Possible Ozone-Induced Long-Term Changes in Planetary Wave Activity in Late Winter

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ABSTRACT

Using NCEP–NCAR reanalysis data, decadal trends in planetary wave activity in Northern Hemisphere high latitudes (50°–90°N) in late winter and early spring (January–February–March) were studied. Results show that wave activity in both the stratosphere and the troposphere has been largely reduced and exhibits statistically significant downward trends since the 1980s. In the stratosphere, the wave activity is decreased by about 30%, which is mainly due to less Eliassen–Palm (E–P) flux from the troposphere into the stratosphere. In the troposphere, the vertical E–P flux is reduced by about 30%, while equatorward horizontal E–P flux is increased by 130%. This suggests a significant refraction of planetary waves away from the high latitudes. The significant negative trends in wave activity in late winter are in contrast to the authors' previous finding of no significant changes in planetary wave activity in early winter.

The timing of the significant decline in wave activity, which starts from the early 1980s and exists only in late winter and springtime, suggests that such a decrease of wave activity is possibly a result of stratospheric ozone depletion in the Arctic. Therefore, a mechanism is proposed whereby Arctic ozone depletion leads to an enhanced meridional temperature gradient near the subpolar stratosphere, strengthening westerly winds. The strengthened winds refract planetary waves toward low latitudes and cause the reduction in wave activity in high latitudes.

Decreasing vertical E–P fluxes are found to extend to near the surface. At 850 mb, vertical E–P fluxes have been reduced by about 10% since 1979. Such a reduction in wave activity might be responsible for the observed late-winter and springtime warming over Northern Hemisphere high-latitude continents during the last two decades.

1. Introduction

Recent studies on the Northern Hemisphere annular mode (NAM) or Arctic Oscillation (AO; e.g., Thompson and Wallace 1998; Thompson et al. 2000, among many others) raised questions of whether planetary wave fluxes from the troposphere into the stratosphere have been reduced and what caused the reduction in wave activity during the past few decades. These studies showed that the NAM index exhibits an upward trend toward its high-index polarity in recent decades and that the upward trend is consistent with other climate tendencies, such as the remarkable warming over Northern Hemisphere high-latitude continents. Since the NAM can be considered approximately as a zonal mode (Hartmann et al. 2000), the upward trend in the NAM index implies a systematic decrease in wave activity according to the theory of wave–mean flow interaction (Andrews et al. 1987). These further imply that the change in the whole wave–mean flow system might have been driven by some external forcing in the past two or three decades.

Using the Goddard Institute of Space Studies (GISS) general circulation model (GCM), Shindell et al. (1998, 1999, 2001a) carried out a series of simulation studies to enquire what external forcing are possibly responsible for the trends in the NAM index. They examined the relative importance of external forcing factors, such as increasing greenhouse gases, stratospheric polar ozone depletion, aerosol injection from volcanic eruptions, and solar forcing, and showed that the increase in greenhouse gases is the most important factor for generating an upward trend in the NAM index and a decline in planetary wave activity comparable to the observation. They suggested that the meridional temperature gradient near the subtropical tropopause is the key, linking changes of atmospheric constituents to changes of atmospheric dynamics such as the NAM and planetary wave activity. When greenhouse gases are increased, they cause warming in the upper troposphere at low latitudes and cooling in the lower stratosphere at high

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latitudes. The enhanced meridional temperature difference near the tropopause between low and high latitudes leads to strengthened zonal winds, which consequently refract planetary waves away from the high latitudes.

The simulation results provide a plausible interpretation for the upward NAM-index trend and declining wave activity. However, it is not clear whether the greenhouse effect at the present condition is sufficiently strong to generate significant changes in the meridional temperature gradient field in the real atmosphere. Using reanalyzed observational data, Hu and Tung (2002, hereafter HT) showed that in early and midwinter [November–December–January (NDJ)] vertical zonal wind shears near the extratropical tropopause exhibit no positive trend during the past few decades. On the other hand, Randel et al. (2002) and Zhou et al. (2001) reported a decrease in wave activity in the stratosphere during late winter [January–February–March (JFM)]. These results suggest that the wave–mean flow system behaves very differently between early and late winters over the past few decades, and that, if there is an external forcing that is responsible for the decline in wave activity in the stratosphere, the forcing must work actively only during late winter.

