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Persistence of the lower stratospheric polar vortices

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Abstract. The persistence of the Arctic and Antarctic lower stratospheric vortices is examined over the period from 1958 to 1999. Three different vortex-following diagnostics (two using potential vorticity and one based solely on the zonal winds) are compared and are shown to give very similar results for the breakup date. The variability in the timing of the breakup of both vortices is qualitatively the same: There are large interannual variations together with smaller decadal-scale variations and there is a significant increase in the persistence since the mid-1980s (all variations are larger for the Arctic vortex). Also, in both hemispheres, there is a high correlation between the persistence and the strength and coldness of the spring vortex, with all quantities having the same interannual and decadal variability. However, there is no such correlation between the persistence and the characteristics of the midwinter vortex. In the Northern Hemisphere, there is also a high correlation between the vortex persistence and the upper tropospheric/lower stratospheric eddy heat flux averaged over the 2 months prior to the breakup. This indicates that the variability in the wave activity entering the stratosphere over late winter to early spring plays a key role in the variability of the Arctic vortex persistence (and spring polar temperatures) on both interannual and decadal timescales. However, the extreme values of Arctic vortex coldness and persistence during the 1990's are not echoed as a similar extreme in the eddy heat flux. This suggests that the recent increase in vortex persistence is not solely due to changes in the wave activity entering the stratosphere.

1. Introduction

Arctic winters during the early and middle 1990s have been characterized by low polar temperatures and record low ozone amounts when compared to the last four decades over which regular observations are available [e.g., *Pawson and Naujokat 1999; Randel and Wu 1999*]. These low temperatures and ozone have been linked to an intensification and enhanced persistence of the lower stratospheric Arctic vortex [*Zurek et al., 1996; Coy et al., 1997*]. There has also been a tendency for enhanced persistence of the Antarctic lower stratospheric vortex over the last decade [*Waugh and Randel, 1999*]. However the long-term variability of the persistence (timing of the breakup) of the vortices has not been examined, and it is not clear whether the persistence of the vortices during the 1990s is anomalous over a longer time period. In other words, is the delay in the breakup in the 1990s within the limits of natural decadal-scale variability, or is it suggestive of a fundmental change in circulation (such as might be due to changes in the chemical composition of the atmosphere)?

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In this paper we quantify the variability, over the last 40 years, in the timing of the breakup of both the Arctic and Antarctic vortices. We compare the timing of the breakup as defined using three different vortex-following diagnostics (two involving potential vorticity and one based solely on the zonal winds) and show that all three give similar results. The analysis is based primarily on data from the National Centers for Environmental Prediction (NCEP) reanalyses (REAN) [*Kalnay et al., 1996*] covering 1958-1999, but we also assess the dependence on the source of the meteorological analyses by comparing the Arctic vortex breakup dates with those derived from the Freie Universitat Berlin data (FUB) [*Pawson et al., 1993*], for the period 1966-1998.

As well as examining the variations in the timing of the breakup of the vortices we also examine the relationship between the breakup date and other aspects of the stratospheric structure and circulation. In particular, we examine the relationship between the breakup and the vortex strength and polar temperatures in winter and spring, and with the wave activity entering the stratosphere (as diagnosed by the eddy heat flux).

In section 2 the three diagnostics of the vortex breakup are described, and it is shown that all give very similar results. The variability of the timing of the breakup of the Arctic vortex, and its relationship to other quantities, is then examined in section 3. Both NCEP REAN and FUB data are used, and there is excellent agreement between the two data sets. In section 4 the variability in persistence of the Antarctic vortex is examined, and concluding remarks are in section 5.

2. Breakup Diagnostics

The stratospheric polar vortex is characterized by a strong cyclonic jet and a region of high potential vorticity (PV), with the wind maximum coinciding with the region of steep PV gradients at the edge of the vortex [e.g., *Schoeberl et al., 1992*]. As there is large day-to-day variability in the location and shape of the vortices, particularly the Arctic vortex [e.g., *Waugh and Randel, 1999*, and references therein], vortex-following diagnostics are best suited to accurately quantify the breakup (and other characteristics) of the vortex.

One such diagnostic is based on the area enclosed within a given PV contour. The breakup date can be defined as the date when the area within this PV contour, chosen to be representative of the vortex edge, falls below a critical value [*Manney et al., 1994; Waugh and Randel, 1999*]. Using this diagnostic the breakup date will depend on two parameters: the value of PV used to represent the vortex edge and the critical area used to define the existence of a vortex. The values of PV within the vortex edge region could change from year to year (or from decade to decade) and this diagnostic may be sensitive to such changes.

An alternative diagnostic which allows for changes in the PV within the edge region is that developed by *Nash et al.* [1996]. They developed a criteria on the basis of the meridional gradients of PV (in an equivalent latitude space based on the PV distribution rather than true geographical latitude) and the maximum wind around PV isolines: The vortex edge is defined as the location of maximum PV gradients constrained by the location of maximum wind speed calculated around the PV isolines, and the breakup date is defined as the date when the maximum wind speed along the PV isolines falls below a critical value.

Both the above criteria are based on the PV distribution (on an isentropic surface), but as PV is a highly derived quantity, it is useful to have a criterion based solely on the wind field. This is particularly true when applying the criterion to data sets (such as the FUB analyses) where data are available only on a few pressure surfaces, and hence PV cannot be accurately determined.

As noted above, the vortices are characterized by high PV with extrema in zonal winds u within the region of steep PV gradients at the vortex edge. This is illustrated in Figure 1, which shows maps of PV and u for several days in 1993. In midwinter (e.g., January 20, 1993) the PV contours enclose a large area, and there are strong winds within the region of strong PV gradients, whereas as the vortex breaks down in spring (e.g., March 20, 1993), the area within both high PV and u contours decreases. This indicates that the area within u contours may also be used to define the vortex breakup, e.g., breakup could be defined to occur when the total area where u exceeds a specified values falls below a minimum value.

