Troposphere–Stratosphere (Surface–55 km) Monthly Winter General Circulation Statistics for the Northern Hemisphere—Interannual Variations

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ABSTRACT

Individual monthly mean general circulation statistics for the Northern Hemisphere winters of 1978–79, 1979–80, 1980–81, and 1981–82 are examined for the altitude region from the earth's surface to 55 km. Substantial interannual variability is found in the mean zonal geostrophic wind; planetary waves with zonal wavenumber one and two; the heat and momentum fluxes; and the divergence of the Eliassen-Palm flux. These results are compared with previous studies by other workers. This variability in the monthly means is examined further by looking at both time-latitude sections at constant pressure levels and time-height sections at constant latitudes. The implications of this interannual variability for verifying models and interpreting observations are discussed.

1. Introduction

In a recent paper, Geller et al. (1983) (hereafter referred to as GWG1) presented several monthly general circulation statistics averaged over the four Northern Hemisphere winters 1978–79, 1979–80, 1980–81, and 1981–82 for the altitude range 0–55 km. Circulation statistics presented and discussed in GWG1 were as follows: the zonal average temperature [\(T\)]; the mean zonal wind [\(u\)]; the amplitudes and phases of the planetary waves in geopotential height with zonal wave numbers one, two, and three; the northward heat transport by the standing eddies [\(\delta^* T^*\)], and by the transient eddies [\(u' \tilde{T}^*\)]; the northward transport of westerly momentum by the standing eddies [\(\tilde{u} \tilde{v}^*\)] and by the transient eddies [\(u' \tilde{v}\)], as well as the contributions to these transports by wavenumbers one and two; the Eliassen–Palm flux (hereafter referred to as the E–P flux) propagation vectors for the standing eddies and for the transient eddies as well as the corresponding vectors for wavenumbers one and two individually; and the divergence of the E–P flux due to the standing eddies and for the transient eddies as well as the E–P flux divergence fields resulting from wavenumbers one and two individually. It is the purpose of this paper to discuss the interannual variability that was found in compiling the general circulation statistics of GWG1.

The original goal of GWG1 was to present general circulation statistics in a format for easy comparison to the results of general circulation models of the stratosphere. In this paper, we will discuss what our interannual variability results, as well as some similar results of others, imply for observational programs that are planned to understand the workings of the stratosphere as well as what they imply for the comparison of stratospheric general circulation model results with observations.

2. The dataset

The basic dataset used in this paper is the 18-level NOAA/NMC temperature dataset described in GWG1. Since this four-year dataset was derived using a number of different observing and analysis systems, the temperature corrections discussed in GWG1 were applied to this dataset. These temperatures were used to construct the geopotential height field using the hydrostatic equation with 1000 mb geopotential height fields as lower boundary conditions. Geostrophic winds were then derived from the geopotential height fields.

As in GWG1, the vertical coordinate used is log pressure. This is related to pressure altitude and geometric altitude as was indicated in Fig. 1 of GWG1. However, unlike GWG1 we also show geometric height on the figures in this paper.

3. Zonally averaged temperatures

Figure 1 shows Northern Hemisphere monthly mean zonally-averaged temperatures for the months of December, January, and February for the winters of 1978–79, 1979–80, 1980–81 and 1981–82. These zonally
Fig. 1. Northern Hemisphere monthly mean zonally-averaged temperatures \( [T] \) (K) for the months of December, January and February for the winters 1978–79 through 1981–82. An approximate altitude scale is given at the far right of this and other altitude–latitude section figures in this paper.
averaged temperatures are shown for the latitudes 0–90°N and for altitudes from the earth's surface to about 55 km. This corresponds to about eight scale heights in altitude (from about 1000 to 0.4 mb). The four Decembers (or Januaries or Februaries) can be compared by inspecting down a column and the evolution of a particular winter can be inspected by following across a row. We believe that we can identify geophysical differences as opposed to random or systematic differences resulting from the observational and analysis techniques because the analyses of the satellite temperature fields have been calibrated to rocketsonde measurements as a function of altitude and latitude by the procedures presented in GWG1. Also, Gelman et al. (1982) have estimated that individual satellite-derived values are characterized by rms errors that are no more than 4–7 K. One temperature value on a monthly zonally averaged latitude–altitude section represents the average of thirty (number of days in a month) times approximately fifty (the number of determinations around a typical middle latitude circle). Thus, the random error in the determination of the monthly mean zonally average temperature should be considerably less than 1 K. The systematic error should be much less than error estimates for the rocketsonde temperature measurements which are about 1–3 K over the altitude range 35–55 km. Errors in the temperature field will translate into errors in the wind field given the hydrostatic buildup procedure and subsequent geostrophic wind determination. For this reason, this paper concentrates on discussions of large qualitative differences in derived statistics, which we believe are real, rather than small quantitative differences, which may be a result of the data analysis procedure.