Late winter/early spring [February–March (FM)] is the time when sunlight returns to the Arctic stratosphere and the radiative effect of recent Arctic ozone depletion is felt. Severe ozone depletion in the Arctic generates strong cooling in the polar region and creates enhanced temperature contrast between the polar region and midlatitudes during late winter and springtime. The enhanced temperature gradient leads to strengthened westerly winds in the subpolar stratosphere, which would refract planetary waves toward low latitudes. Therefore, it is plausible that the decline in wave activity in late winter and springtime could be a result of the observed downward ozone trend over the past two to three decades. The possible effect of ozone depletion on atmospheric circulations has been speculated and studied in GCM simulation works. Graf et al. (1998) found that there are significant responses of high-latitude temperature and geopotential fields in the lower stratosphere when observed ozone depletion is imposed in their GCM. Shindell et al. (2001a) showed in their simulations that stratospheric ozone depletion could generate significant climate changes near the high-latitude surface in late winter and springtime. However, the responses to ozone depletion in these simulations were found to be weaker than the observed changes. Volodin and Galin (1998, 1999) reported that anomalous warming over the Northern Hemisphere high-latitude continents during 1989–94 could be reproduced when the observed ozone depletion over the same period was forced in their model. However, their result has not been reproduced in other GCMs. Our main goal in this study is to address, using reanalyzed observational data, whether the decline in wave activity in late winter and springtime is induced by ozone depletion. It has recently been speculated, based on observations, that the reduction in planetary wave activity might have been responsible for the stronger, colder, and more persistent stratospheric Arctic vortex (Newman et al. 1997; Waugh et al. 1999), fewer stratospheric sudden warmings (Labitzke and Naujokat 2000), and less ozone transport from the midlatitudes into the stratospheric Arctic (Coy et al. 1997; Randel et al. 2002) in recent years. However, the problem is whether these phenomena are a result of the reduction in wave activity caused by some external forcing in the troposphere or whether the decline in wave activity is itself a result of ozone depletion in the stratosphere. We hope to present some circumstantial evidence in this study in support of the latter possibility.

The paper is presented as follows. Data sources are briefly introduced in section 2. We study linear trends in planetary wave activity in both the stratosphere and troposphere in section 3. The relationship between ozone depletion and the reduction in wave activity is explored in sections 4. Results are summarized in section 5.

2. Data

The data used in this study is the 45-yr (1958–2002) reanalysis data from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR). Eliassen–Palm (E–P) fluxes are computed from daily wind and temperature fields. The ozone data used here is taken from the monthly-mean zonal Total Ozone Mapping Spectrometer/Solar Backscatter Ultraviolet (TOMS/SBUV) merged total ozone datasets produced by NASA's Goddard Space Flight Center.

It is generally thought that the NCEP–NCAR reanalysis data after 1979 is more reliable for stratospheric studies since satellite data is included in the reanalysis. Therefore, for the longer-term trend studies we mainly use here the reanalysis data over 1979–2002, while the part over 1958–78 is included for comparison of an era prior to the ozone depletion, but not used to generate long-term trends.

3. Planetary wave activity

a. E–P fluxes in the stratosphere

To evaluate E–P fluxes in the high-latitude stratosphere, we first define a box from 50° to 90°N in latitude and from 100 to 20 mb in height, same as in HT. In this box, the total vertical E–P flux at 100 mb, denoted by $F_{100\mathrm{mb}} \approx \int_{50°\mathrm{N}}^{90°\mathrm{N}} \rho_0(100\ \mathrm{mb})a^2 \cos\phi f\overline{v'\theta'}/\theta_{0z}\, d\phi$, measures the overall wave activity coming from the troposphere into the box; E–P flux across 20 mb, denoted by $F_{20\mathrm{mb}} \approx \int_{50°\mathrm{N}}^{90°\mathrm{N}} \rho_0(20\ \mathrm{mb})a^2 \cos\phi f\overline{v'\theta'}/\theta_{0z}\, d\phi$, is the amount getting out of the box and going into the upper stratosphere; E–P flux across the boundary of 50°N, denoted by $F_{50°\mathrm{N}} \approx -\int_{100\mathrm{mb}}^{20\mathrm{mb}} \rho_0(z)a \cos\phi\overline{u'v'}\, dz$, is the horizontal

