Quantifying the wave driving of the stratosphere

Paul A. Newman

NASA Goddard Space Flight Center, Greenbelt, Maryland

Eric R. Nash

SM&A Corporation (East), Largo, Maryland

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Abstract.

The zonal mean eddy heat flux is directly proportional to the wave activity that propagates from the troposphere into the stratosphere. This quantity is a simple eddy diagnostic which is easily calculated from conventional meteorological analyses. Because this "wave driving" of the stratosphere has a strong impact on the stratospheric temperature, it is necessary to compare the impact of the flux with respect to stratospheric radiative changes caused by greenhouse gas changes. Hence, we must understand the precision and accuracy of the heat flux derived from our global meteorological analyses. Herein, we quantify the stratospheric heat flux using five different meteorological analyses, and show that there are 30% differences between these analyses during the disturbed conditions of the northern hemisphere winter. Such large differences result from the planetary differences in the stationary temperature and meridional wind fields. In contrast, planetary transient waves show excellent agreement amongst these five analyses, and this transient heat flux appears to have a long term downward trend.

Introduction

The zonal mean eddy heat flux in the upper troposphere is fundamental for understanding stratospheric behavior. It is a principal term of the thermodynamic equation, and under quasi-geostrophic assumptions, it can be related to the momentum of the stratosphere through the transformed Eulerian mean (TEM) formulation (*Edmon et al.* [1980]). In this TEM formulation, the eddy heat flux forms the vertical component of the Eliassen-Palm flux (E-P flux) vector, and the divergence of this E-P flux acts as a body force on the mean flow [*Edmon et al.,* 1980]. Hence, the eddy heat flux is a fundamental parameter for understanding the impact of waves from the troposphere on the stratospheric mean state.

Numerous works have used the E-P flux divergence to understand the evolution of both the stratosphere and the troposphere (e.g., *Edmon et al.* [1980]). *Andrews, Mahlman, and Sinclair* [1983] used a model to show that the E-P flux divergence and the Coriolis force from the residual circulation formed a near balance in the transformed Eulerian mean momentum equation. These studies demonstrated that the eddy heat flux has a strong impact on the stratospheric temperature and wind speeds. Because of greenhouse gas effects, and the non-linear relationship of temperature to ozone loss, understanding the observed relationship of the heat flux to temperature has become a primary concern for understanding climate change in the stratosphere. Hence, the precision and accuracy of the eddy heat flux estimates is a fundamental parameter for interpreting stratospheric trends.

Recent studies have suggested a connection between wave activity and recent cold winters. *Zurek et al.* [1996] suggested that winters during the 1990s had been colder and the vortex had been more isolated during the winter period. *Coy et al.* [1997] additionally suggested that the cold late winter of 1997 directly resulted from the extremely low wave activity propagating into the stratosphere during the February–March period of 1997. *Waugh et al.* [1999] have examined the persistence of the lower stratospheric polar vortex and relate it to the eddy flux in the lower stratosphere. Recent modeling studies suggest that greenhouse forcings may alter the eddy heat flux, cooling the polar lower stratosphere, and exacerbating polar ozone loss [*Shindell et al.,* 1998]. Such studies force a quantitative reckoning of the quality of stratospheric eddy heat flux estimates.

In this paper we will discuss some of the details of the eddy heat flux. First, we will review some of the analyses that we use to calculate the heat flux. In the second section, we will review the annual cycle of the heat flux, show its vertical structure, and discuss the features that principally contribute to it. In the third section we will show long-term estimates of the heat flux and analyzed differences between heat flux estimates from various analyses. In particular, we will focus attention on the years 1996, 1997, and 1998. The final section will draw conclusions and discuss observational improvements for better eddy heat flux estimates.

Meteorological analyses

We use five analyses to determine the quality of the heat flux during the January–February period. These are the National Centers for Environmental Prediction's (NCEP) Climate Prediction Center (CPC) stratospheric analysis, the NCEP Global Data Assimilation System (GDAS), the jointly produced NCEP/NCAR (National Center for Atmospheric Research) reanalysis, the United Kingdom's Meteorological Office (UKMO) analysis, and the Goddard Space Flight Center's Data Assimilation Office (DAO) analysis. Of these five analyses, three are operational products which have undergone numerous changes over the last few years. However, the DAO analysis and NCEP/NCAR reanalysis are both continuous, consistent assimilation systems, but the DAO analyses are only available for a few years, while the NCEP/NCAR data are available for more than 20 years. We only use data after 1979 because of the problems associated with analyses prior to incorporation of satellite data [*Pawson and Fiorino,* 1998; *Santer et al.,* 1999].