All three of the above breakup criteria are subjective, in the sense that the critical parameters involved (contour values and minimum area or wind speed) have to be determined by visual inspection of PV and u maps. However, once this "tuning" is done for a few years, the criteria can be used objectively over longer time series. We have compared the breakup dates of the Arctic vortex at 500 K ($\approx$ 20 km) between 1979 and 1999 using fields derived from NCEP Climate Prediction Center (CPC) stratospheric analyses and the three diagnostics: area within PV contours ("PV area"), area within u contours ("U area"), and the *Nash et al.* [1996], criterion ("PV and U"). Figure 2 shows the variation in breakup date for all three diagnostics, where PV = 4.6 $\times 10^{-5}$ Ks^2/kg and a minimum area corresponding to equivalent latitude $\varphi_E = 80°$ is used in the PV area criterion, u = 25 m/s and φ_E =75° in the U area criterion, and u = 15.2 m/s in the PV and U criterion (as by Nash et al., [1996]). The year-to-year variation in breakup date is very similar for all three diagnostics; that is, all show 1987 as an early breakup, 1990 and 1997 as late breakups, and a slight increasing trend in the lateness of the breakup throughout the period (although there is a notable decrease in the persistence in the last 2 years). This good agreement indicates that any one of the three diagnostics can be used to quantify the variability in the vortex breakup.

Although vortex-following diagnostics which account for the change in shape and location of the vortex are most appropriate for quantifying the breakup of the vortices, it is worth examining whether zonal mean fields can be used. Comparison of the zonal mean zonal winds with the above breakup dates (not shown) suggests that the date when zonal mean winds at 60°to 70°N fall below 10 m/s may be used to define the vortex breakup.

There is, of course, some sensitivity in the breakup date to the parameters used in each criterion; for example, see Figure 12 of *Waugh and Randel* [1999] for sensitivity of the PV area diagnostic and Figure 3a below for that of the U area diagnostic. Hence the actual date for a given year will depend on the parameters used. However, as we show below, the decadal-scale variability is relatively insensitive for reasonable choices of critical

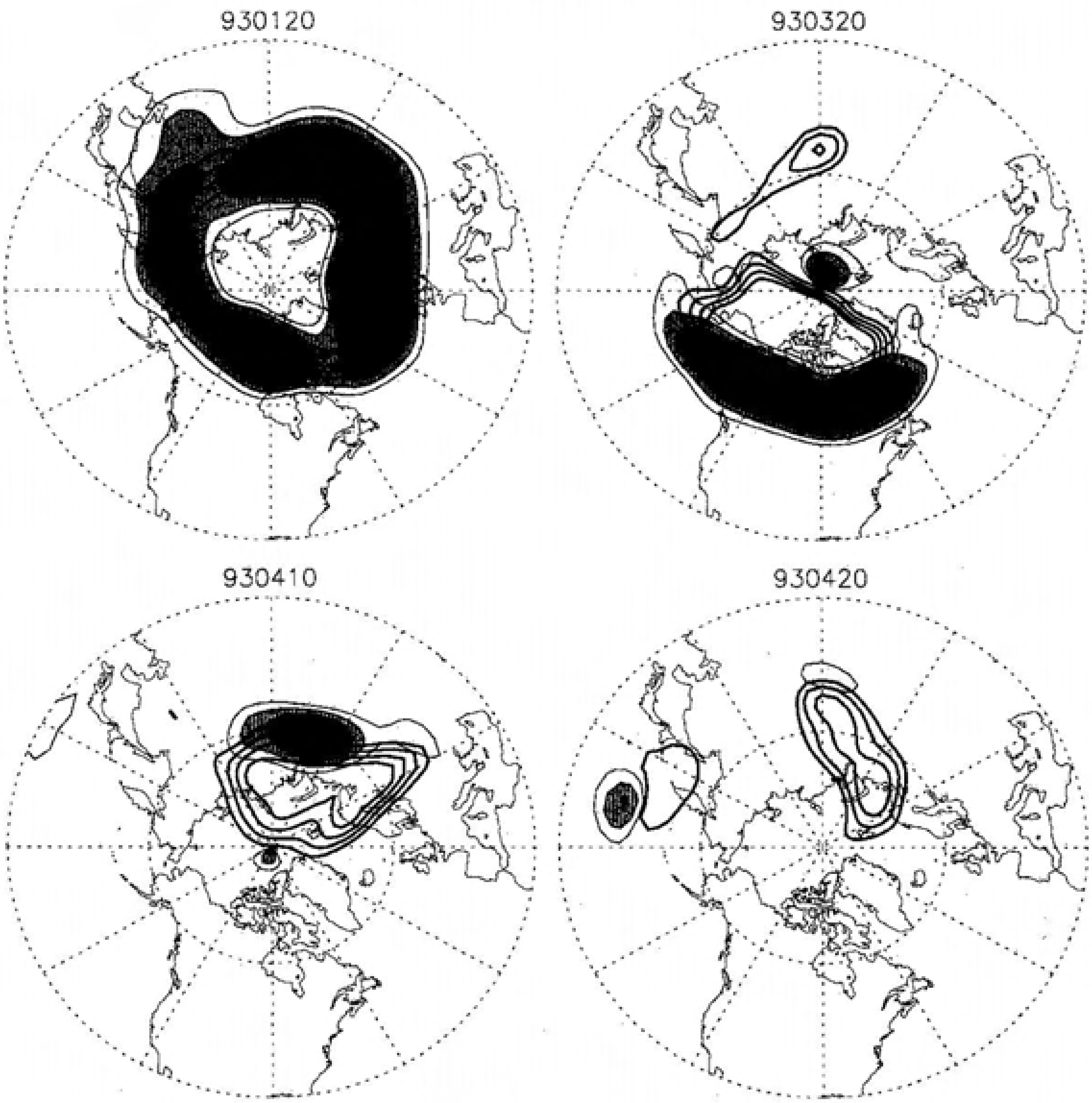

Figure 1. Maps of potential vorticity PV (contours) and zonal wind u (shaded) on January 20, March 20, April 10, and April 20, 1993. Contours plotted correspond to PV=(4.0, 4.5, 5.0, and 5.5)$\times10^{-5}$ Ks^2/kg and u=(25, 30, and 35) m/s. Data are from NCEP CPC analyses. Read 930320 (year, month, day) as March 20, 1993.

values, so that the choice of these parameters does not impact conclusions about long-term variations.

3. Arctic Vortex

3.1. Vortex Breakup Date

We now examine the variability in the timing of the Arctic vortex breakup over the last four decades using NCEP REAN data. Figure 3a shows the variation in breakup date, at 500K, between 1958 and 1999 using the U area diagnostic: The thin curves correspond to the individual dates for each year, whereas the thick curves correspond to a smoothed version of the data intended to highlight decadal time scale variations. The solid curves correspond to the values of u and φ_E shown in Figure 2, whereas the dashed curves show the corresponding date using critical values of φ_E larger by 5° (there is a similar sensitivity if the value of u is decreased by 5 m/s). As by *Randel and Wu* [1999] (hereinafter referred to as RW99), the decadal-scale time series are calculated using a running weighted average over adjacent years with a Gaussian-shaped filter with 4-year half-width (see RW99 for details). One-sided weighting is used for data on either end of the time series.