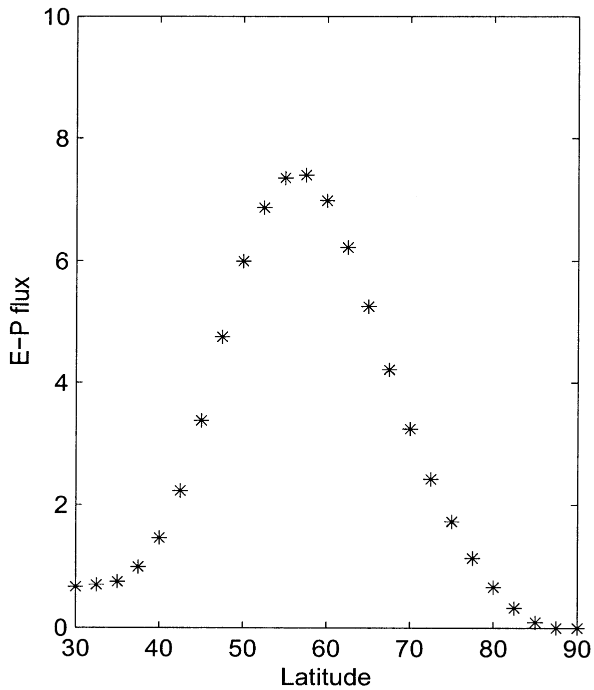

FIG. 1. The 45-yr Jan-mean vertical E–P fluxes at 100 mb as a function of latitudes. The E–P flux unit is 10^{10} kg m s^{-2}.

E–P flux coming into the box from low latitudes. Here, u', v', and θ' are velocity and potential temperature deviations from their zonal means, θ_{0z} is the vertical gradient of the background potential temperature, and ϕ, f, a, and ρ_0 indicate latitude, Coriolis parameter, earth's radius, and background air density respectively. The combination of the three E–P flux components, that is, $F_{\mathrm{netS}} = F_{20\mathrm{mb}} - F_{100\mathrm{mb}} + F_{90°\mathrm{N}} - F_{50°\mathrm{N}} = F_{20\mathrm{mb}} - F_{100\mathrm{mb}} - F_{50°\mathrm{N}}$, is the "net" E–P flux out of the box ($F_{90°\mathrm{N}}$ is assumed to be zero), which represents the total E–P flux divergence averaged over the box (Note that F_{netS} differs from F_{netT}. The latter will be used later to denote the divergence in the tropospheric box).

We chose such a box for two reasons. First, we are mainly interested in wave activity in the high-latitude lower stratosphere. Second, wave activity from the troposphere into the stratosphere is mainly through latitudes from 40°–75°N. Figure 1 shows the 45-yr January-mean vertical E–P flux component at 100 mb as a function of latitude. More than 90% of the E–P flux is found between 40° and 75°N. One can extend the box to 40°N, as in Randel et al. (2002). The results should be similar to that to be reported below.

Figure 2 shows JFM mean vertical E–P fluxes at 20, 50, and 100 mb, total horizontal E–P flux, $F_{50°\mathrm{N}}$, and net E–P flux, F_{netS}, as a function of years. In contrast to their behavior from the 1960s to 1978, vertical E–P fluxes at all three levels show significant downward trends over 1979–2002. At 100 mb, the net change in JFM E–P flux over the 24 years is $\delta F_{100\mathrm{mb}} \approx -1.1 \times 10^{11}$ kg m s^{-2}, about 30% reduction of wave flux from the troposphere into the stratosphere. At 20 mb, the net change is $\delta F_{20\mathrm{mb}} \approx -0.3 \times 10^{11}$ kg m s^{-2}, about 20% reduction. Thus, the net change in vertical E–P fluxes within the box is $\delta F_{20\mathrm{mb}} - \delta F_{100\mathrm{mb}} \approx 0.8 \times 10^{11}$ kg m s^{-2} (Fig. 2d). Over the same period, the net change in horizontal E–P fluxes crossing 50°N is $\delta F_{50°\mathrm{N}} \approx 0.3 \times 10^{11}$ kg m s^{-2} (Fig. 2e), which is smaller (The situation is different near 200 mb; see later). Here, the negative sign of $F_{50°\mathrm{N}}$ means that the total horizontal E–P flux is equatorward, and the positive sign of $\delta F_{50°\mathrm{N}}$ means that total equatorward horizontal E–P fluxes are reduced in the stratospheric box over 1979–2002. Overall, the net change of E–P flux divergence averaged over the stratospheric box is $\delta F_{\mathrm{netS}} = \delta F_{20\mathrm{mb}} - \delta F_{100\mathrm{mb}} - \delta F_{50°\mathrm{N}} \approx 0.5 \times 10^{11}$ kg m s^{-2}, a 30% increase. Since F_{netS} is negative, this trend actually is a decrease in the magnitude of F_{netS}. This is a rather large change in the stratospheric dynamics. The decrease in E–P flux convergence in the high-latitude stratosphere is largely due to less E–P fluxes from the troposphere into the stratosphere because δF_{netS} is mainly determined by $\delta F_{100\mathrm{mb}}$. The reduction in E–P fluxes from the troposphere into the stratosphere is consistent with a significant downward trend in wavenumber-1 amplitudes in the stratosphere (wavenumber-2 amplitudes also decreased, but not significantly; figures not shown). According to the theory of wave-mean flow interaction, such a decrease in E–P flux convergence should correspond to stronger westerly winds in the high-latitude stratosphere. Indeed, observations showed that the Arctic polar vortex has been getting stronger and persisting longer (Newman et al. 1997; Waugh et al. 1999).