As pointed out previously in GWG1, there is a systematic lessening in the meridional gradient of \( \hat{T} \) in the upper stratosphere from December to February during each winter. This is seen for all four winters. Some months show substantially stronger meridional temperature gradients than others. For instance, these gradients are stronger in December 1979 and 1981 than in December 1978 and 1980. This will be seen more obviously when we look at the monthly mean zonal winds. The months with stronger meridional temperature gradients have greater vertical shears in the mean zonal wind, as implied by the thermal wind relation.

The overall patterns of the \( \hat{T} \) field show little interannual variability. Some quantitative differences are quite noticeable, however. For instance, the polar lower stratosphere is about 10 K lower in December 1980 than the other three Decembers, and the polar lower stratosphere in February 1979 and 1981 is about 5 K higher than for the other two Feburaries.

Another way of looking at the interannual variability in \( \hat{T} \) is seen in Fig. 2 which shows a time–height section of the zonally averaged temperature at 60°N during the four winters. In this figure, one sees the continual warming of the middle stratosphere as generally downward sloping isotherms. One sees stratospheric warmings as sharp increases in the isotherm slopes. We can use Fig. 2 to discuss the temperature evolution in the middle stratosphere during these four winters by generally following the 220 K isotherm. The winter of 1978–79 was characterized by slow warming during December and the first two-thirds of January with accelerated warming during the last one-third of January and the first half of February. There

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Time-height section of the zonally averaged temperatures \( \hat{T} \) (K) at 60°N for the winters 1978–79 through 1981–82.}
\end{figure}
was then a cooling of about ten days duration followed by the sudden warming at the end of February. The winter of 1979–80 showed no warming during December with minor warming pulses during the first half of January and the middle of February. The winter of 1980–81 showed very slight warming during December through the first half of January with accelerated warming from then through the first one-third of February and cooling thereafter. The winter of 1981–82 showed no warming through the first two-thirds of December with steady warming through the first two-thirds of January at which time a sharp increase in the rate of warming took place. The rest of the winter showed, if anything, a small net cooling.

Labitzke (1982) has analyzed a 26-year dataset for monthly mean 30 mb radiosonde temperatures over the North Pole. Referring to our Fig. 1, we see that reference is to December 1980, the Januarys of 1979, 1980, and 1981 and February 1980 as being very cold. This is consistent with our cold December 1980 lower stratosphere temperature, but not with our February 1980 results. Also, Labitzke (1982) and Holton and Tan (1982) have pointed out that the Northern Hemisphere winter polar lower stratosphere has a tendency to be colder in years in which the quasi-biennial oscillation at the equator is in its westerly phase. For our four years, the winters of 1978–79 and 1980–81 fall into this category. Other factors suggested to be related to interannual variability in the Northern Hemisphere lower stratosphere include the Southern Oscillation (van Loon et al., 1981 and Wallace and Chang, 1982).

Hamilton (1982b) has shown monthly mean cross sections of the zonally averaged temperature for several of the months of our sample as determined from NOAA once weekly charts analyzed by man–machine using satellite and rocket data. His results look very much like ours with differences between our results and his being at most a few degrees Kelvin. This is probably a consequence of his using weekly rather than daily data, together with differences in the analysis procedure used on these two NOAA datasets.