The NCEP's GDAS produces forecasts and analyses in various modes. We use Medium Range Forecast model output. This is an operational model which has undergone many changes [*McPherson et al.,* 1979; *Kalnay et al.,* 1990; *Kanamitsu et al.,* 1991; *Derber et al.,* 1991; *Caplan et al.,* 1997]. It is a spectral model run with a truncation of 62 (T62), and ingests satellite radiances instead of temperature retrievals. The data are available on pressure levels from 1000 to 10 hPa, and the horizontal grid is 2.5° longitude by 2.5° latitude. These data will be referred to as the MRF62 data.

The NCEP/NCAR reanalyses are also produced from this same T62 GDAS model except that the input is from the satellite temperature retrievals. This model is run in a fixed mode through all years [*Kalnay et al.,* 1996]. The data are available on the same grid and pressure levels as the MRF62 data. These data will be referred to as the REAN data.

The Climate Prediction Center at NCEP produces analyses based on the T126 GDAS model and use an objective anlaysis of satellite and radiosonde data to extend the pressure levels from 70 to 0.4 hPa [*Gelman et al.,* 1986; *Nagatani et al.,* 1988; *Finger et al.,* 1993]. The horizontal grid is a 65 by 65 point stereographic projection which we interpolate to a grid of 5° longitude by 2° latitude. At 100 hPa and below, these data are solely based on the T126 GDAS product, a higher resolution product than the MRF62 product discussed above. Temperatures and geopotential heights are basic products of this tropospheric-stratospheric hybrid system, while consistent balanced winds are produced at all levels by our group using the method described in *Randel* [1987] and *Newman et al.* [1988]. These data will be referred to as the CPC data.

The UKMO assimilation system uses a gridpoint model with a horizontal resolution of 3.75° longitude by 2.5° latitude [*Lorenc et al.,* 1993; *Cullen,* 1993; *Swinbank et al.,* 1994]. The data are available on pressure levels to 0.4 hPa. *Manney et al.* [1996] have compared the UKMO and CPC products and have found that CPC temperatures at stratospheric altitudes are lower and more consistent with the radiosondes than the UKMO data. Near 100 hPa, both analyses show small biases with respect to the radiosondes.

The DAO assimilation uses a gridpoint model with a horizontal resolution of 2.5° longitude by 2° latitude [*Schubert et al.,* 1993; *Suarez and Takacs,* 1995]. This assimilation was produced for the Stratospheric TRacers of Atmospheric Transport mission. Comparisons of DAO output have been made with UKMO data [*Coy and Swinbank,* 1997] and with CPC data [*Coy et al.,* 1994]. *Coy and Swinbank* [1997] showed that the UKMO and DAO zonal mean winds were within 1 m s^{-1} of one another, while the zonal mean temperatures compared to within 1 K in the northern mid-to-high latitudes.

Eddy heat flux climatology

Climatological estimates of the stratospheric and tropospheric eddy heat flux have been shown in a number of atlases [*Oort,* 1983; *Wu et al.,* 1984; *Wu et al.,* 1987; *Randel,* 1992]. *Pawson and Kubitz* [1996] used analyses from the Free University of Berlin to show the behavior of the eddy heat flux in the middle stratosphere. Here, we use the REAN analyses to provide a more extended discussion of the morphology of the eddy heat flux.

Vertical variations

The eddy heat flux reaches its largest values in the stratosphere. Figure 1a shows the total January zonal mean eddy heat flux from the REAN analysis averaged over the 21-year period of 1979–1999. The flux has maximal values of over 120 K m s^{-1} at 10 hPa near 65°N. The flux increases exponentially with altitude as the eddy wave amplitude Figure 1 grows. This large increase of the amplitude with altitude results from the decrease of atmospheric density. Since the wave energy is proportional to the density and the square of the wave amplitude, an upward propagating wave's amplitude increases exponentially such that the wave's energy is conserved. The largest eddy heat flux values in the lower stratosphere (100–200 hPa) are found between 50° and 55° N.