Comparison of the breakup date for the two different values of φ_E shows large differences for some of the years, with these years generally being those with early breakups. Examination of daily maps shows that for these years the vortex weakened in February/early March and this weak vortex then remained for a month or longer. Because of this a slight change in the def-

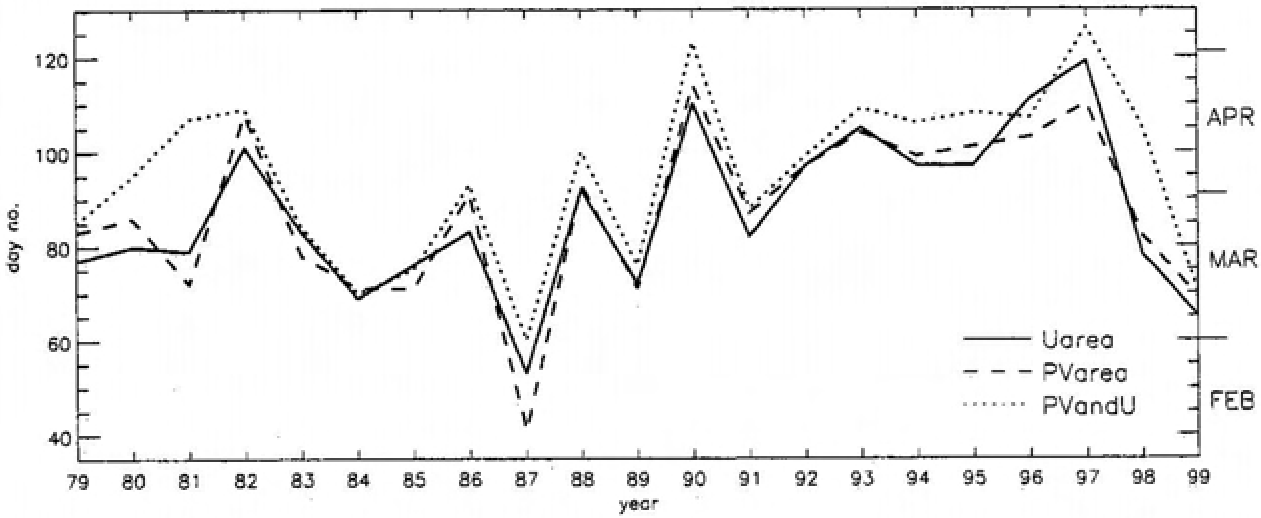

Figure 2. Variation of breakup date from 1979 to 1999 determined using the U area (solid curve), PV area (dashed curve) and PV and U (dotted curve) diagnostics applied to 500 K fields from NCEP CPC analyses. See text for details.

inition of the existence of a vortex can result in a large change in the breakup date. In years with a late breakup the transition from strong to no vortex is generally much quicker, and there is much less sensitivity to parameters used to define the breakup date. Note that, as is discussed below, the breakups in the early part of the record are generally earlier than those in the latter part, and because of the above sensitivity when there are early breakups the agreement between the different values of φ_E is poorer during the earlier period (that is, comparisons of the different diagnostics over the 1979-1999 period show better agreement than comparisons over the whole period).

Although the exact timing of the breakup can be sensitive to the parameters used, the general features are the same. There is considerable variability in the timing of the vortex breakup, with the breakup occurring anytime between February and early May. Together with this large interannual variability, there are smaller decadal (and longer) timescale variations, with late breakups generally occurring in late 1960s and mid-1990s, and early breakups occurring in late 1950s-early 1960s and mid-1980s. The tendency for late breakups in the 1990s appears anomalous, and there has been an increase in the persistence of the vortex over the 42-year period (although, as noted earlier, there was an early breakup in 1999).

As discussed in section 2, for suitable parameter choice, there is good agreement between the breakup date defined using the U area and PV and U criterion applied to the NCEP CPC data for 1979 to 1999; see Figure 2. But the results of Figure 3a suggest there may have been more sensitivity during the the 1960s and 1970s when there were, generally, earlier breakups. Figure 3b compares U area and PV and U (for the same parameter values as in Figure 2) using the NCEP REAN data covering the longer period from 1958 to 1999. For some years, there is a large difference between the different diagnostics (as large as 30 days), but the general interannual and decadal variability are the same. Also, the differences between the different diagnostics are comparable to the differences in breakup date for different values of φ_E in the U area diagnostic (see Figure 3a).

To test the sensitivity of the results to the source of the meteorological analyses the breakup dates derived from the NCEP REAN analyses are compared with those from the NCEP CPC and FUB analyses (note that unlike the NCEP REAN analyses a general circulation model is not used to form the NCEP CPC or FUB analyses). Figure 4 compares the breakup dates, defined using the U area diagnostic applied to 50 hPa fields, from FUB at 10° resolution (from 1966 to 1998), FUB at 5° resolution (1974 to 1998), NCEP CPC (1979 to 1999), and NCEP REAN (1958 to 1999). There is generally very good agreement between the breakup dates derived from the different analyses, both on interannual and decadal timescales. The largest differences occur in the period from 1967 to 1970. However, when the comparison is repeated using critical value of φ_E reduced by 5°, there is a smaller difference between NCEP REAN and FUB during this period (not shown). Note that the differences in breakup dates using different analyses are generally smaller than those using a different breakup diagnostic or a different parameter in a given diagnostic (e.g., compare Figures 3 and 4).

The above agreement between the different analyses gives us confidence that the calculated variability in the vortex breakup is real and not an artifact of the analyses. In the remainder of this paper we generally only show plots based on NCEP REAN data, but using the FUB data instead results in very similar plots, and the