4. Mean zonal winds

Figure 3 shows the monthly mean zonal wind latitude–altitude sections in the same format as was shown in Fig. 1 for the zonally averaged temperatures. In GWG1, it was found that the mean zonal winds in the upper stratosphere were strongest in December and weakest in February. For individual winters, the situation is more complicated than this. For instance, in December 1978, the maximum westerly winds in the upper stratosphere are in excess of 90 m s\(^{-1}\) centered at about 35°N. By January, we see a split jet with westerlies in excess of 70 m s\(^{-1}\) in the upper stratosphere at 25–30°N with a secondary maximum of the westerlies of about 60 m s\(^{-1}\) at about 60°N. February 1979 again shows a split jet with a wind maximum in excess of 80 m s\(^{-1}\) at 25–30°N and another wind maximum in excess of 30 m s\(^{-1}\) near the Pole. In December 1979, the geostrophic mean zonal wind in the upper stratosphere is in excess of 140 m s\(^{-1}\). At this level, the wind maximum is at about 40–45°N. In January 1980, the upper stratosphere westerlies have weakened to about 70 m s\(^{-1}\). The wind maximum at these levels is at about 45°N, but the axis of the wind maximum slopes toward higher latitudes with decreasing altitude so that the westerlies are stronger in polar regions than was the case in December 1979. In February 1980, the mean zonal winds have weakened so that the maximum mean westerlies are about 40 m s\(^{-1}\), and they occur at about z = 6 (40 km or ~3 mb) at about 55°N. In December 1980, the maximum upper stratospheric westerlies are in excess of 90 m s\(^{-1}\) and occur at about 50°N. The axis of the wind maximum slopes poleward with decreasing altitude so that the polar westerlies are sizeable. By January 1981, the winds have weakened so that the westerly wind maximum of about 70 m s\(^{-1}\) is at z = 6 at 55°N. In February 1981, the winds have further weakened so that the upper stratosphere wind maximum is about 50 m s\(^{-1}\) and is at 35°N. In December 1981, the maximum upper stratosphere westerlies are about 100 m s\(^{-1}\) and occur at about 40°N. The January and February 1982 wind fields are very similar with local wind maxima of about 35 m s\(^{-1}\) occurring at z = 5 (about 35 km or 7 mb) at a latitude of 65–75°N. There is also a wind maximum of 40–50 m s\(^{-1}\) in the upper stratosphere at about 45–50°N. Thus, we see a good deal of interannual variability in both the magnitude and location of many of the features in the mean zonal wind field although the same general patterns seem to occur during each of the four winters as the winter proceeds from December through February. Of course, one loses a great deal of information about how this interannual variability comes about by looking at monthly averages alone. Some insight into this is gained by looking at the time–latitude sections of the mean zonal wind at the 1 mb pressure altitude shown in Fig. 4 and the time-altitude sections of the mean zonal wind at 60°N that are shown in Fig. 5. Looking first at Fig. 4, we see that the December mean zonal wind at 1 mb is characterized by strong westerlies in excess of 80 m s\(^{-1}\) at low latitudes that extend through the first half of December 1978 (centered at about 35°N). In the winter of 1979–80, this feature extends throughout December until mid-January (centered at about 40°N). The winter of 1980–81 is quite different in that this early winter band of strong westerlies is at much higher latitudes (centered around 50°N). It also persists throughout the first two-thirds of January 1981. In the winter of 1981–82, this feature is back down at low latitudes (centered at about 35°N) and lasts through the entire month of December only.
Figure 4 shows a great deal of variability in the mean zonal wind at all latitudes. The predominant time scale of this variability appears to be 1–2 weeks. Several periods of easterlies are seen to persist for a few days at high latitudes during the 1978–79 winter. None are seen during the 1979–80 winter, and two high-latitude
easterly patches are seen in the 1980–81 winter with three such patches during the winter of 1981–82.

