Stationary anomalies in stratospheric meteorological data sets

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Abstract. Several northern hemisphere stratospheric meteorological data sets are shown to contain stationary anomalies. We consider four possible explanations for the anomalies: 1) real stationary wave features; 2) biases in the analysis and assimilation methods; 3) errors in data input into the analysis and assimilation systems; and 4) tidal signals that are undersampled in the daily analyses. Because the easterly flow in the summer stratosphere is not consistent with stationary waves and the anomalies are present in multiple analyses, we conclude that the anomalies are a combination of biases in the input data and tidal signals that are aliased to zero frequency by daily sampling. Because the anomalies are large, they can have significant impacts on many applications of the data, including trajectories and chemical transport calculations.

Introduction

A number of meteorological institutions analyze or assimilate stratospheric meteorological data to produce global gridded estimates of meteorological parameters. Institutions producing these data on a regular basis include the National Centers for Environmental Prediction (NCEP) in the United States, the United Kingdom Meteorological Office (UKMO), the Data Assimilation Office (DAO) at NASA Goddard Space Flight Center (GSFC), and the European Center for Medium Range Weather Forecasting (ECMWF). These gridded data products are used in a very wide range of meteorological research, including dynamical studies and diagnostics of the stratospheric circulation, Lagrangian trajectory calculations for transport studies, and chemical transport modeling.

We have been using NCEP and UKMO winds to compute Lagrangian trajectories to interpret summertime stratospheric ozone observations from the Polar Ozone and Aerosol Measurement II instrument (POAM II), which operated on the French SPOT satellite [Bevilacqua, 1997]. In the course of this research we noticed systematic differences between POAM II ozone observations and trajectory calculations. This has led to evidence of significant stationary anomalies in several stratospheric data sets.

Data and methods

The NCEP data consist of daily (12 Z) global geopotential heights from the Climate Analysis Center stratospheric analysis

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Paper number 9GOL01716.
0094-8554/98/9GOL01716S05.00

(70 - 0.4 hPa) and the NCEP tropospheric/lower-stratospheric analysis (1000 - 100 hPa) that have been assembled into a single data set by Randel [1992]. Below 5 hPa the northern hemisphere NCEP analysis uses radiosondes with 11ROS Operational Vertical Sounder (TOVS) as the first guess, while above 5 hPa the analysis is based entirely on TOVS temperatures. Due to the sparsity of radiosonde data, the southern hemisphere analysis uses only TOVS temperatures. Details of the data set and known problems can be found in Gelman et al. [1994], Randel [1992], and Trenberth and Olson [1987]. Winds are inferred from geopotential heights using linear balance as in Randel [1992]. Estimates of the precision of the NCEP temperatures and geopotential heights are given in Gelman et al., 1994, although these estimates may be somewhat too large (M. Gelman, personal communication).

The UKMO system continuously assimilates operational radiosonde data and TOVS temperature profiles into a general circulation model (GCM), using the Analysis Correction data assimilation scheme [Lorenc et al., 1991]. The data are output once per day at 12 Z on the UARS (Upper Atmosphere Research Satellite) pressure grid (from 1000 hPa to 0.316 hPa). Further details are given by Swinbank and O'Neill [1994]. Estimates of the precision of UKMO height and wind fields are given in the UKMO data quality document that is distributed with the data.

The GSFC DAO assimilation system uses an analysis forecast cycle, in which data from 6-hourly optimum interpolation analyses are gradually inserted into a numerical model using a procedure known as Incremental Analysis Update [Bloom et al., 1996]. The assimilation system is similar to that described by Schubert et al. [1993], but the GCM extends through the stratosphere and uses a rotated grid with computational poles on the Equator.

Results

Figure 1 shows the NCEP time-mean eddy geopotential height $Z^* = Z - [Z]$ and meridional velocity $\bar{v}^* = v - [v]$ at 10 hPa for the period 1 June 1993 to 31 August 1995. The overbar indicates the time average, brackets indicate the zonal average, and * indicates the deviation from the zonal mean. The $Z^*$ field is dominated by a hemispheric pattern with negative anomalies over North America and western Europe, and positive anomalies over eastern Europe and Asia. The hemispheric-scale pattern is composed of several medium-scale anomalies, with the largest located over central Asia, the Aleutian Islands, the North Atlantic Ocean, and the Arabian Peninsula. Velocity anomalies are closely associated with height anomalies, as would be expected when using balanced winds. For example, the time-mean $v$-wind at 180° E and 60° N is $\sim -6 \text{ m s}^{-1}$.
NCEP Time-Mean Eddy $Z$

NCEP Time-Mean Eddy $v$

Figure 1. NCEP time-mean eddy geopotential height $\bar{Z}$ and meridional velocity $\bar{v}$ at 10 hPa for the period 1 June 1995 to 31 August 1995.

