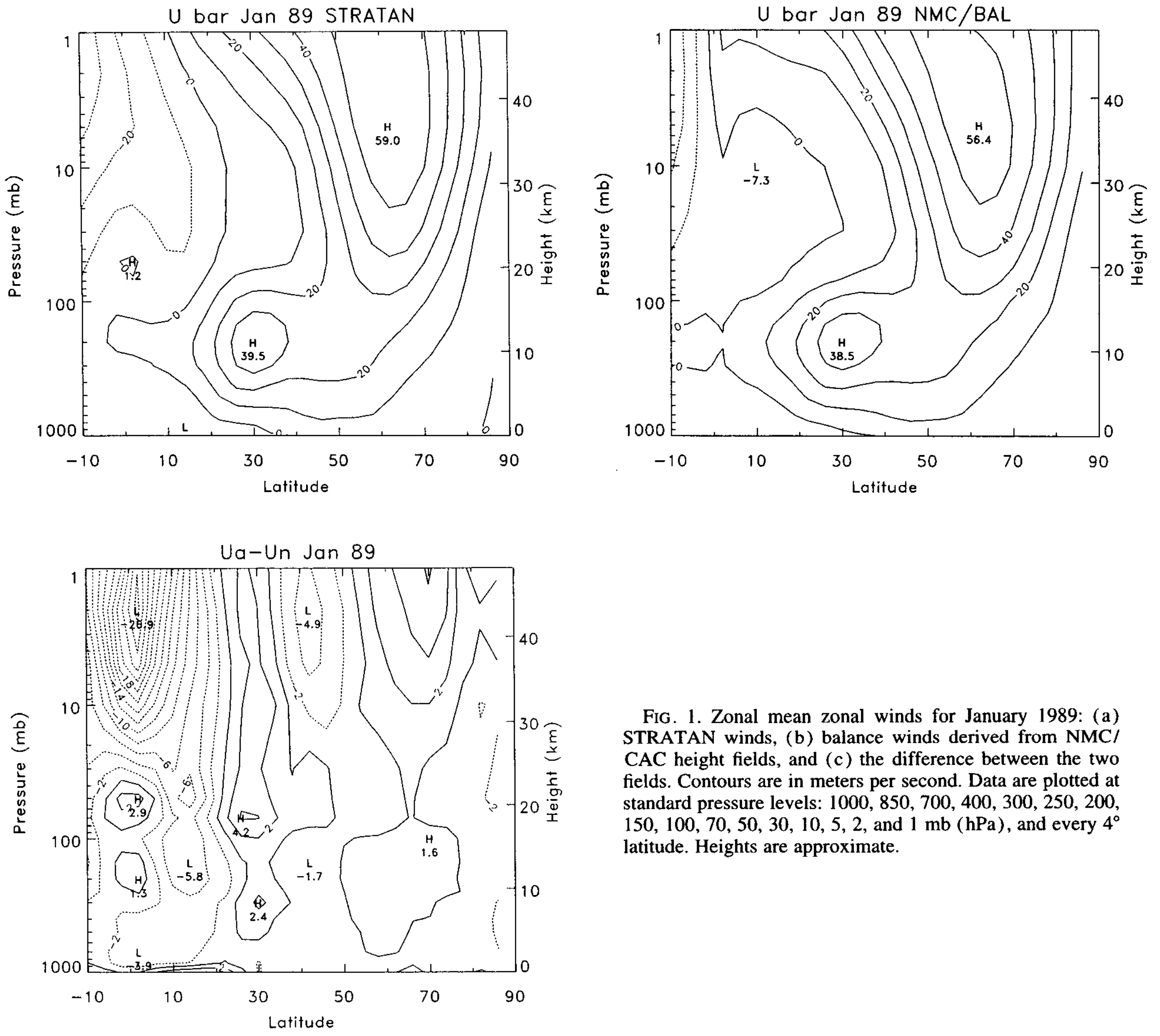

FIG. 1. Zonal mean zonal winds for January 1989: (a) STRATAN winds, (b) balance winds derived from NMC/CAC height fields, and (c) the difference between the two fields. Contours are in meters per second. Data are plotted at standard pressure levels: 1000, 850, 700, 400, 300, 250, 200, 150, 100, 70, 50, 30, 10, 5, 2, and 1 mb (hPa), and every 4° latitude. Heights are approximate.