A different view of this same variability in the mean zonal wind is seen in the time–altitude sections of the mean zonal wind at 60°N, in Fig. 5. At 60°N strong westerlies ([u] \(\geq\) 40 m s\(^{-1}\)) are seen to descend through the middle stratosphere in mid-December, 1978, and persist through the first two-thirds of January 1979. During this period, there are pulses of strong westerlies ([u] \(\geq\) 70 m s\(^{-1}\)) of about one week's duration appearing in the upper stratosphere. Later, weaker pulses appear with easterlies descending below \(z = 4\) (about 20 mb or 27 km) in connection with the major stratospheric warming of February 1979. In the winter of 1979–80, the [u] = 40 m s\(^{-1}\) isopleth is also seen to descend in mid-December, but persists until mid-February. In the 1980–81 winter, the 40 m s\(^{-1}\) isopleth is already in the mid-stratosphere when December 1980 begins and

Fig. 5. As in Fig. 2, but for mean zonal winds [u] (m s\(^{-1}\)).
persists until late January. Shortly thereafter, weak easterlies are seen to descend down to $z = 5.5$ (about 4 mb or 40 km) for a few days. During the 1981–82 winter, the 40 m s$^{-1}$ isopleth descends into the middle stratosphere in late December 1981 and persists for only about thirty days. Weak easterlies are seen to descend down to $z = 6$ (about 3 mb or 42 km) in late January.

Thus, Figs. 4 and 5 show qualitatively similar patterns in the mean zonal wind during each of these four winters, but the timing and magnitude of the features vary considerably in each of the four years. This variability in timing and intensity leads to the variability in the monthly mean zonal wind seen in Fig. 3.

Quiroz (1981) has done similar computations of monthly mean zonal wind for the winters of 1975–76, 1976–77, 1977–78, and 1978–79. Our overlapping calculations of mean zonal winds for the winter of 1978–79 look quite similar to the results of Quiroz (1981), but there are some differences. For instance, in January 1978–79, we get stronger upper stratosphere winds at low latitudes. Such differences could be due to differences in the lower boundary conditions in geopotential height and different temperature corrections. Quiroz (1981) found a similar level of interannual variability as we do. Hamilton (1982a,b) also produced monthly mean cross sections of the mean zonal geostrophic wind for the period July 1976–April 1980 using weekly Northern Hemisphere analyses of temperatures and geopotential heights. He shows figures for $[u]$ for December 1978 and 1979 and January 1979 and 1980 which agree quite well with ours, except for January 1979 where Hamilton does not show the jetlike structure near the stratopause at low latitudes. Smith (1983) has also calculated monthly averaged mean zonal winds for the period January 1973–February 1977 from Selective Chopper Radiometer data. While this period of analysis does not overlap ours, Smith’s mean zonal wind results show the same type of interannual variability as ours. It is also interesting that the analyses of Holton and Tan (1982), Labitzke (1982), and Wallace and Chang (1982) of 30 mb data indicate that the polar night jet tends to be stronger during Northern Hemisphere winters when the equatorial quasi-biennial oscillation is in its westerly phase. No such tendency is seen in our analyses for the mean zonal winds to be greater during the winters of 1978–79 and 1980–81, but, of course, our dataset is of very short duration.

5. Planetary waves

Figure 6 shows latitude–altitude plots of the monthly mean amplitudes of zonal wavenumber one in the geopotential field for the 12 months being examined in this paper. Both the size and location of the wavenumber one amplitude maxima are seen to vary from year to year. GWG1 pointed out that for their monthly averages over four years, wavenumber one was largest in January and smallest in December, with the February values being intermediate. For the individual winters, however, this is not always the case. For the winter of 1978–79, wavenumber one is largest in January and smallest in December as was the case for the four-year average results of GWG1. In the winter of 1979–80, however, wavenumber one is about the same size in January and February, although it reaches its maximum amplitude at a lower altitude in February, with the December amplitudes being about one-half of the January and February values. For the winter of 1980–81, the largest planetary wavenumber one amplitudes occur in January with minimum amplitudes in February. A similar situation occurs during the winter of 1981–82. This latter winter is exceptional, however, in the very small amplitudes of wavenumber one in February.