Figure 2 is a longitude-time cross section of the instantaneous meridional velocity $v$ at 60°N and 30 hPa. Large-amplitude quasi-stationary and eastward-propagating traveling waves dominate the wintertime circulation when winds are westerly (white areas). As the stratosphere warms in the summer and the winds reverse, some westward-propagating wave features remain in April and May. Coherent traveling features are difficult to detect during June, July, and August; but several stationary features are obvious. These include a large positive wind anomaly (red) of about 5 m s$^{-1}$ between about 20° and 50° E and a stationary negative wind anomaly (blue) centered at 180° E with a weaker positive anomaly to its east. Although it is difficult to distinguish during the winter seasons, there is some indication that the anomalies persist throughout the year. Both these anomalies are relatively small scale (zonal wavenumber 4–6), and both are essentially perfectly stationary.

Figure 2 demonstrates that the stationary anomalies in Figure 1 are persistent and not the result of sampling. It also illustrates that the zonal gradients of $\bar{Z}$ at this level are not a pure wavenumber 1, but are localized around 30° and 180° E.

Figure 3 shows $\bar{Z}$ at 10 hPa from the UKMO assimilation for the same time period as the NCEP analysis in Figure 1. The large-scale height anomalies at higher latitudes in Figures 1 and 3 are very similar. In the subtropics the UKMO analysis is much flatter than NCEP. The high-latitude velocity anomalies in the UKMO assimilated data (not shown) are somewhat weaker than in the NCEP analysis.

Both the NCEP and UKMO data are available once daily, which raises the possibility that either aliasing of real diurnal signals or diurnal biases in the measurements could be responsible for the stationary anomalies. Figure 4 shows $\bar{Z}$ at 1 hPa from the DAO assimilation for JJA of 1995 at 6-hourly intervals. At 12 Z the DAO analysis is very similar to the coincident NCEP and UKMO analyses (not shown), but the 6-hourly snapshots reveal that the apparently stationary wavenumber 1 is in fact westward-propagating with a period of 1 day. The wave 1 tidal signal dominates $\bar{Z}$ at 1 hPa. At 10 hPa it is slightly smaller in amplitude than the stationary features shown in Figures 1 and 3, and it is not evident at 100 hPa.

Discussion and conclusions

The NCEP, UKMO, and DAO stratospheric data sets contain persistent anomalies in the geopotential height and wind fields in middle and high latitudes of the northern hemisphere. The anomalies are of two kinds: medium-scale stationary features that...
are tied to the geography and a wave 1 tidal signal that is aliased to zero frequency by once-daily sampling. The medium-scale stationary features have somewhat larger amplitude than the diurnal tide at 10 hPa, while the tidal signal increases rapidly with height and dominates the height field at 1 hPa.

The stationary medium-scale anomalies are unlikely to be real features of the circulation because theory predicts that forced stationary waves should be evanescent in the easterly zonal flow in the summer-hemisphere stratosphere [Charney and Drazin, 1961]. Following Andrews, Holton, and Leovy, [1987, p. 177], we can estimate the vertical scale of a stationary wave for the simple case of constant zonal flow $\bar{u}$ and Brunt-Väisälä frequency $N$. Assuming wave-like behavior in the horizontal, the vertical part of the solutions of the linearized, quasigeostrophic, potential vorticity equation have the form $\bar{\psi} = e^{i\Lambda z}$, where $\bar{\psi}$ is the streamfunction and $\Lambda$ is the vertical wavenumber, which is given by

$$\Lambda = \frac{1}{2H} \left[ \frac{1}{4H^2} + \epsilon^{-1} \left( \frac{\beta}{|\bar{u}|} - c \left( k^2 + l^2 \right) \right) \right]^{1/2}. \tag{1}$$

In (1) $H$ is the scale height, $\epsilon = f^2 / N^2$, $f$ is the Coriolis

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**Figure 3.** UKMO time-mean eddy geopotential height $\bar{Z}$ at 10 hPa for the period 1 June 1995 to 31 August 1995.