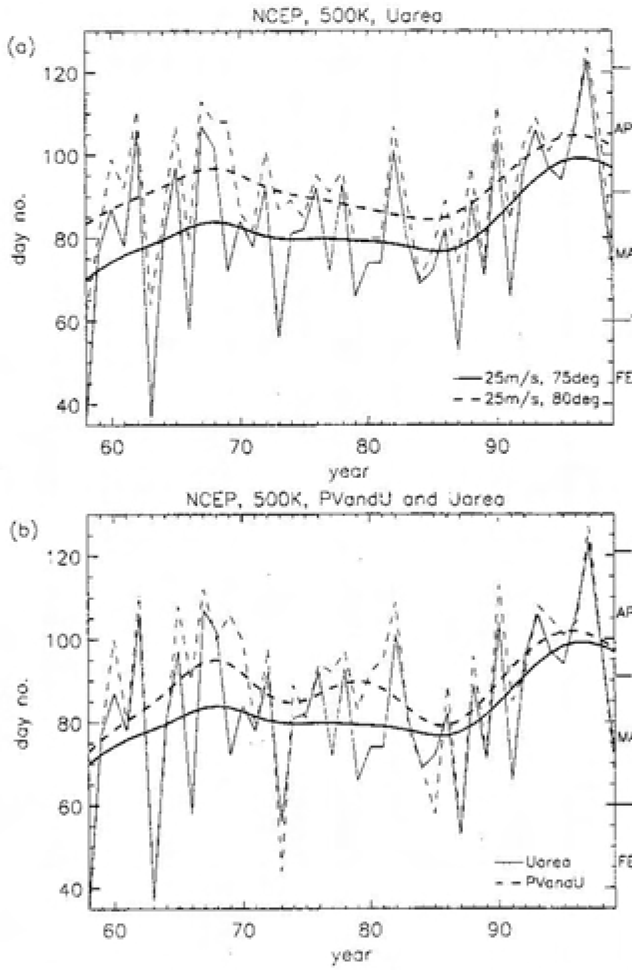

Figure 3. Variation of breakup date from 1958 to 1999 determined using 500 K fields from NCEP reanalyses. (a) Breakup defined using U area diagnostic with values shown in Figure 2 (solid curves) and a critical equivalent latitude larger by 5° (i.e., $\varphi_E = 80°$) (dashed curves). (b) Breakup defined using U area (solid curves) and PV and U (dashed curves) diagnostics, both with values shown in Figure 2. In both Figures 3a and 3b the thin curves correspond to the individual dates for each year, whereas the thick curves correspond to time-filtered data.

conclusions hold for both data sets. Also, we use the U area diagnostic, with u= 25 m/s and φ_E =75°, applied to 50 hPa fields to define the breakup date.

3.2. Relationship to Temperatures and Wave Activity

The above diagnostics show that there have been significant variations in the timing of the Arctic vortex breakup over the last 42 years. We now examine how these variations relate to variations in other aspects of the atmospheric structure and circulation.

Figure 5 shows scatterplots of January, February, and March mean zonal mean 50 hPa temperature at 80°N versus breakup date for the 42-year NCEP record (the linear correlation coefficients are given in the top right of each plot). These plots show that the timing of breakup is closely linked to February and March polar temperatures, with a later breakup generally occurring for a colder vortex. However, there is no such relationship between January temperatures and the vortex breakup. A similar relationship (or lack of) is also found for other measures of vortex "coldness", for example, the area colder than T=195 K [*Pawson and Naujokat, 1999*] (not shown). Furthermore, there is the same relationship between breakup date and vortex strength as diagnosed using the difference in the zonal mean geopotential height between 50° and 60°N [e.g., *Graf et al., 1995*], see Figures 5d-5f. Hence, while the timing of the vortex breakup is closely related to the coldness and strength of the spring vortex, the breakup is not coupled with the coldness/strength of the midwinter vortex.

As well as being notable for the occurrence of cold, persistent vortices, the 1990s are also notable for the relative lack of major warmings (and extremely disturbed vortices; see Figure 14 of *Waugh and Randel* [1999]). The lack of major warmings, together with generally cold, persistent vortices, suggests that the two features are related. Comparison of dates of major warmings with the vortex breakup dates shown in Figure 4 shows a clear relationship between breakup date and major warmings during February, but there is no connection with December or January warmings. February warmings are associated with early breakups (with breakup in years with a February warming occurring before March 20), but both early and late breakups have occured in winters with earlier major warmings (e.g., there were January major warmings in 1968 and 1987, but an April breakup occurred in 1968, whereas a February breakup occurred in 1987). The lack of a strong correlation between breakup date and pre-February major warmings

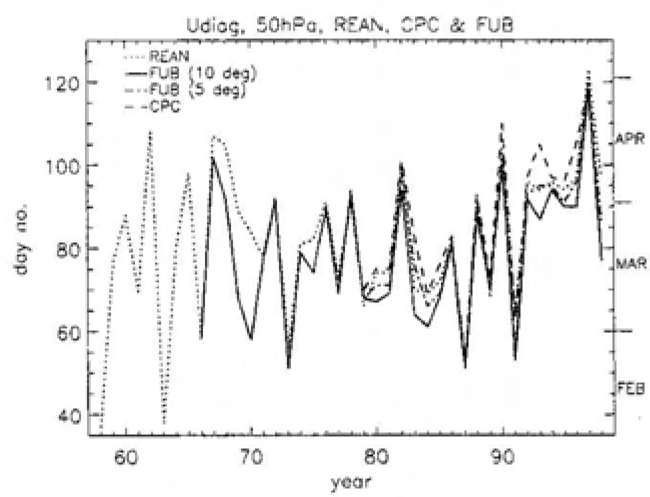

Figure 4. Comparison of breakup dates using U area diagnostic (parameters as in Figure 2) applied to 50 hPa fields from NCEP REAN (dotted curve; 1958 onwards), FUB 10° resolution (solid curve; 1966 onwards), FUB 5° resolution (dot-dashed curve; 1974 onwards), and NCEP CPC (dashed curve; 1979 onwards) data sets.