ently, the nonlinear balance wind analysis in strong jet regions tends to emphasize small amplitude waves in the height field. These waves are believed to be an artifact of the analysis and are possibly a residual of the satellite tracks remaining in the height fields. This difference is also discussed in Steenrod et al. (1992).

b. 19 February 1989

As noted by Fairlie et al. (1990) and Newman et al. (1990), a major wave-2 sudden stratospheric warming occurred in February 1989. Figure 5 compares the STRATAN and NMC/CAC balance winds at 30 hPa on 19 February 1989, at the height of the warming. For the STRATAN winds to be used for transport studies, they must be valid on a daily basis. As shown in Fig. 5, the STRATAN winds and NMC/CAC balance winds agree well during this large amplitude wave-2 event. The differences appear mainly in the small-scale features around the low near 90°W.

The Eliassen–Palm (EP) flux divergences for 19 February 1989 for STRATAN winds and temperatures and NMC/CAC winds and temperatures are shown in Fig. 6. The EP flux divergence gives a measure of the zonal wind change due to the planetary waves, and is expected to be large and negative in the stratosphere on the 19th as the mean flow is reduced during the sudden warming. Both the STRATAN and NMC/CAC balance analyses show qualitative agreement in the stratosphere and troposphere, except near the pole above 10 hPa. The polar difference may be due to the NMC/CAC heights being smoothed over the pole when the NMC/CAC heights are stored on a polar stereographic grid instead of a latitude–longitude grid. Neither field shows the large positive regions some-

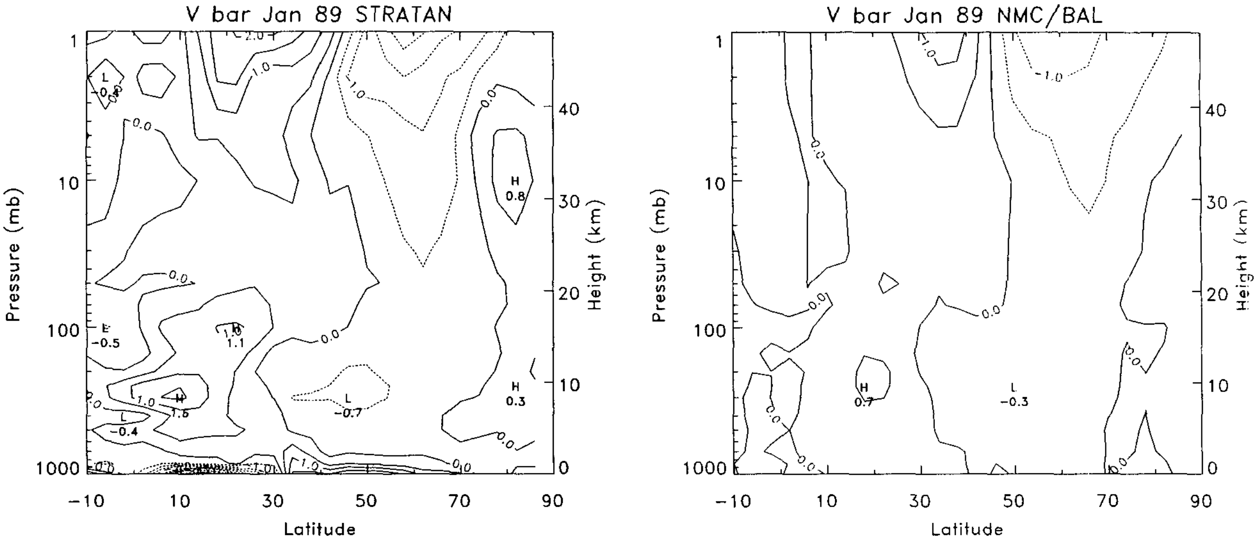

FIG. 2. Zonal mean meridional winds for January 1989: (a) STRATAN winds and (b) balance winds derived from NMC/CAC height fields. Contours are in meters per second. Data are plotted at standard pressure levels: 1000, 850, 700, 400, 300, 250, 200, 150, 100, 70, 50, 30, 10, 5, 2, and 1 mb (hPa), and every 4° latitude. Heights are approximate.

times encountered near the pole when geostrophic winds are used to calculate the EP flux divergence (Boville 1987).