Wave scale contributions to the heat flux

The stratospheric heat flux is dominated by planetary waves. Figure 1b displays the wave 1–3 contribution to the total eddy heat flux. Above 100 hPa, the total is nearly identical to this wave 1–3 contribution. The dominance of the flux by planetary waves results from the inability of smaller-scale waves to propagate into the stronger westerly flow of the stratosphere. This dominance by the larger-scale features is in good agreement with the Charney-Drazin theory of wave propagation [*Charney and Drazin,* 1961]. The background flow field filters out smaller-scale waves propagating upward into the stratosphere.

Stationary and transient wave contributions to the heat flux

Figures 1c and 1d show the stationary and transient components of the zonal mean eddy heat flux in the troposphere and stratosphere. The eddy heat flux is dominated by the stationary waves. The higher amounts of the transient eddy heat flux in the lower troposphere are from smaller-scale waves. This dominance of the stationary planetary waves results from the stationary planetary-scale forcings of topography and land-sea contrasts, and by the slow phase velocities of planetary Rossby waves.

Heat flux annual cycle

Figure 2 shows the annual variation of the eddy heat flux over the year at 100 hPa in the northern hemisphere mid-latitudes. The white line shows the 20-year average (January 1979 to December 1998) of the total eddy heat flux (all waves) smoothed with a 31-day running mean. The grey shading shows the range of values for each day over these 20 years. The flux is quite small during the summer period, consistent with the weaker tropospheric wave activity, and our theoretical expectation that waves cannot propagate up into the stratospheric easterly flow. Wave activity begins to build up during the fall, and the eddy flux reaches its greatest magnitudes during the December–February period. Figure 2

As noted above, the eddy heat flux at 100 hPa is dominated by planetary waves during winter. The thin dotted line on Figure 2 shows the eddy heat flux contribution of waves 1–3. Virtually all of the heat flux during this mid-winter period is contributed by these planetary waves. Wave numbers higher than 3 account for only about 1 K m s^{-1}. There is only a relatively small variation amongst the various analyses for these higher wave numbers. Interestingly, the relative contribution of these large-scale waves is less during the spring and fall period. In fact, the eddy heat flux for medium-scale waves displays a distinct semi-annual cycle with peaks in both the spring and fall. Again, this is in general agreement with the Charney-Drazin theory that allows the propagation of smaller-scale waves into the stratosphere when the westerly flow is weak.

Heat flux day-to-day variability

The day-to-day variation of the eddy heat flux is quite large. Also superimposed on Figure 2 are the daily values of the eddy heat flux from July 1996 through June 1997. The heat flux can vary as much as 20 K m s^{-1} over only a few days, and is almost always positive. The peak event for this particular winter occurred in mid-November, reaching a value of about 30 K m s^{-1}. The December–February average flux value is 15.5 K m s^{-1}, with a standard deviation of about 10.1 K m s^{-1}. The probability distribution function for all of these daily values is reasonably Gaussian with a slight skewness towards lower values.

Heat flux horizontal structure

The 21-year time average of January eddy heat flux at 100 hPa as a function of latitude and longitude is shown in Figure 3. The regions which principally contribute to the the positive zonal mean eddy heat flux are: 1) the poleward warm air advection in Eastern Siberia, and 2) the southward advection of cold air in the Scandanavia region. A weak southward advection of warmer air in the northern Canada region adds a negative contribution to the zonal mean flux. The regions which principally contribute to the flux can be generally understood as topographically forced features (i.e., stationary features) [*Plumb,* 1985]. This forcing is a non-linear combination of flow over the topography and the thermal forcing associated with this same topography [*Ringler and Cook,* 1997]. The peak contribution to the heat flux in Eastern Siberia results from the forcing associated with the topography in the Tibetan region [*Plumb,* 1985]. Figure 3

Eddy heat flux interannual variability

The interannual variability of the eddy heat flux is quite large. Figure 4a displays the total eddy heat flux at 100 hPa averaged for the two-month period of January–February between 40° and 70°N. The CPC values (solid line-plusses) range from a maximum near 18 K m s^{-1} in 1979 and 1983 to a minimum of about 6 K m s^{-1} in 1997. Figure 4

There is a decrease of this total eddy heat flux from the early 1980s to the mid-1990s, with some recovery in the last two years. As was shown in the previous section, the eddy heat flux is dominated by the planetary waves 1–3 (Figure 4b). Further, most of this planetary wave eddy heat flux is from the stationary waves (Figure 4c). The stationary flux shows a quasi-biennial variation. While the transient wave activity represents a significant amount of the heat flux (Figure 4d), the interannual variations of the transient heat flux are smaller than the stationary interannual variability. Nevertheless, the transient variations can be as high at 6 K m s^{-1} (e.g., 1989).