The significant trends in wave activity in late winter is in contrast to the behavior of wave activity in early winter. Hu and Tung showed that wave activity in early winter has no significant changes over the past few decades. It appears that there exists a qualitative difference in the long-term trends in wave activity between early and late winter. To demonstrate such a difference in detail, we illustrate monthly mean vertical E–P fluxes at 100 mb and their trends in Fig. 3. For early-winter months [November–December (ND)], there are no significant changes in E–P fluxes over the 45 years. In fact, $F_{100\mathrm{mb}}$ in the two months exhibits a slight increase over 1979–2002, though the increase is not statistically significant. Vertical E–P fluxes in FM appear to have a markedly different long-term variation from that in the early-winter months. In February and March, the E–P fluxes first increase from the 1960s to about 1980, then decrease after the mid-1980s to present. These results suggest that there is a systematic decline in wave activity in late winter and that January is the transition time during which stratospheric wave activity changes from a slight increase of early winter to a significant decrease in late winter.

Linear trend analysis indicates that none of the trends in individual monthly mean wave activity is statistically

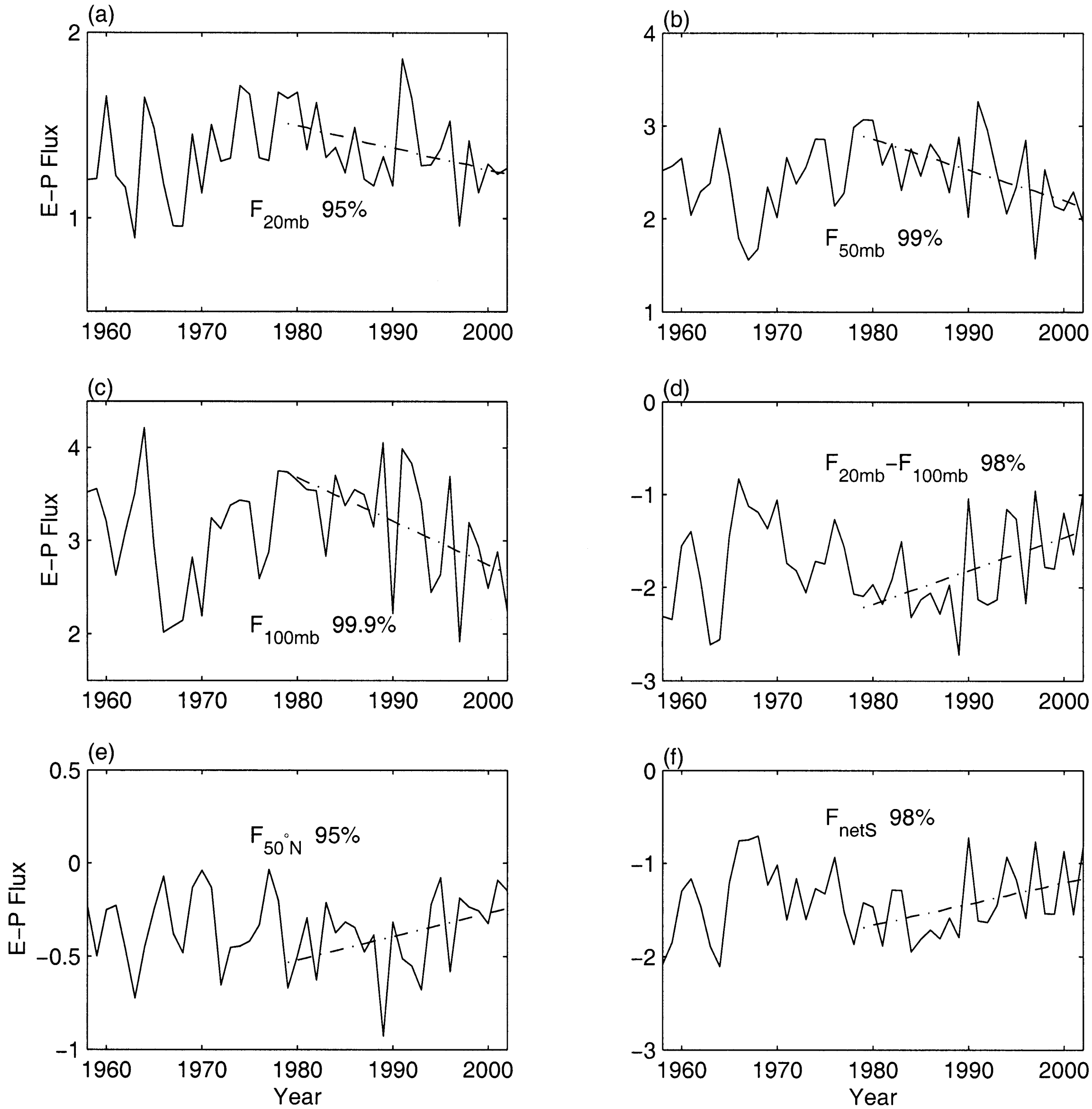

FIG. 2. JFM E–P fluxes in the stratosphere: (a) F_{20mb}, (b) F_{50mb}, (c) F_{100mb}, (d) $F_{20mb} - F_{100mb}$, (e) $F_{50°N}$, (f) F_{net}. Trends are calculated over 1979–2002. Statistical significance levels of Student's t tests for the trends are marked. The E–P flux unit is 10^{11} kg m s^{-2}.

significant at the 95% significance level. This is also reported by Randel et al. (2002). When a 3-month average is taken, however, the negative trends in E–P fluxes in JFM become statistically significant, while the positive trend in NDJ is still not significant, as shown in HT. The lack of statistical significance for trends in monthly mean wave activity is presumably because of large fluctuations of wave activity over monthly timescales. The large fluctuations are primarily caused by the so-called ''stratospheric vacillation,'' which has a period of approximately 2 months (Holton and Mass 1976). If one compares Figs. 3c with 3d, one can find that a trough in January often corresponds to a peak (primarily corresponding to a stratospheric sudden warming event) in February. Such large fluctuations over intraseasonal timescales can be reduced when a 3-month average is taken. This is the main reason why 3-month (JFM) averages are used in calculating E–P flux trends in this study.

Using three different reanalysis datasets, from NCEP–NCAR, the European Centre for Medium-Range Weather Forecasts (ECMWF), and the Climate Prediction Center (CPC), Randel et al. (2002) also found that E–P fluxes at 100 mb have slight long-term increases in ND and significant decreases during JFM, with the largest decrease in February. Zhou et al. (2001) reported similar results for monthly mean wave activity from the NCEP–NCAR reanalysis.