4. Discussion and conclusions

Data assimilation brings together sophisticated objective analysis routines and general circulation models (GCMs). In theory and practice, the GCM brings tremendous power to the analysis of meteorological data. The GCM provides a framework to assure physical consistency of the observation throughout the domain. In addition, the GCM brings a dynamic component that propagates information from data-rich to data-poor regions and provides estimates of unobserved quantities. In fact, in the stratosphere effectively only temperature is observed, and therefore, even the horizontal wind components are unobservables provided by the GCM. Finally, and crucial to estimation theory–based data assimilation, the GCM provides a first estimate of the observables to the objective analysis routine. This leads to a quantitative method of data quality control.

The assessment of stratospheric wind fields has benefited greatly from constituent observations and transport experiments. Transport experiments using STRATAN winds (Rood et al. 1989, 1991) provide an independent measure of the quality of the wind analyses. These transport experiments show that STRATAN provides an excellent estimate of the synoptic- and planetary-scale wind speed and divergence fields in the upper troposphere and the stratosphere. The experiments have also revealed some profound difficulties with the long-term transport characteristics of assimilated data products (Weaver et al. 1993). In a 2D framework, the long-term problems can be interpreted as a misrepresentation of the residual circulation and is related to the thermodynamic balance achieved by the assimilation. Such problems are common to assimilated data products, and Trenberth and Olson (1987) have presented a clear picture of how the Hadley circulation can vary as a function of assimilation algorithm. Recent improvements to the assimilation system (described in Schubert et al. 1993) have reduced these problems by incorporating a new assimilation method known as Incremental Analysis Update (IAU) in which the analysis increments at each grid point are gradually introduced into the assimilation system over a 6-hour period as small forcing terms in the momentum and thermodynamic equations. Constituent transport experiments provide a paradigm for understanding atmospheric processes, and as more constituent data are available for the troposphere there should be a new era of understanding in tropospheric dynamics.

The direct comparisons with NMC/CAC balanced winds presented here further quantify some of the strengths and weaknesses of the STRATAN winds. Focusing specifically on middle latitudes, in the lower stratosphere, the horizontal winds from STRATAN and the NMC/CAC balance estimate are comparable, though only the STRATAN winds have the meaningful divergent winds necessary for vertical transport studies. When considering the global case, however, there is no doubt that assimilation ultimately offers the best method to obtain wind estimates in the atmosphere. Some of the advantages are listed below.

a. Tropics

One of the most obvious strengths of the assimilation is the ability to produce a global wind estimate that