Eddy heat flux difference estimates

Mean differences

Differences between eddy heat flux estimates from various analysis schemes are quite large. Figure 4 also displays the eddy heat flux estimates from five different analysis systems (see the data section for descriptions of these systems). In 1997, the mean value of these analyses is about 9 K m s^{-1}. The REAN data have a maximum value of about 11.5 K m s^{-1}, while the CPC data have a minimum of about 6.5 K m s^{-1}. This difference suggests a variation of about 28% among analyses which ostensibly use the same input data. Comparisons to other years suggest that the analyses typically have differences of 2 to 3 K m s^{-1}. Overall, the analysis differences between the CPC and REAN data give a 1σ uncertainty of about 15%.

For the 21-year period, the REAN data give the highest values of heat flux, while CPC give the lowest. The values vary within 20% ($\pm$ 2 K m s^{-1}) of a mean value of about 12 K m s^{-1} for the January–February average. The REAN heat fluxes are higher than CPC fluxes by 1.6 K m s^{-1}. The slope coefficient of the regression of REAN vs. CPC is 0.857, which indicates that the differences become larger for the lowest flux values. For the later years, the UKMO and DAO data have low heat flux values in all years except 1997.

Differences in eddy heat flux estimates generally result from the larger-scale waves. The eddy heat flux estimated from the contributions of waves 1–3 are also shown in Figures 4b–d for the total, stationary, and transient heat flux. The smaller-scale waves contribute a slight portion of the differences shown in Figure 4a. The differences between transient estimates amongst the analyses are quite small, generally less than 1 K m s^{-1}. The differences between heat flux estimates is found in the planetary stationary waves.

We considered, in detail, fluxes for January–February of 1996, 1997, and 1998. The REAN fluxes were higher than the CPC fluxes by 3.3, 4.7, and 0.2 K m s^{-1}, respectively. The difference in 1997 is the largest for any single year of the 20-year period. In considering just the first three waves of meridional wind (v) and temperature

(T), the REAN fluxes were higher by 3.0, 3.8, and 0.01 K m s^{-1} in 1996, 1997, and 1998, respectively.

Eddy ensemble differences

The heat flux is calculated by the covariance between the eddy temperature (T') and eddy meridional wind (v'). We estimate the “true” values of these quantities as ensemble averages of four analyses (REAN, MRF62, UKMO, and DAO) for each day in this 40°–70°N region. We exclude the CPC analysis because of extreme bias low temperatures found in 1997 in the North Pacific-Alaska region. We analyzed heat fluxes from the combined first three wave numbers of T' and v' from the four analyses. We then looked at the differences of each analysis (including CPC) from this ensemble mean.

The ensemble means of meridional wind and temperature departures from the zonal mean are given by

$$\begin{aligned} T'_a &= \frac{T'_{REAN} + T'_{MRF62} + T'_{UKMO} + T'_{DAO}}{4} \\ v'_a &= \frac{v'_{REAN} + v'_{MRF62} + v'_{UKMO} + v'_{DAO}}{4} \end{aligned}$$

where the subscript a indicates the ensemble mean and the prime indicates departures from the zonal mean. The departure of each analysis from the enemble mean (ϵ) is given by

$$\begin{aligned} \epsilon_{T_i} &= T'_i - T'_a \\ \epsilon_{v_i} &= v'_i - v'_a \end{aligned}$$

where the subscript i inidicates a particular analysis (i.e., CPC, REAN, MRF62, UKMO, or DAO).

The heat flux for an individual analysis consists of four terms:

$$\begin{aligned}\overline{v_i' T_i'} &= \overline{(v_a' + \epsilon_{v_i})(T_a' + \epsilon_{T_i})} \\ &= \overline{v_a' T_a'} + \overline{v_a' \epsilon_{T_i}} + \overline{\epsilon_{v_i} T_a'} + \overline{\epsilon_{v_i} \epsilon_{T_i}}\end{aligned}$$

the overbar indicates the zonal mean. The first term on the RHS $(\overline{v_a' T_a'})$ is simply the ensemble mean flux, the second term $(\overline{v_a' \epsilon_{T_i}})$ can be considered the residual resulting from the temperature, while the third term $(\overline{\epsilon_{v_i} T_a'})$ is the residual resulting from the wind field. The residual terms are simply the fluxes due to the differences with the ensemble analysis. The last term on the RHS $(\overline{\epsilon_{v_i} \epsilon_{T_i}})$ is an order of magnitude smaller than the second and third terms and does not contribute significantly to the total.