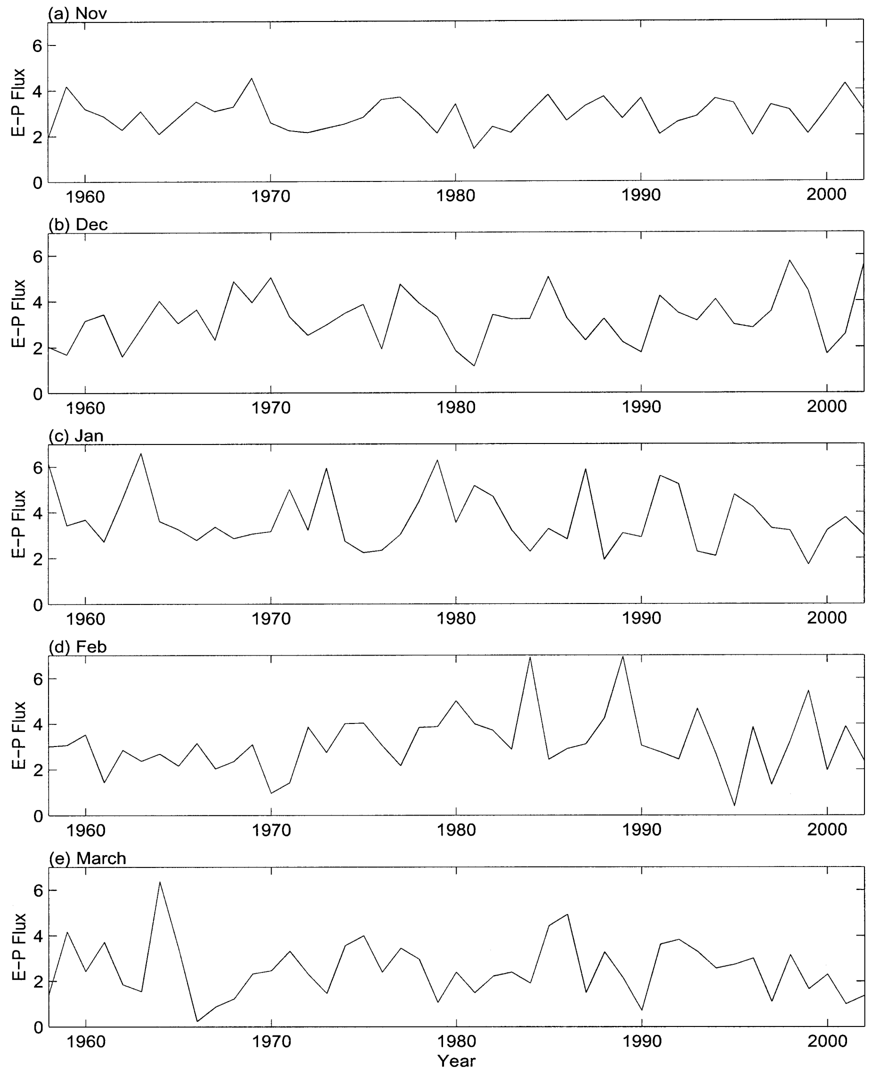

FIG. 3. Monthly mean F_{100mb}: (a) Nov, (b) Dec, (c) Jan, (d) Feb, and (e) Mar. The E–P flux unit is 10^{11} kg m s^{-2}.

b. E–P fluxes in the troposphere

Planetary waves are generated in the troposphere and from there propagate upward into the stratosphere. Thus, it is natural to think that the reduction in planetary wave activity within the stratospheric box may arise from either less wave generation in the troposphere or more deflection of E–P fluxes away from high latitudes due to altered planetary wave propagation. To investigate this, we define a box in the high-latitude troposphere, extending from 850 to 100 mb and from 50° to 90°N. Since 100 mb is some distance above the tropopause, our ''tropospheric box'' here actually includes part of the lower stratosphere.

Figures 4a,c,e,g show vertical E–P fluxes in ND at 200, 400, 600, and 850 mb, respectively, integrated over 50°–90°N. None of these trends in early winter is statistically significant. Total vertical E–P fluxes in JFM at the four levels are shown in Figs. 4b,d,f,h. The late-winter E–P fluxes demonstrate significant negative trends over 1979–2002 (except for that at 600 mb, whose significance level is about 90%). The results suggest that the trends in vertical E–P fluxes in the high-latitude troposphere are consistent with that in the stratosphere. That is, the decline in wave activity is found only in late winter and early spring and it started from the early 1980s. Prior to that the trends are mostly positive but not statistically significant.

Figure 5 shows horizontal E–P fluxes at four tropospheric levels at 50°N for ND and JFM. First, the signs of the horizontal E–P fluxes between ND and JFM are opposite. In early winter, the E–P fluxes at all the four levels are positive (poleward). In contrast, the horizontal E–P fluxes in late winter are all negative (equatorward). Second, the trends in horizontal E–P fluxes in ND and