The transient behavior of wavenumber one can be seen in Fig. 7 which shows time–latitude plots at 1 mb of the wavenumber one amplitudes, for the four December–February periods. Looking at Fig. 7, we see that during each of the three month winter periods being examined, several pulses in wavenumber one amplitude are seen at 1 mb. These have their largest amplitudes at latitudes of 55–75°N. The number and intensity of the pulses vary from year to year. By comparing Figs. 6 and 7, one can also estimate that portion of planetary wavenumber one that shows a traveling, as opposed to a stationary, wave behavior. For instance, looking at days 63 through 91 in 1982 in Fig. 7, we see that the daily planetary wavenumber one values exceed 800 m for more than two-thirds of February 1982 at 65°N. Looking at February 1982 in Fig. 6, however, we see that the monthly mean amplitude at $z = 7$ (≈1 mb) at 65°N was about 150 m. This implies that most of the planetary wavenumber one activity in February 1982 was due to traveling waves so that over the month the changing phases largely cancelled one another. Looking at our 12 months in this way, we see that traveling wavenumber one amplitudes were particularly high in January 1979, February 1980, February 1981 and both January and February 1982.

Figure 8 shows the monthly mean wavenumber two amplitudes. Again we see quite a lot of interannual variability in both the location and size of the wavenumber two maxima. GWG1 found that for their four-year dataset that wavenumber two amplitudes were largest in January, next largest in February, and smallest in December. Such is not the case for the individual years shown here. In 1978–79, the stationary wave two amplitudes were largest in February and smallest in December. In 1979–80, they were largest in January and smallest in December. In 1980–81, they were largest in December and smallest in February, and in 1981–82, largest in January and February and smallest in December.

Figure 9 shows the transient behavior of the wavenumber two amplitudes at 1 mb for each of the four
FIG. 6. Northern Hemisphere monthly mean geopotential height amplitudes (m) of zonal wavenumber one for the winters 1978–79 through 1981–82.
winters being examined. Again, we see pulses in the wavenumber two amplitudes of characteristic period one to two weeks occurring at 1 mb. Their maximum amplitudes tend to occur at latitudes of 45°–70°N. The number, intensity and duration of these pulses is seen to vary from year to year. As was the case for wavenumber one, we can compare Figs. 8 and 9 to estimate that portion of planetary wavenumber two that shows a traveling, as opposed to a stationary, wave behavior. Using the same line of reasoning that we used for wavenumber one, we see that traveling wavenumber two amplitudes were particularly high in February 1979, February 1980, January 1981 and January 1982.

In comparing Figs. 7 and 9, we see the tendency for the wavenumber two maxima to occur at times between occurrences of wavenumber one maxima. Thus, a similar time phasing between wavenumbers one and two is seen at 1 mb to that which was seen in Labitzke's (1977, 1978) results at 30 mb.

Several investigators have looked at the interannual variability of planetary waves in the stratosphere previous to the present investigation. Van Loon et al. (1973) used global radiosonde data to look at the structure of Northern Hemisphere stationary planetary waves up to the pressure altitude of 10 mb for the seven Januaries 1964 through 1970. They found great variability in wave one and two in the stratosphere. For instance, at 10 mb the January planetary wavenumber one amplitudes varied by about a factor of 10 and wavenumber two varied by about a factor of 4 over this seven-year sample. Our results are consistent with these results of van Loon et al. (1973). Another analysis of planetary waves up to stratosopause levels was done by Smith (1983), whose results showed that for a four-year sample, the average January planetary wave one and two amplitudes were smaller than those for December and February. This is another indicator of interannual variability.

Holton and Tan (1982) have suggested that some of the interannual variability in stationary planetary waves one and two may be identified with the phase of the quasi-biennial oscillation. This result has also been reported by Labitzke (1982). This effect is small compared to the observed interannual variability that we observe, however.