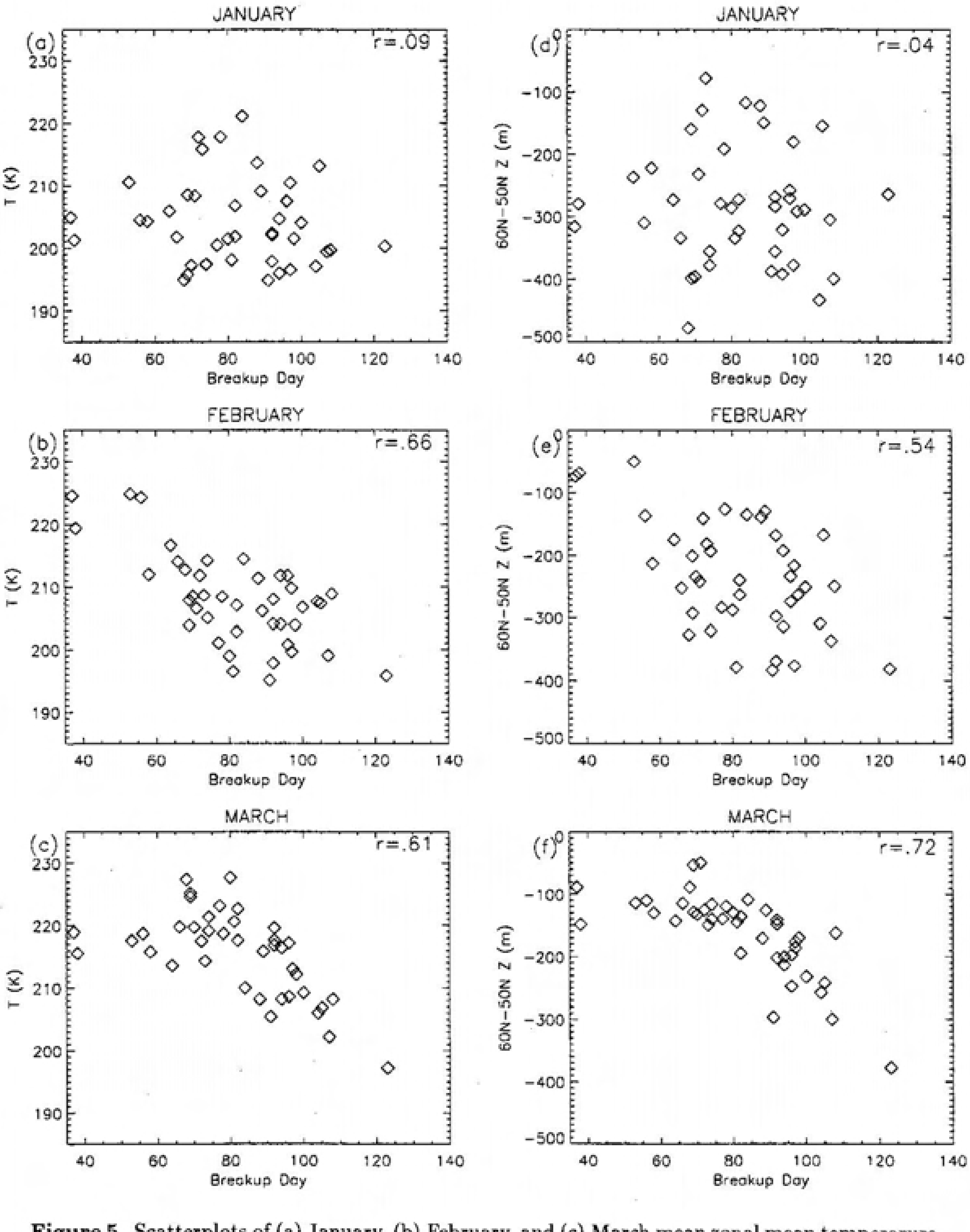

Figure 5. Scatterplots of (a) January, (b) February, and (c) March mean zonal mean temperarure at 80°N and (d) January, (e) February, and (f) March mean 50°-60°N zonal mean geopotential height versus breakup date for the 42-year NCEP record. The linear correlation coefficients are given in the top right of each plot.

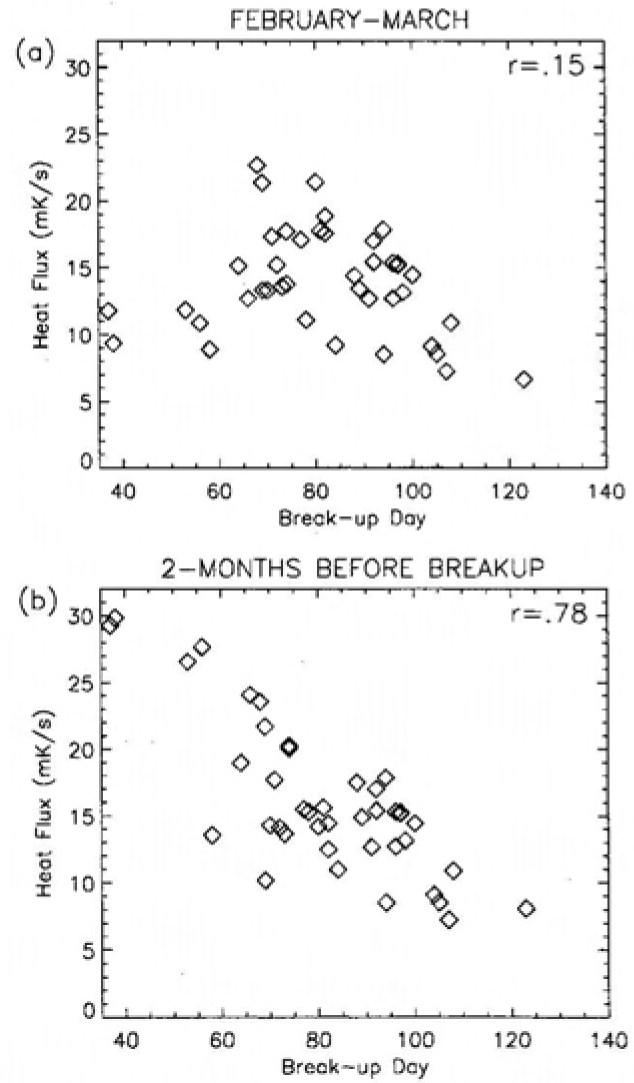

Figure 6. Scatterplots of 100 hPa eddy heat fluxes averaged over 45° to 75°N versus breakup date for (a) the February-March mean and (b) the mean over 2 months before month of breakup for the 42-year NCEP record.

is consistent with the above lack of correlation with January vortex temperatures and strength (e.g., Figures 5a and 5d).

RW99 showed that the changes in March polar temperatures in the 1990s match well the observed changes in total ozone; that is the overall space-time patterns of cooling and decrease in total ozone are very similar. Similar behavior is observed in the Antarctic, and GCM simulations clearly demonstrate that the temperature changes are primarily a radiative response to a decrease in total ozone [*Mahlman et al., 1994; Shindell et al., 1997*]. The similarity between hemispheres suggests that the radiative response to decreases in ozone may be an important component of the Arctic cooling as well. Because of the close relationship between spring temperatures and breakup date this then implies that radiative response to decreased ozone may also contribute to the persistence of the Arctic vortex. However, the possible role of variability in other factors that may influence the polar stratosphere, such as tropospheric circulation and wave propagation into the stratosphere, have not been eliminated.