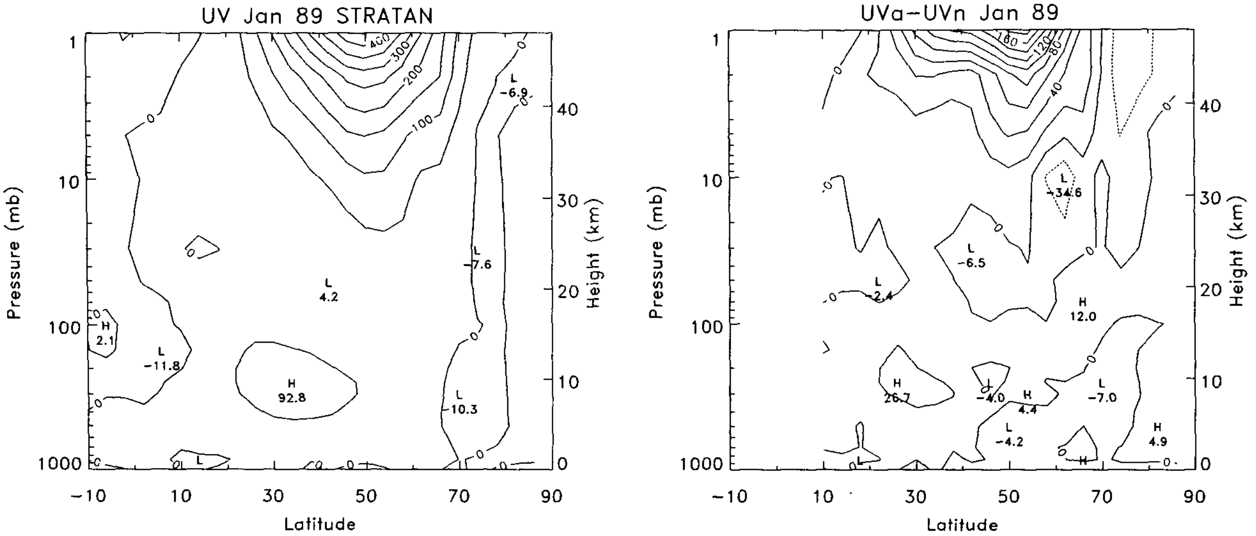

FIG. 3. Zonal mean momentum flux, $\overline{u'v'}$, comparison for January 1989: (a) momentum flux from the STRATAN winds and (b) STRATAN winds momentum flux minus NMC/CAC balance winds momentum flux. Units are m^2s^{-2}.

reduces the uncertainties in the Tropics that are common to balance estimates. Problems remain in the Tropics, but, as proven by transport studies, the STRATAN winds do provide a useful estimate of tropical winds and temperatures.

b. QBO

The assimilation has also captured the weakening QBO westerlies during January 1989. STRATAN has difficulty capturing tropical waves. For instance, analyses of the period from December 1978 through May 1979 show that the Kelvin wave signal does not survive the assimilation process. In general, the tropical analyses prove noisy, and the decoupling of the thermal and momentum fields causes difficulties in the analysis. Improved assimilation techniques that reduce data selection impact and improved multivariate tropical analysis should improve the tropical wind and wave estimates.

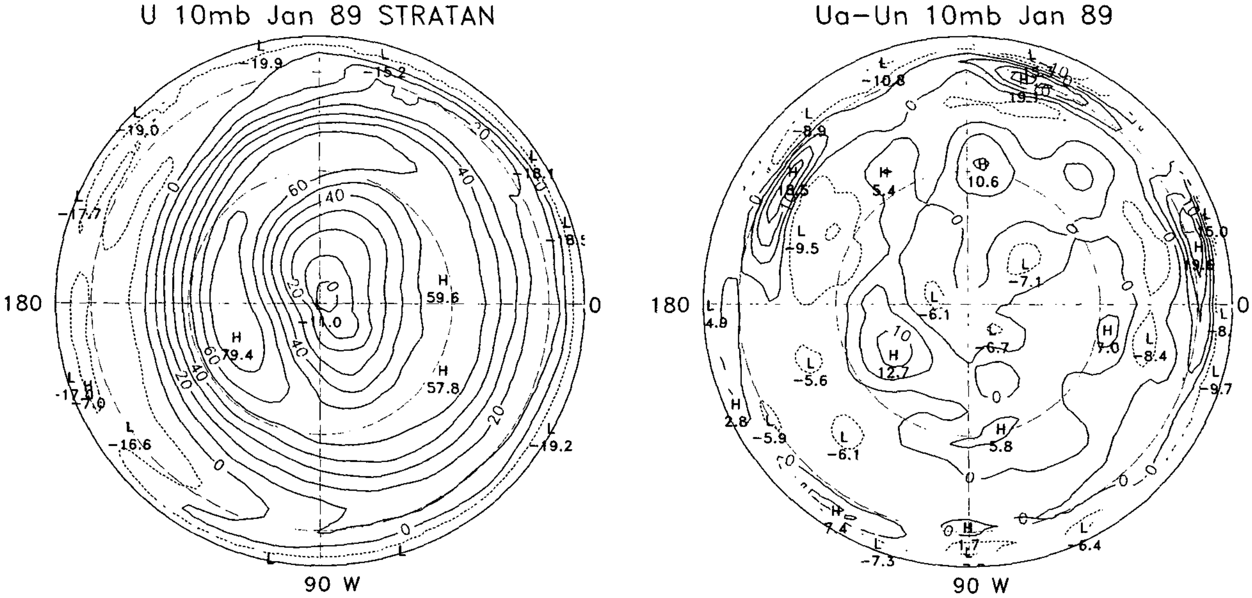

FIG. 4. Mean zonal wind comparison at 10 hPa for January 1989: (a) the STRATAN wind analysis and (b) the STRATAN wind analysis minus the NMC/CAC balance wind analysis. The units are meters per second. The fields are shown on an orthonormal projection with the data plotted from 10°N to the North Pole. The equator is the dark outside line, 30°N is the outermost dashed lined, and 60°N is the innermost dashed line.