Meridional winds. The time-mean meridional wind generally has strong northward flows centered in the North Pacific (175°W) and North Atlantic (35°W), while strong southward flows are found over the northern Rocky Mountains and Europe. Figure 5a shows our v_a' ensemble mean for January–February 1997 at 100 hPa as a function of longitude and time. Strong northward flow in the northern Pacific (red-brown color near 175°W) causes the strong positive heat flux seen in Figure 3. Note that this meridional wind is dominated by stationary features consistent with the climatology. The ϵ_v deviations from this ensemble average in Figure 5a are shown in Figures 5b–f. The ϵ_v deviations in Figure 5b show that the CPC southerly flow over the Rocky Mountains is weaker than the ensemble average, while the REAN ϵ_v meridional

Figure 5

wind deviations (Figure 5c) and MRF62 deviations (Figure 5d) are stronger than the ensemble in the North Pacific.

Temperatures. The 100 hPa eddy temperature field shows that the 1997 CPC data have a serious temperature residual. This CPC temperature residual is inconsistent with radiosonde temperatures, while the other analyses show generally good agreement with the radiosondes. Figure 6a shows the eddy temperature for the ensemble average (T_a). The ϵ_T deviations from this ensemble average are shown in Figures 6b–f. The CPC temperatures (Figure 6b) are cooler in the North Pacific and warmer in the North American and European regions. The largest negative departure is about 3 K. The maximum deviations of the other analyses from the ensemble generally have departures of less than 1.2 K. Figure 6

Flux. The product of the eddy v' and T' shown in Figures 5 and 6 reveals both the source and regional contributions to the deviations of the heat flux estimates seen in Figure 7. The $\overline{v_a' T_a'}$ ensemble average (Figure 7a) shows a similar pattern to the v_a' and T_a' ensembles, where a maximum is found around 175°W, consistent with the climatology. The total heat flux deviation $(\overline{v_a' \epsilon_{T_i}} + \overline{\epsilon_{v_i} T_a'} + \overline{\epsilon_{v_i} \epsilon_{T_i}})$ from this $\overline{v_a' T_a'}$ ensemble average are shown in Figures 7b–f. The CPC analysis (Figure 7b) underestimates the eddy heat flux because it underestimates the warm temperatures in the North Pacific $(\overline{v_a' \epsilon_T})$. The contribution by the $\overline{\epsilon_v T_a'}$ wind deviations are minimal. Local departures of almost 36 K m s^{-1} are found in this region. Figure 7

The REAN heat fluxes (Figure 7c) are higher than the $\overline{v_a' T_a'}$ ensemble eddy heat flux because of the higher REAN meridional winds in the North Pacific $(\overline{\epsilon_v T_a'})$. The contribution by the $\overline{v'_a \epsilon_T}$ REAN temperature deviations from the ensemble is minimal. The MRF, UKMO, and DAO analyses (Figures 7d–f) all show generally above-average heat flux values in the areas where the ensemble mean is high. Local departures are about ± 12 K m s^{-1}.

The REAN (Figure 5c) and MRF62 (Figure 5d) ϵ_v winds are consistently higher by about 1.2 m s^{-1} than the v'_a mean in the region of maximum $\overline{v'_a T'_a}$ ensemble flux near 175°W. The UKMO (Figure 5e) and DAO (Figure 5f) ϵ_v wind deviations have minima in this same region. The maximum in the CPC ϵ_v wind deviation (Figure 5b) occurs in the region of maximum southward v'_a wind. The DAO ϵ_v winds have a dominant wave 3 pattern in all years analyzed.