To examine the variations in the wave propagation into the stratosphere, we calculate the upper tropospheric/lower stratospheric eddy heat fluxes $H = \overline{v'T'}$. The eddy heat flux is proportional to the vertical component of Eliassen-Palm (EP) flux [*Andrews et al., 1987*], and is a measure of the amount of wave activity entering the stratosphere. *Coy et al.* [1997] showed that the February-March average 100 hPa eddy heat fluxes (averaged over 45° to 75°N) decreased during the 1990s, coincident with the more persistent vortices, and that the fluxes were the lowest over the 1979-1997 record in 1997 when the vortex lasted the longest. Figure 6a shows the relationship between February-March average 100 hPa H and breakup date over the 1958-1999 period (a similar relationship is found with 200 hPa H). Although there is a lot of scatter over all the data, there is a reasonably close relationship for breakups in March onward (with later breakups occurring when fluxes are relatively weak). The lack of a correlation for early breakups is because H is averaged over February-March and includes post-breakup wave activity (for early breakups). If H is averaged over the 2 months before the breakup month rather than just February-March (i.e. if the breakup occurs in March H is averaged over January and February) the correlation between breakup date and H is greatly improved; see Figure 6b. This clearly shows that the eddy heat fluxes prior to the vortex breakup are larger if the breakup occurs earlier in the season (or, in other words, larger heat fluxes are required to breakup the vortex earlier in the season). Note that, consistent with the above, incorporation of a simple linear Newtonian cooling (as a parameterization of diabatic heating) within a transformed Eulerian mean framework leads to a thermodynamics equation whose solutions show that heat flux is correlated to the mean temperature with a 1-2 months lead time (P. Newman, manuscript in preparation, 1999).

There is some concern regarding the stability of the NCEP REAN heat fluxes between the periods with and without satellite data. This arises from the dependence of the eddy heat flux on the baroclinic structure of the planetary waves and the sensitivity of the analyses to the data types available [e.g., *Mo et al., 1995; Kanamitsu et al., 1997*] and their interactions with the numerical model used in the data assimilation system. To check the consistency of the NCEP REAN heat fluxes we compare in Figure 7 the February-March average of the stationary component of 100 hPa eddy heat fluxes derived from the NCEP REAN and FUB analyses (note that there have been no significant changes in the FUB analysis system over this period). Only the stationary component is shown as only monthly-mean 100 hPa

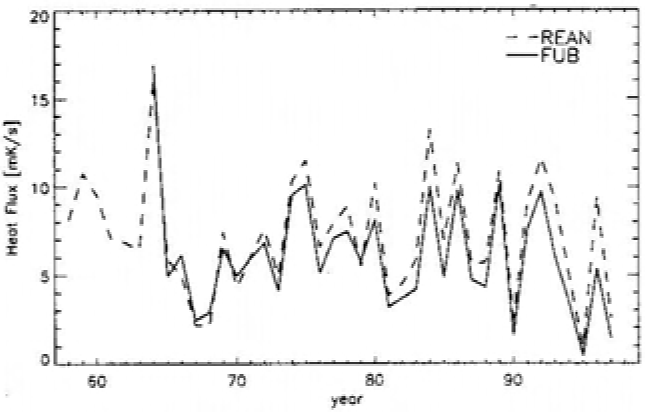

Figure 7. Comparison of February-March mean stationary component of 100 hPa eddy heat fluxes, averaged over 40° to 80°N, from NCEP REAN (dashed curve) and FUB (solid curve).

fields are available from FUB; however the temporal variations of the stationary component and of the total heat flux are very similar, e.g., Figure 5 of *Coy et al.* [1997]. Although there are differences in magnitude of the NCEP REAN and FUB heat fluxes. there is excellent agreement in the interannual and decadal variations, indicating that these variations are real.

The scatterplots in Figures 5 and 6 show that the vortex persistence, spring polar temperatures, and late-winter/spring eddy heat fluxes are closely linked. All three quantities have the similar decadal-scale variability, as can be seen in Figure 8, which shows the decadal-scale variation of each field (thick solid curves; thin solid curves correspond to individual years). All three quantities have very similar decadal-scale variations: The cold spring temperatures and late vortex breakups of the late 1960s and middle 1990s are associated with relatively low heat fluxes, and the stronger heat fluxes are observed in connection with the warm, early breakup years of the late 1970s and 1980s. However, the very late breakups and low temperatures in the 1990s are not accompanied by similarly extreme heat fluxes (the values of H in the mid-1990s are similar to those in the late 1960s). This suggests that the extreme changes in breakup and temperatures in the 1990s are not solely related to changes in wave activity entering the stratosphere. Alternatively this can be seen by comparing the dotted and solid thick curves for the breakup date and temperatures in Figure 8: the dotted curve is the breakup date and temperature "predicted" from the heat fluxes using a linear fit over the first 20 years. The observed breakup dates (temperatures) during the 1990s are later (colder) than the pre-1980s relationship would predict. An additional possible cause for the low temperatures (and late breakups) in the 1990s could be the radiative response to polar ozone depletion (e.g., RW99).