6. Heat and momentum fluxes

Geller et al. presented averaged monthly mean altitude–latitude plots of the northward flux of sensible heat by the standing eddies [\(\bar{u}^*T^*\)] and by the transient eddies [\(u'\bar{T}'\)] for the four-year dataset. Also, presented were plots of the northward flux of westerly (or eastward) momentum by the standing eddies [\(u^*P^*\)] and by the transient eddies [\(u'P'\)]. The heat and momentum fluxes due to wavenumber one and two were also shown. GWG1 found, for the four-year averages, that the standing eddy fluxes of heat and momentum were largest in January. This was a consequence of the large wavenumber one amplitudes in January which were found to dominate the wavenumber two contributions. GWG1 found, for the four-year averages, that the transient eddy fluxes of heat and momentum were largest in February. They also found that wavenumbers one and two were of comparable importance in producing these transient eddy fluxes.
Figure 8. As in Fig. 6, but for wavenumber two.

Figure 10 shows altitude–latitude plots of the northward flux of sensible heat by the standing eddies for each of the 12 winter months. The patterns for all 12 months are very similar, with southward transports at low latitudes and northward transports maximizing in high latitudes in the upper stratosphere (z ≈ 6), al-
though the amplitude and location of the maximum show significant variation from year to year. For all of the four years examined here, however, the largest value of \( \overline{\partial^2 u^*} \) occurs in January. Looking at the contributions of wavenumber one and two individually (not shown), we see that for ten of the 12 winter months, wavenumber one accounts for at least two-thirds of the standing eddy flux of heat. The two exceptions are December 1980 in which wavenumber two accounts for about three-fourths of \( \overline{\partial^2 u^*} \) and February 1982 in which wavenumber two accounts for about two-thirds of \( \overline{\partial^2 u^*} \).

Figure 11 shows altitude–latitude plots of the northward transport of sensible heat by the transient eddies for each of the 12 winter months. Just as was the case for the standing eddy flux of heat, the \( \overline{\partial^2 u^*} \) values at low latitudes are small and negative, and the middle and high latitude values in the middle and high stratosphere are large and positive. For most, but not all, of the months a small negative region of \( \overline{\partial^2 u^*} \) at low latitudes and high latitudes is also seen. For three of the four winters, the largest transient eddy heat transports occur in February. In the 1978–79 winter, however, all three months show roughly the same maximum values of \( \overline{\partial^2 u^*} \). Looking at the contributions of wavenumber one and two individually (not shown), we see that for seven of the 12 months the wavenumber one contribution dominates the \( \overline{\partial^2 u^*} \) distribution, for one month (February 1979, when a major wavenumber two warming took place) wavenumber two dominates, and for four months wavenumbers one and two contribute about equally.

Figure 12 shows the altitude–latitude plots of the northward transport of westerly momentum by the standing eddies for each of the 12 winter months. The patterns for all 12 months are similar with negative values of \( \overline{\partial^2 u^*} \) at all altitudes in low latitudes and at low latitudes in middle and high latitudes, with large positive values at middle and high latitudes in the middle and upper stratosphere. However, within this general pattern are seen significant variations in the location and intensity of features. For individual years, the January values of \( \overline{\partial^2 u^*} \) are not necessarily the largest values such as was seen in the four year averages of GWG1. As was the case for \( \overline{\partial^2 u^*} \), the wavenumber one contribution to \( \overline{\partial^2 u^*} \) dominates that from wavenumber two for all months except December 1980 and February 1982.

Figure 13 shows the altitude–latitude plots of the northward transport of westerly momentum by the transient eddies for each of the 12 winter months. There is a great deal of variability in the distribution of \( \overline{\partial^2 u^*} \) although most of the months show a single broad midlatitude positive maximum in the upper stratosphere. Looking at the contributions of wavenumber one and two individually (not shown), we see that there is no systematic dominance by wavenumber one or two. More specifically, the wavenumber one contribution to \( \overline{\partial^2 u^*} \) is found to dominate in five of the 12 months, wavenumber two dominates for three of the months and the two wavenumbers contribute about equally for four of the months.