Radiosonde comparison

We have checked the REAN winds by directly comparing them to rawinsonde winds. The two month averages (January–February) of radiosondes over the 21 years of data generally show the REAN data to have a slightly positive bias in both temperature (0.2 K) and meridional wind (0.1 m s^{-1}) in the North Pacific-Alaska region. These small REAN biases combine with the eddy meridional wind and temperature values (6.5 m s^{-1} and 6.8 K, respectively) to produce an average 1.6 K m s^{-1} overestimate of the eddy heat flux at the stations in this region. We speculate that the relatively low model top in the REAN assimilation system may be contributing to this slight amplification of the heat flux (e.g., see Figure 6b in *Ruosteenoja* [1999]).

CPC comparisons to radiosonde temperatures show that the CPC data are much too cold at 100 hPa in 1997, and have a negative wind bias. These CPC biases lead to a consistent underestimate of the eddy heat flux in the North Pacific-Alaska region.

The results for 1997 are marginally consistent with both 1996 and 1998. A similar CPC temperature underestimate in the North Pacific is found in 1996, but is about 3 times smaller. In 1998, the CPC eddy temperature field in the North Pacific matches the ensemble average. The REAN analysis consistently shows a stronger northward flow in the North Pacific in both 1996 and 1998.

NH Winter eddy heat flux trends

Both winters of 1997–1998 and 1998–1999 had relatively large heat flux values. This suggests that the low values characteristic of the mid-1990s may have been a long-term interannual fluctuation. Nevertheless, we calculated the trend of the total January–February 100 hPa eddy heat flux shown in Figure 4, as well as at 50 hPa. There is a downward trend of about 1.6 to 1.7 K m s^{-1} per decade at 100 hPa (see Table 1). In addition, at 50 hPa, the there is a significantly larger downward trend of 3.6 K m s^{-1} per decade in the the REAN analysis. Even larger is the downward trend in the CPC analysis of over 5 K m s^{-1} per decade. The trends are about the same when considering the first three wavenumbers. All of these trends are statistically significant. Table 1

The downward trends of the transient heat flux are the main contributors to the overall trends. The trends in the stationary components of the heat flux are small and not statistically significant. While the transient heat flux trends are a bit smaller than the combined total, the variance of the transients is much lower. It remains to be seen if this is part of a longer-term climatic fluctuation or an indication of a continuing downward trend.

We have reexamined the heat flux estimates for February and March that are discussed in *Coy et al.* [1997]. They pointed out that the February–March 1997 heat fluxes at 100 hPa were lower by a factor of 2 than those of any other year from the NCEP time period (1979–present). Comparisons to the REAN, DAO, MRF62, and UKMO data for this same period and region generally bear this conclusion out. While correcting the NCEP temperature error identified previously would increase our heat flux estimate for this period, the increase would be no more than 2 K m s^{-1} from about 4 to 6 K m s^{-1}, consistent with the estimates from the other analyses. Therefore, in spite of the 1997 NCEP temperature error, the 1997 estimate is still the lowest on record by a substantial amount.

Conclusions

The zonal mean eddy heat flux is the principal quantity for estimating the impact of tropospheric waves propagating into the stratosphere. The mean estimates of the eddy heat flux are generally consistent with our overall expectations from Charney-Drazin theory. Because this eddy wave driving has an overwhelming impact on the stratospheric mean circulation, it is necessary to understand the degree of credibility with which we can estimate this eddy heat flux.

We have used five different analyses to estimate the eddy heat flux. These analyses are based on our conventional observational network, along with satellite information.

The analyses show differences as large as 20–30% with respect to ensemble mean heat flux values. These estimates are 2-month averages over extended latitudinal ranges. Such large uncertainties and inconsistencies seriously inhibit our ability to explain the impact of climate change in the stratosphere.

The eddy heat flux is derived from the meridional wind speed and the temperatures of the lower stratosphere and upper troposphere. Based on the ensemble averages of analyses, we conclude that there are serious, large-scale inconsistencies between the analyses in these regions in both the temperature and wind field structures. The analysis differences result from stationary planetary biases in the wind and temperature fields.

Such large-scale stationary biases suggest either large-scale biases in ground observations systems, or problems with models used to produce assimilation-based analyses. Radiosonde intercomparisons show significant height field biases at 100 hPa between sondes using radar height measurements (e.g., the Russian MARS radiosonde), and sondes using barometric measurements (e.g., Vaisala sondes) [*Ivanov, et al.,* 1991]. *Bowman et al.* [1998] have shown obvious summer meridional flow field biases that may be a result of these raob biases. Such small wind biases would not be obvious in the strong winter circulation, but these wind biases could seriously bias the more sensitive heat flux. Further, since numerical forecast models are integral parts of assimilation systems, model limitations (e.g., model top height) or parameterizations (e.g., gravity waves) may create erroneous circulations or responses in unsampled or poorly sampled regions of the atmosphere.