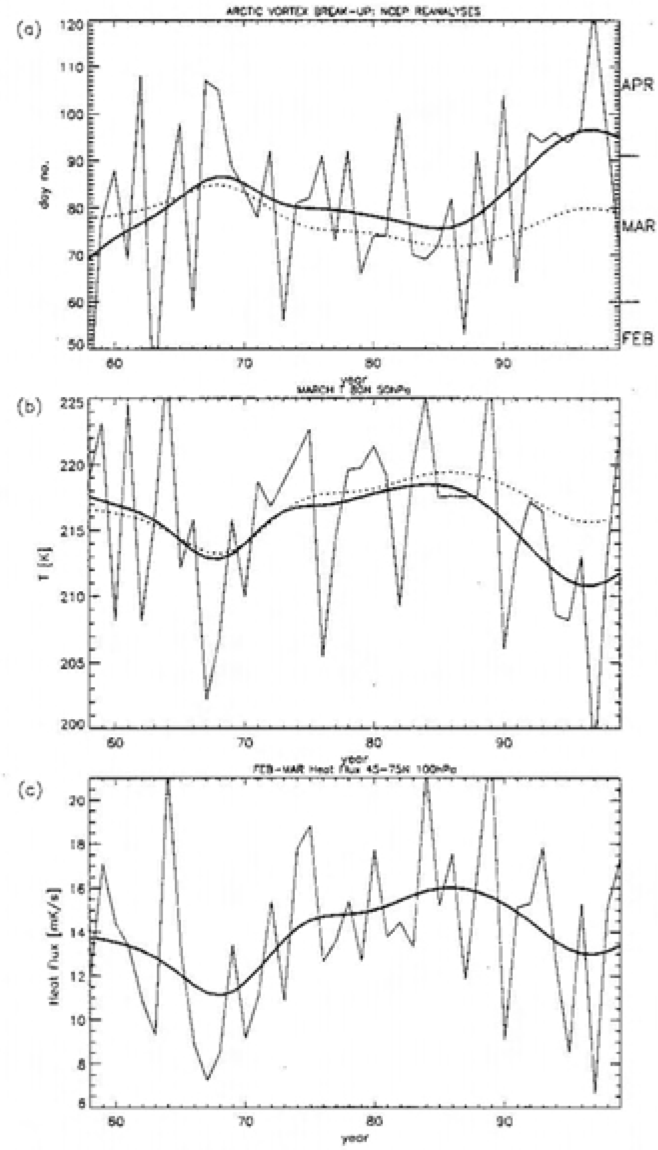

Figure 8. Temporal variation of (a) breakup date, (b) March T at 80°N, and (c) February-March 100 hPa heat flux between 45° and 75°N for 1958 to 1999, for individual years (thin solid curves) and time-filtered data (thick solid curves). Dotted curves in Figures 8a and 8b show the breakup date and temperature, respectively, derived from the heat fluxes using a linear fit over the first 20 years.

4. Antarctic Vortex

We now examine the variability in the vortex persistence, spring temperatures, and eddy heat fluxes in the Southern Hemisphere, using the NCEP REAN data. Figure 9 shows the variation in breakup date at 50 hPa (using the U area diagnostic) (Figure 9a), November 50 hPa temperatures (Figure 9b), and October-November 100 hPa eddy heat flux (Figure 9c) over the 1958 to 1998 period. The thin curves correspond to the individ-

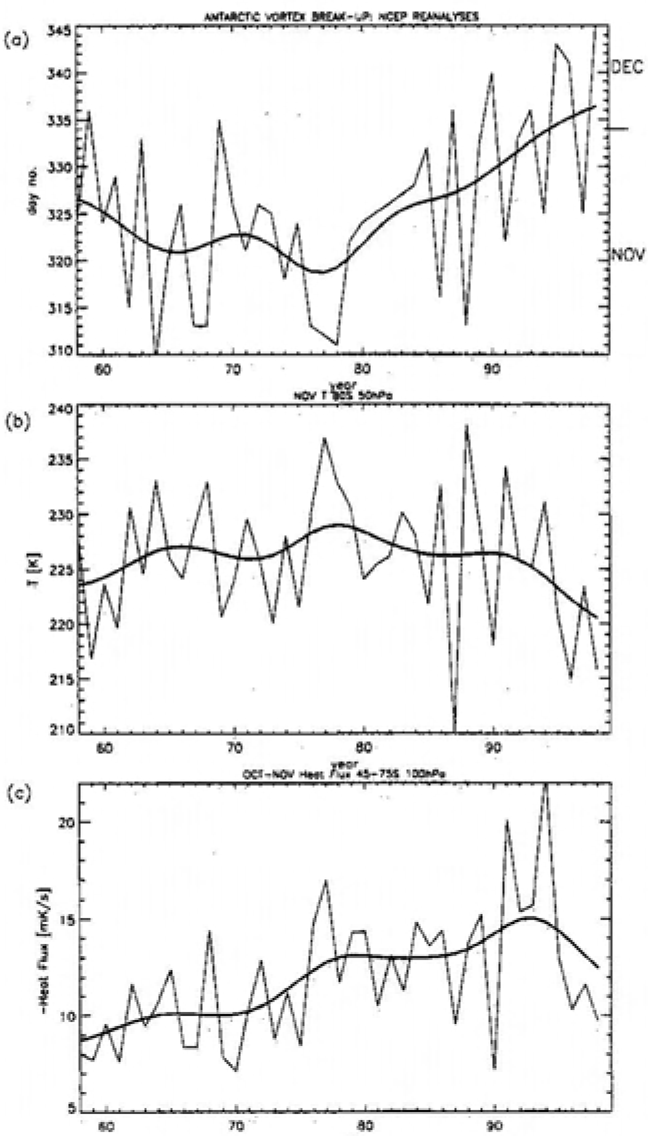

Figure 9. Variation of (a) breakup date of Antarctic vortex, (b) November T at 80°S, and (c) September-October 100 hPa heat flux between 45° and 75°S for 1958 to 1998. Thin solid curves correspond to the individual dates for each year, and the thick solid curves correspond to decadal filtered data.

ual dates for each year and the thick curves correspond to decadal filtered data.

The variability of the Antarctic vortex breakup since 1979 shown in Figure 9a is consistent with the analysis of *Waugh and Randel* [1999] (who used NCEP CPC analyses and the PV area diagnostic applied to 500 K fields). The variability of the timing of the breakup of the Antarctic vortex is qualitatively similar to that of the Arctic vortex, i.e. large interannual variations together with smaller decadal-scale variations, but the magnitude of the variations are smaller (note change in scales with Figure 8). There is also a tendency for increased persistence of the Antarctic vortex since the mid-1980s, which is again smaller than for the Arctic vortex.

Comparing Figures 9a and 9b we see that there is again a high correlation between breakup date and spring (November) polar temperatures, both on the interannual and decadal timescale (there is also a similar correlation with vortex strength, not shown). As in the Northern Hemisphere, there is no correlation with temperature 2 or more months earlier (not shown); in fact there is very little interannual variability in polar temperatures during southern winter. Although spring temperatures have similar decadal-scale variations as the breakup date, the low temperatures in the 1990s are not anomalous as there are similar values for the late 1950s and early 1960s. Because of the lack of satellite data incorporated in the NCEP REAN analyses before 1979 (when the only southern high-latitude data available are those from radiosondes at Antarctic stations, and all stations have incomplete records during the 1960s) the reliability of the reanalyses in southern high latitudes is not known.

RW99 analyzed the temperature records from the Antarctic stations, and compared them with NCEP REAN temperatures. The radiosondes show a clear decreasing trend in the spring 100 hPa temperature of around 8 K per decade since 1980 (with only small decadal variations before this time). RW99 noted reasonable agreement for interannual temperature variations between the radiosondes and the reanalyses but also noted that there were biases (NCEP REAN temperatures colder by up to 3 to 8 K) and, occasionally, large differences at some stations. A similar analysis of radiosonde data at 50 hPa shows a much smaller trend than at 100 hPa, and at several stations the 50 hPa temperature in late 1950s and early 1960s is comparable with that in the early to midde 1990s (although it should be noted that the time-filtered data from the South Pole station show a decrease in temperature through the 40-year period). Furthermore, there is better agreement between the NCEP REAN and radiosonde temperatures for decadal variations at 50 than at 100 hPa. However, some large differences still exist and the long-term variations in the temperatures, as well as the vortex strength and breakup date, from the reanalyses need to be treated with caution.