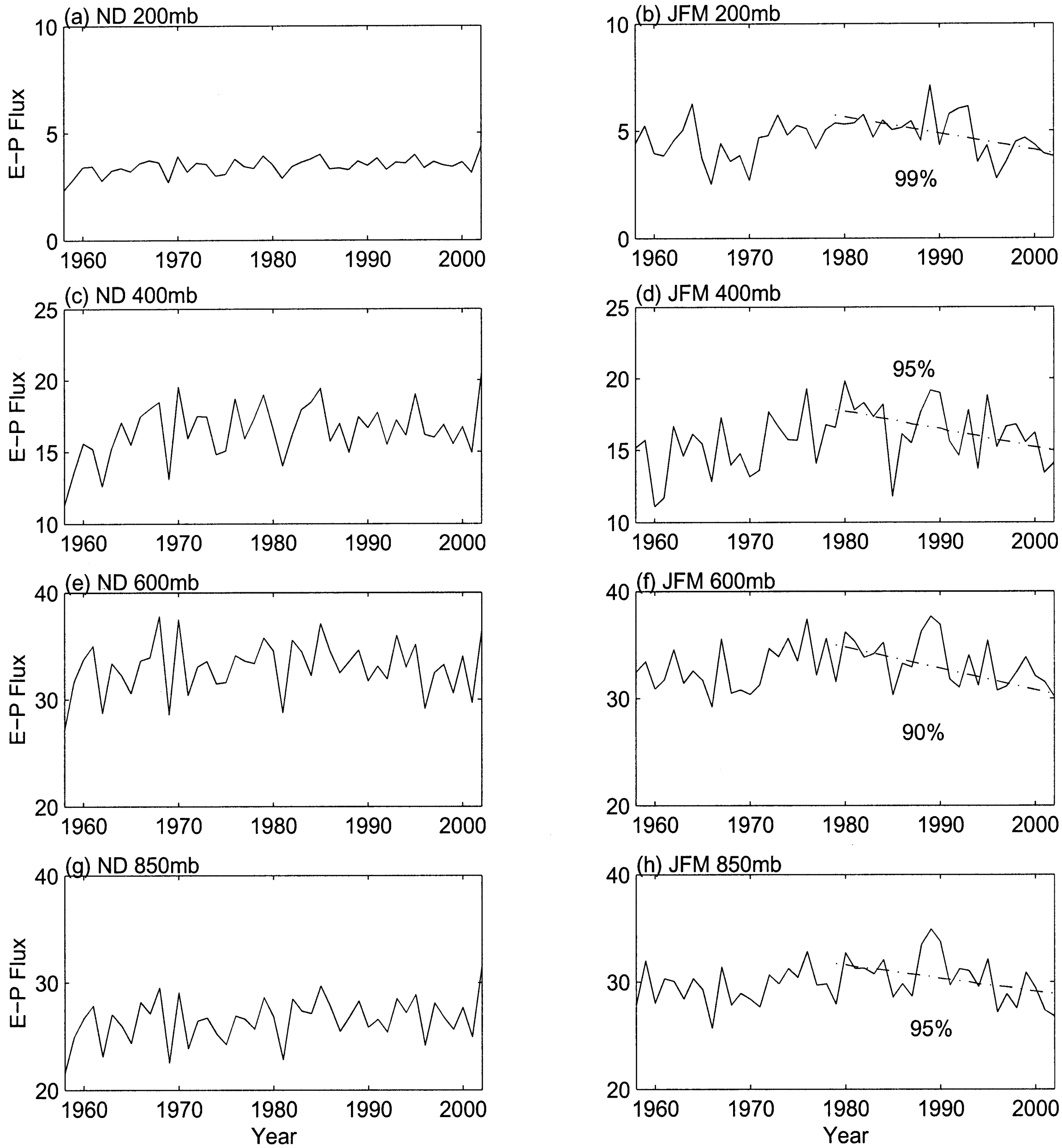

FIG. 4. Vertical E–P fluxes in the troposphere. The E–P flux unit is 10^{11} kg m s^{-2}.

JFM exhibit opposite tendencies. In ND, the horizontal E–P fluxes show mostly positive trends over the 45 years. In JFM, the E–P fluxes exhibit negative trends over 1979–2002, suggesting that more wave activity is refracted away from high latitudes. Note that all other trends in the horizontal E–P fluxes are not statistically significant, except for the JFM trend at 200 mb (Fig. 5b), just above the tropopause. This is the region for significant horizontal propagation of Rossby waves.

Figure 6 summarizes the E–P flux budget in the tropospheric box. In ND (Figs. 6a,c,e), none of $F_{50°N}$, $F_{100mb} - F_{850mb}$, and F_{netT} shows significant trends. In JFM (Figs. 6b,d,f), $F_{50°N}$ is negative (equatorward) and exhibits a negative trend (i.e., more negative) over 1979–2002, with a significance level of about 90%. The net change of $F_{50°N}$ over 1979–2002 is $\delta F_{50°N} \approx -1.9 \times 10^{11}$ kg m s^{-2}, about 130%. This is a rather large change, suggesting a remarkable equatorward deflection of wave fluxes from high latitudes, though the significance of the trend is not sufficiently high. The difference of total vertical E–P fluxes between 100 and 850 mb is negative and has a significant trend over 1979–2002. The net change of the vertical E–P flux difference is $\delta F_{100mb} - \delta F_{850mb} \approx 1.9 \times 10^{11}$ kg m s^{-2}. The E–P flux divergence over the tropospheric box is $\delta F_{netT} = \delta F_{100mb} - \delta F_{850mb} - \delta F_{50°N} \approx 3.8 \times 10^{11}$ kg m s^{-2}, about 14% increase