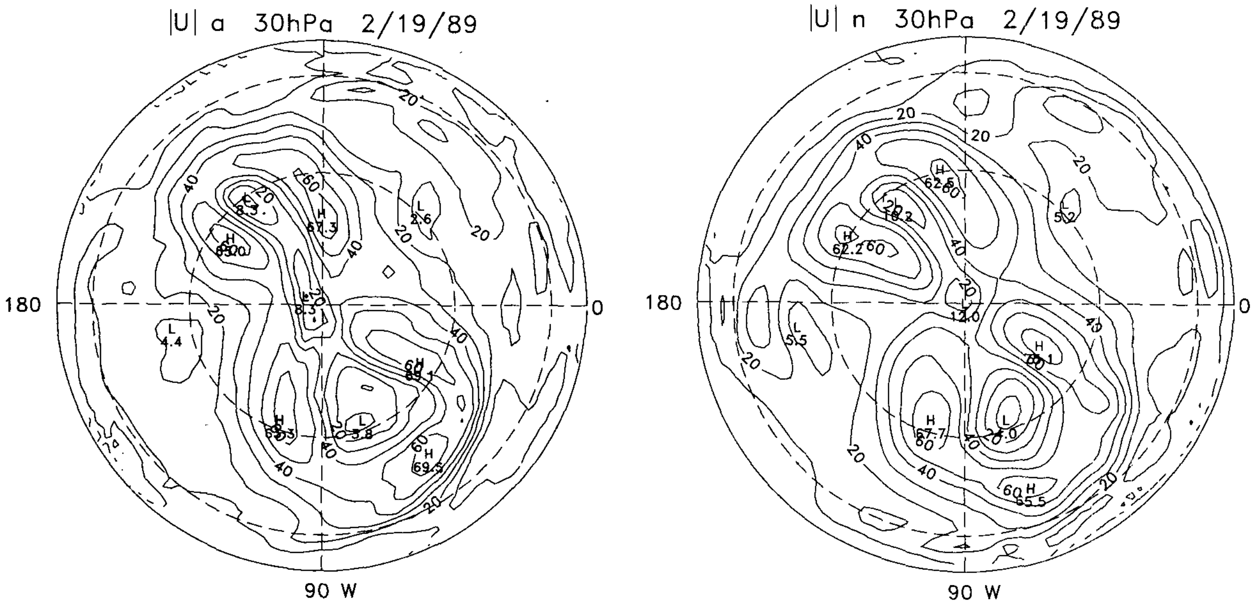

FIG. 5. Wind magnitudes (m s^{-1}) at 30 hPa for 19 February 1989: (a) STRATAN and (b) NMC/CAC balance winds. The fields are shown on an orthonormal projection with the data plotted from 10°N to the North Pole. The equator is the dark outside line, 30°N is the outermost dashed lined, and 60°N is the innermost dashed line.

c. *Upper stratosphere*

Compared to the NMC/CAC balanced winds, STRATAN also gives a better estimate in the upper stratosphere. Since a major part of the upper-stratospheric wave structure is determined by waves propagating up from the troposphere, the GCM used in STRATAN should be able to accurately propagate information upward from the more data-rich (mostly radiosondes) troposphere. The NMC/CAC balanced winds consistently show bloblike structures in the core of the jet that are suggestive of being a residue of the satellite orbits. These blobs are determined to be physically unrealistic in the assimilation procedure and are removed. Therefore, in comparison to balanced winds, the assimilation provides a useful estimate in the entire stratospheric domain.