Even more caution should be applied when interpreting the eddy heat flux shown in Figure 9c. Given the differences between radiosonde and NCEP REAN temperatures at 100 hPa together with the derived nature of the eddy heat flux, it is unlikely that any robust conclusions can be drawn from the data before 1979 (when satellite date became available). Furthermore, *Mo et al.* [1995] examined the impact of satellite data on the NCEP REAN assimilation system by performing assimilation experiments for August 1985 with and without satellite data and found a major impact on heat flux

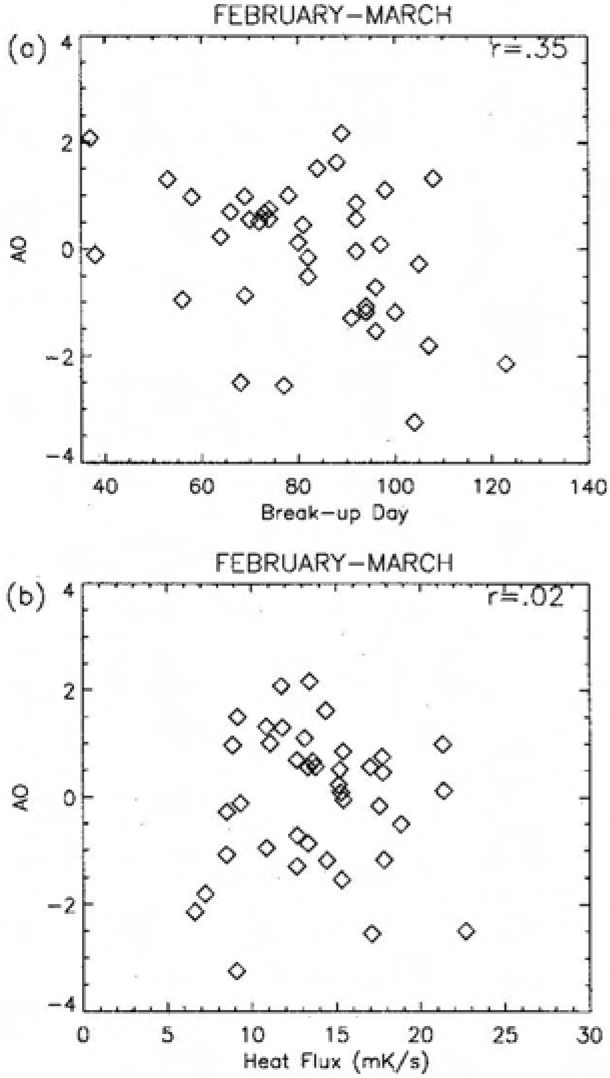

Figure 10. Scatterplots of February-March mean Arctic Oscillation (AO) index versus (a) breakup date and (b) February-March mean 100 hPa eddy heat flux, for the 42-year NCEP REAN record.

in all levels of the Southern Hemisphere (see their Figure 6). This shows that H in the Southern Hemisphere may be significantly affected by the model used in the assimilation, and highlights the uncertainties with the consistency of the NCEP REAN data between the presatellite and post satellite periods. In fact, there appears to be a stepwise change in H around the time when satellite data were introduced (Figure 9c). Because of this we do not think that the NCEP REAN data over the whole period can be used to determine whether a relationship exists between the eddy heat flux and vortex persistence or spring temperatures in the Southern Hemisphere.

However, the eddy heat fluxes since satellite data have been available may be more robust. If we consider just the last 20 years, there is still not a strong correlation between the breakup date and H; in fact, there is an increasing trend in the magnitude of H during the period of cooling and enhanced persistence. This indicates that the increased Antarctic vortex persistence since the 1980s cannot be attributed to decreases in the wave activity entering the stratosphere.

5. Conclusions

The variability in the Arctic and Antarctic vortices' persistence are qualitatively the same. For each vortex, there are large interannual variations in the timing of the breakup together with smaller decadal-scale variations, including a significant (compared with natural variability) increasing tendency over the last decade. However, the variations for the Arctic vortex are larger, with the delay in the Arctic vortex breakup over the last decade being around 15 days compared with 8 days for the Antarctic vortex. There is also a strong relationship between persistence and spring polar temperatures for each vortex (with colder temperatures in years with a later breakup). There is, however, no such relationship with the midwinter vortex temperatures (or strength), indicating that there is not a simple coupling between midwinter conditions and the vortex persistence.

In the Northern Hemisphere, there is also a high correlation between the persistence and the upper tropospheric/lower stratospheric eddy heat flux averaged over the 2 months prior to the breakup. This indicates that the variability in the wave activity entering the stratosphere over late winter to early spring plays a key role in the variability of the vortex persistence (and spring polar temperatures). However, although the eddy heat flux has similar interannual and decadal variations to persistence, the extreme values of temperature and vortex persistence during the 1990s are not echoed as similar extrema in the heat flux. This suggests that the recent Arctic vortex persistence is not due solely to changes in the wave activity entering the stratosphere.

Because of uncertainty in the reliability of the Southern Hemisphere NCEP reanalyses, caution is advised regarding conclusions about the relationship between vortex characteristics and the eddy heat fluxes in the Southern Hemisphere. However, the data since 1979 (when satellite data are incorporated) show a strengthening of the Southern Hemisphere heat flux, so the recent Antarctic cooling and vortex persistence cannot be attributed to a decrease in wave activity entering the stratosphere.

As the upper tropospheric/lower stratospheric eddy heat flux over late winter to early spring plays a key role in determining the persistence of the polar vortex and spring polar temperatures (at least in the Northern Hemisphere), it is important to understand what controls the eddy heat fluxes and what has been the cause for the decadal-scale variations in the heat flux over the last 40 years. One possible cause of these decadal-scale variations could be low-frequency oscillations in the tropospheric circulation. However, we have compared the variations in breakup date and heat fluxes with indices for the various teleconnection patterns that explain the majority of low-frequency variability in the wintertime troposphere (e.g., Pacific / North America (PNA) pattern, North Atlantic Oscillation (NAO), and Arctic Oscillation (AO) [*Wallace and Gutzler 1981; Thompson and Wallace 1998*]) and do not find a strong correlation with individual, or two or three combined, indices. For example, Figure 10 shows the lack of relationship between the February-March mean AO index and the breakup date (Figure 10a) and eddy heat fluxes (Figure 10b). So what controls the upper tropospheric/lower stratospheric eddy heat fluxes (and, in particular, their decadal variations) remains unknown and needs to be investigated in the future.

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