The inconsistencies between analyses in turn produce the eddy heat flux uncertainties. In particular, the REAN data have a positive wind and temperature biases in the North Pacific-Alaska region with respect to an ensemble average of four of the analyses used in this study. This positive anomaly leads to an excessive eddy heat flux in comparison to the ensemble average heat flux. The CPC analyses have slightly colder temperatures in this North Pacific-Alaska region, leading to a reduced heat flux. In the 1997 CPC analyses, this region is excessively cold, leading to very low values of the eddy heat flux.

The eddy heat flux estimate from the large-scale transient waves are in excellent agreement between analyses used herein. The eddy heat flux in the lower stratosphere is dominated by stationary planetary waves, and this stationary planetary wave flux has a large interannual variability between winters. On the other hand, the transient waves contribute about one-third of the total heat flux. While the stationary wave flux in the January–February period has decreased since 1979, this is not a significant trend. On the other hand, the transient wave flux in the January–February has significantly decreased over the last two decades.

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P. A. Newman and E. R. Nash, Code 916, NASA Goddard Space Flight Center, Greenbelt, MD, 20771. (e-mail: newman@code916.gsfc.nasa.gov; nash@code916.gsfc.nasa.gov)

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Figure 1. January 1979–1999 zonal mean eddy heat flux from the REAN analysis. (a) Total flux; (b) waves 1–3 total flux; (c) waves 1–3 stationary flux; and (d) waves 1–3 transient flux. Contours are 10 K m s^{-1}.

Figure 2. Zonal mean eddy heat flux at 100 hPa averaged over the 40°–70°N region from the REAN analysis. The solid black line show daily values for the July 1996 to June 1997 period, the thick white line is a 20-year average (1979–1998) of 31-day smoothed values, and the dotted black line is the contribution of waves 1–3 to this 20-year average. The grey shading shows the range of daily values over the 20-year period.

Figure 3. Eddy heat flux at 100 hPa averaged over January for the 21-year period 1979–1999. Contours are 10 K m s^{-1}.

Figure 4. Zonal mean eddy heat flux at 100 hPa averaged over the 40°–70°N region for the January–February period of 1979–1999. (a) Total flux; (b) waves 1–3 total flux; (c) waves 1–3 stationary flux; and (d) waves 1–3 transient flux. The solid line with plusses shows the CPC data, the dotted line with stars shows the REAN data, the diamonds indicate the MRF62 data, the triangles indicate the UKMO data, and the squares indicate the DAO data.

Figure 5. Eddy meridional wind averaged over the 40°–70°N region for the (a) ensemble mean (v_a') and departures from the ensemble mean (ϵ_v) of the (b) CPC, (c) REAN, (d) MRF62, (e) UKMO, and (f) DAO analyses. Data are plotted as a function of longitude and day for the January 1 to February 28, 1997 period.

Figure 6. As in Figure 5, but for eddy temperature enemble mean (T_a') and departures from this mean (ϵ_T).

Figure 7. As in Figure 5, but for eddy heat flux enemble mean ($\overline{v_a' T_a'}$) and departures from this mean ($\overline{v_a' \epsilon_{T_i}} + \overline{\epsilon_{v_i} T_a'} + \overline{\epsilon_{v_i} \epsilon_{T_i}}$).

Table 1. Trend Coefficient for Heat Flux 1979–1999

	100 hPa				50 hPa			
	REAN		CPC		REAN		CPC	
	Coeff.	Conf.	Coeff.	Conf.	Coeff.	Conf.	Coeff.	Conf.
Total	-1.70	96.3	-1.56	94.4	-3.63	97.8	-5.25	99.7
Total (Waves 1–3)	-1.88	97.8	-1.70	96.4	-3.39	97.6	-5.01	99.7
Stationary (Waves 1–3)	-0.65	75.4	-0.28	61.5	-0.79	67.8	-1.84	85.3
Transient (Waves 1–3)	-1.23	99.2	-1.42	99.4	-2.59	99.4	-3.17	99.8

Coefficients are in units of K m s^{-1} per decade. Confidence levels are in units of %.