We have not shown plots of our computed daily values of the heat or momentum fluxes in this paper. They show similar pulselike behavior to that of the planetary waves (Figs. 7 and 9).
Fig. 10. Northern Hemisphere monthly mean northward flux of sensible heat by the standing eddies \([\vec{e} \cdot \vec{T}]\) (K m s\(^{-1}\)) for the winters 1978–79 through 1981–82. Regions of negative values are shaded.
Fig. 11. As in Fig. 10, but for the northward flux of heat by transient eddies \( \left[ \sqrt{\psi'} \right] \) (K m s\(^{-1}\)).
Fig. 12. Northern Hemisphere monthly mean northward flux of eastward momentum by the standing eddies, $\langle u^*e^* \rangle$ (m$^2$ s$^{-2}$) for the winters 1978–79 through 1981–82. Regions of negative values are shaded.
Fig. 13. As in Fig. 12, but for the northward flux of eastward momentum by the transient eddies $[u'v']$. 
Hamilton (1982a,b) has computed heat and momentum fluxes for his analyzed four-year period, but he did not separate his results into standing and transient results as we did. For our common months of analysis with Hamilton, there is reasonable agreement between the two computations although our results tend to give somewhat larger monthly transports for several months. Again, this is not unexpected, given our differences in analysis method from Hamilton.

7. Eliassen–Palm flux divergences

Geller et al. showed computed E–P flux propagation vectors that were calculated from their four-year monthly-mean standing and transient eddies. They also showed the computed monthly-mean E–P flux divergence fields. In addition, they showed the contributions to the standing and transient eddy E–P flux propagation vectors and the divergence field of wavenumbers one and two individually. These same calculations have also been carried out for each of the 12 months. In this section, we will briefly discuss and show selected results.

In general, the E–P flux propagation vectors for the individual months very much resemble the four-year average patterns that were presented by GWG1. There are features that show up in individual months that are uncharacteristic of the four-year average results, however, and these can be easily identified with anomalies in the heat or momentum flux fields. For instance, there is more of a vertical component in the standing eddy E–P flux vectors and less turning toward the equator in the high-latitude upper stratosphere in December 1980 than is seen in either the December pattern of GWG1 or in the other three Decembers. Looking at Figs. 10 and 12, we see that this month was characterized by a larger standing eddy heat flux and a smaller standing eddy momentum flux than usual which is, of course, consistent with the E–P flux results. The transient eddy E–P flux propagation vectors are directed poleward in February 1979 and 1980 in the polar middle stratosphere but are directed more vertically upward in February 1981 and 1982. Looking at Fig. 13, we see large equatorward transient momentum fluxes in this region during February 1979 and 1980, whereas these fluxes are directed poleward in February 1981 and 1982 and are smaller in magnitude. Comparing both the standing and transient eddy E–P flux vectors to their wavenumber one and two components, one sees that the E–P flux patterns show a bit more resemblance to the wavenumber one field than to the wavenumber two field, but that both wavenumbers are needed to reproduce the pattern of the total.

The 12 monthly-mean E–P flux divergence fields are shown in Fig. 14 for the standing eddies and in Fig. 15 for the transient eddies. Looking at the E–P flux divergence from the standing eddies, we first recall the results of GWG1. The four-year averaged monthly mean plots of the standing eddy E–P flux divergence showed predominant weak convergence, except in the polar midstratosphere where all three winter months showed strong divergences (≈10 m s⁻¹/day in December, ≈25 m s⁻¹/day in January, and ≈20 m s⁻¹/day in February) and in the high-latitude upper stratosphere where strong convergences were seen (≈−15 m s⁻¹/day in December, ≈−30 m s⁻¹/day in January, and ≈−15 m s⁻¹/day in February). This mean standing eddy E–P flux divergence was seen to be mainly due to stationary planetary wavenumber one. The same general pattern is seen in the 12 individual monthly mean plots in Fig. 14. The four-year averaged monthly mean plots of the transient eddy E–P flux divergence results of GWG1 showed a broad shallow convergence region in the middle and high latitude troposphere with a divergence region above in middle latitudes but with convergence values in the polar region above. Large convergence values were also seen at high altitudes above z = 6 (2 mb or 45 km). GWG1 also noted that the shallow tropospheric convergence region was produced by wavenumbers higher than two, but that the high-altitude convergence feature was due mostly to wavenumber one. The same general features show up in most of the mean monthly plots of Fig. 15. There are anomalies though. In December 1981, the high-altitude polar convergence feature is very weak, for example.