**Figure 4.** DAO time-mean eddy geopotential height $\bar{Z}$ at 00Z, 06Z, 12Z, and 18Z at 1 hPa for the period 1 June 1995 to 31 August 1995.
parameter, $\beta = \frac{\partial f}{\partial y}$, $[u]$ is the zonal wind speed, $c$ is the wave phase speed, and $k$ and $l$ are the zonal and meridional wavenumbers. We take $H = 7000$ m, $c = 0$, $[u] = -10$ m s$^{-1}$, $N^2 = 5 \times 10^{-4}$ s$^{-2}$, $k = l = 1.25 \times 10^{-6}$ m$^{-1}$ (equivalent to 45° of great circle arc), and we evaluate $f$ and $\beta$ at 60°N. Under these conditions the vertical scale of the wave $L = 3300$ m. A forced wave of this scale decays rapidly with height in the middle stratosphere. Therefore, the stationary medium-scale anomalies are not consistent with stationary wave theory.

The southern hemisphere, where radiosonde data is generally not used in the analyses, does not show the same evidence for stationary medium-scale anomalies as the northern hemisphere (not shown), but does have a tidal signal similar to the northern hemisphere. Because radiosondes are little used in the southern hemisphere analyses, the absence of medium-scale stationary features adds weight to the idea that the northern hemisphere features are the result of some kind of radiosonde bias.

The fact that the largest anomalies occur at the boundaries between North America and Asia, and between Asia and Europe, suggests that regional differences between radiosonde types, operational methods, or calibration methods might be responsible for the observed differences. A second possibility is that the anomalies occur at the boundaries between regions with and without radiosonde data (primarily between northern hemisphere continents and oceans). It is also possible that the biases could be due to uncorrected diurnal effects, such as solar illumination, especially in the once-daily analyses presented here. The observations that the anomalies are weaker in the UKMO assimilation indicates that the multivariate nature of the assimilation method may be partially successful in removing biases in one or the other input variables.

The anomalies appear in the NCEP analysis, the UKMO assimilation, and the DAO assimilation, which are each carried out independently using different algorithms. This argues against the anomalies being the result of internal biases in the analysis or assimilation schemes. The amplitude and phase of the diurnal wave 1 appear to be generally consistent with estimates of the diurnal tide [Hedin et al., 1996; Keckhut et al., 1996], but it is difficult to judge whether the tidal signal is completely realistic, since diurnal biases in the input data could have an effect.

The typical amplitude of the stationary features shown in Figures 1 and 3 at 10 hPa is on the order of 50 m. If a temperature bias exists only in the layer between 100 and 10 hPa and is uniform with height, its magnitude would be ~0.75 K. This is comparable to the estimated precision of the measurements, but, of course, the anomalies are persistent, not variable in time as would be expected from random errors.

Persistent anomalies of the type shown in Figures 1–3 are apparent in the NCEP analysis throughout the period of available data (1979–present). In some years the anomalies have been weak, while in others they have appeared at different longitudes, possibly due to changes in the type or availability of radiosonde data. Longitude-time plots like that in Figure 2 for the other years and for the southern hemisphere are available on the World Wide Web at http://csrcp.tamu.edu/grl97/grl97.html. The magnitude of the anomalies means that care should be taken when interpreting models and analyses that use these data sets. Furthermore, the importance of these data sets to middle atmospheric research mandates further research to understand the anomalies and to develop methods to remove them from the data sets should they prove to be unphysical artifacts.

Acknowledgments. Discussions with Paul Newman during the course of this study were very helpful. Funding for this research came in part from NASA Grant NAGW-3442 to Texas A&M University and from USRA contract NAS5-32484. The authors would like to thank the Distributed Active Archive Center at the Goddard Space Flight Center, Greenbelt, MD 20771 for distribution of the UKMO data sets. For the NCEP data we thank Jim Miller, Mel Gelman, and Bill Randel.

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(Received February 27, 1998; accepted May 8, 1998.)