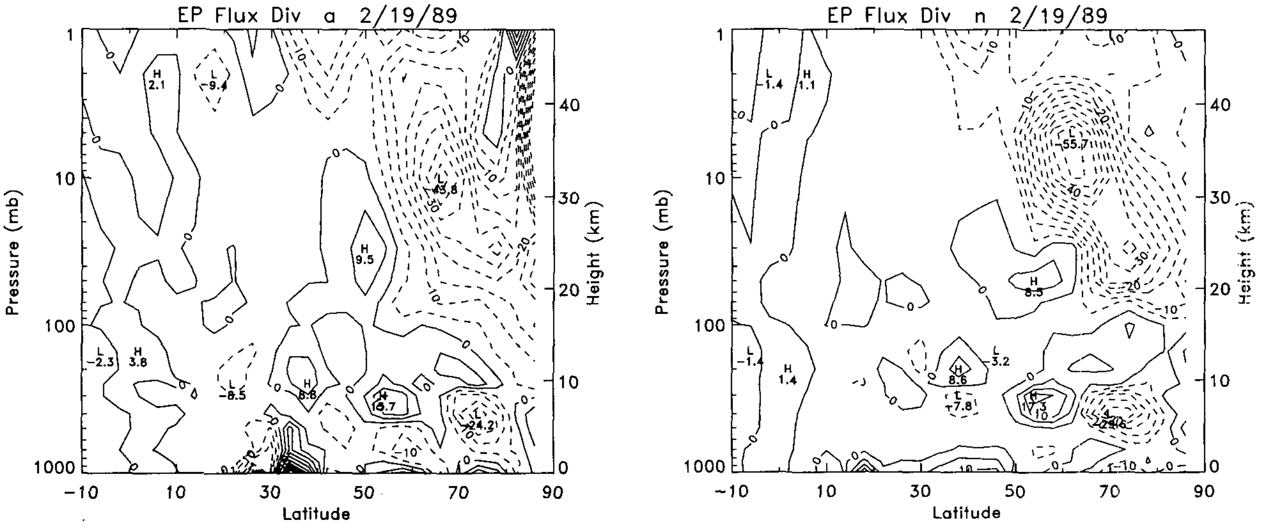

FIG. 6. EP (Eliassen–Palm) flux divergences (m s^{-1} day^{-1}) for 19 February 1989 calculated from (a) STRATAN winds and temperatures, and (b) NMC/CAC balance winds and NMC/CAC temperatures. Heights are approximate.

d. Noise

The removal of this series of apparently spurious blobs at high altitudes is an example of how the model helps to control noise and error in the system. The relationship between the model and small-scale structure is complex. Through advection of information, the model can actually provide a representation of small-scale structure that is correct and beyond either the resolution or coverage of the measurements. The model can filter out spurious features that are not physically maintainable. On the other hand, the primitive equations support the propagation of gravity waves, and many gravity waves are launched by the model. This is especially true during the data insertion when both errors and information are inserted into the system. These gravity waves are more spurious than real, and as they propagate upward their amplitude increases. This generates small-scale structure that can only be characterized as noise, and assimilation analyses tend to be noisier than balanced wind analyses.

Noise also arises from boundary effects and physical parameterizations in the model. In stratospheric analyses, the upper boundary is especially problematic (~0.3 hPa). The gravity waves generated in the lower atmosphere have reached substantial amplitudes. Planetary wave 1 is often at its peak and interactions with the boundary are large. These problems limit the quality of the analysis in the upper stratosphere, and transport experiments have proven to have little quality above 5 hPa. The current research version of STRATAN has placed the model lid much higher than the top analysis level to allow the waves to propagate out of the analysis domain and, hence, be dissipated more benignly.

In summary, the results here show the superiority of assimilated winds to balanced winds not only in monthly averaged quantities but during the February 1989 wave-2 warming as well. STRATAN provides global winds, better-defined jets in the upper stratosphere, and the divergence fields needed for studies of vertical transport. In addition, radiative forcing terms from the assimilation are stored allowing for future budget studies from a variety of perspectives, such as nonlocal control. Currently, datasets are being produced from the time of UARS (Upper Atmosphere Research Satellite) launch in September 1991. These data (stored as described in Schubert et al. 1993) are generally available to the research community.

Acknowledgments. We are grateful to the Earth Observing System (EOS) for providing the computer resources needed to run the data assimilation system. We acknowledge the contribution of the High Speed Research Program (HSRP). We also recognize the personnel in the Data Assimilation Office at NASA/GSFC who are essential to the maintenance and running of the assimilation system.

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