The observational study of the E–P flux propagation vectors and divergence field most similar to what is done in this paper has been done by Hamilton (1982a,b). Hamilton used weekly NOAA/NMC analyses from the ground to 55 km for the period July 1976 through April 1980. He did not separate his calculations of the E–P flux into standing and transient components as we have done. In Hamilton (1982b), the divergence field of the E–P flux for December 1979 was shown. Comparing this to the sum of the standing and transient E–P flux divergences for December 1979 shown in our Figs. 14 and 15, we see a similar pattern except that we show a bit more flux divergence in the polar middle stratosphere. Hamilton (1982a) showed E–P flux divergences for December 1979, January 1979 and January 1980. His results compare reasonably with our results for these months except that our extreme values of convergences and divergences are a bit higher. These differences are probably a result of our using daily values and Hamilton using weekly values.

Another difference between our results and Hamilton's (1982b) is the correlations between monthly-mean E–P flux divergence and the monthly-mean zonal winds. We find no such clear correlation, but Hamilton (1982b) claims to find such a correlation, particularly during the December months.
Fig. 14. Northern Hemisphere monthly mean Eliassen–Palm flux divergence fields in units $10^{-4}$ m s$^{-2}$ resulting from standing eddies. Regions of negative values (i.e., convergence) are shaded.
8. Conclusions

In looking at the 12 winter months that went into the four-year average monthly-mean statistics of GWG1, we have noticed significant interannual variability in the monthly mean zonal winds and in the eddy statistics, in agreement with the work of others. This has important implications for both modeling...
and observational studies of the middle atmosphere. It implies the requirement that any realistic model of the troposphere–stratosphere system should be able to simulate the level of interannual variable in the winter circulation statistics that is observed. One question, however, is how much of the stratospheric interannual variability is attributable to changing boundary conditions (e.g., sea surface temperature and solar variability) and how much is inherent in troposphere–stratosphere dynamics. There is, good reason to believe that much of this variability is inherent in the troposphere–stratosphere system. The tropospheric wave forcing is quite variable during winter (e.g., see Webster and Keller, 1975), and the stratospheric response to a given forcing is quite dependent on the mean zonal wind state (e.g., see Bridger, 1982). Given that the stratospheric response is dependent on the phasing between tropospheric wave forcing and the stratospheric "refractive index" (Matsuno, 1970), one expects that the troposphere–stratosphere system will support a great deal of variability without appealing to variation in the boundary conditions. On the other hand, the observed connection between the Southern Oscillation and the stratospheric variability as noted by van Loon et al. (1981) and Wallace and Chang (1982) suggests that stratospheric variability may be connected to troposphere/sea surface temperature feedbacks.

Running a middle-atmosphere general circulation model for many model years for comparison with data is a very expensive proposition. In the near-term, one should look for features in the observations that repeat winter after winter, in the presence of the interannual variability, for comparison with model results. Also, one might use a mixture of climatological runs with prediction tests against observations to test the behavior of models.

On the observational side, it is important to appreciate that a single winter's observations may well be unrepresentative of the mean behavior of the winter middle atmosphere. For instance, it is desired to understand the transport characteristics of the middle atmosphere in order to use realistic transport formulations in predictions of multi-decadal scenarios of anthropogenically produced ozone change; for example, see WMO, 1981. It is crucial that we study the transport characteristics over many years, using both existing and future datasets, in order to achieve this goal.

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