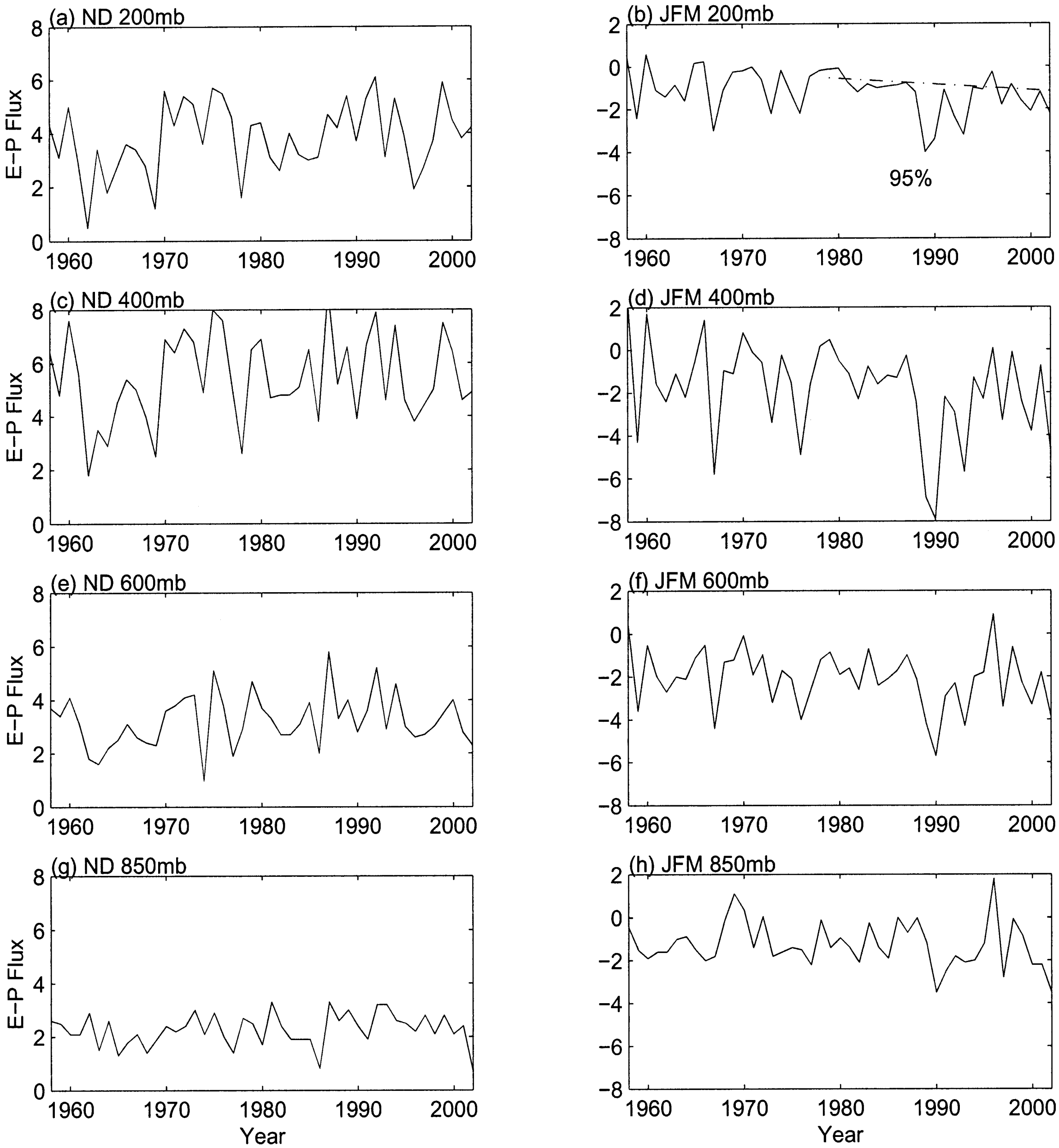

FIG. 5. Horizontal E–P fluxes in the troposphere at 50°N. The E–P flux unit is 10^7 kg m s^{-2}.

(which is actually a decrease in its magnitude). Such an increase in E–P flux divergence should lead to strengthened westerly zonal winds in the high-latitude troposphere.

The above analysis shows that the decrease in vertical E–P fluxes in JFM extends all the way from the stratosphere to near the surface over the 24 years. Over the same period, equatorward horizontal E–P fluxes just above the tropopause have increased dramatically. This suggests that the reduction in wave fluxes at high latitudes is largely due to equatorward refraction of E–P fluxes, although the analysis here does not rule out the possibility that the reduction in wave activity may be partly due to less wave generation in the troposphere. Consider that upward planetary wave propagation is very sensitive to the strength of high-latitude westerly winds. It is plausible that the enhanced equatorward wave refraction and suppressed upward wave propagation may be caused by changes in westerly winds in the high-latitude stratosphere. We explore this in the next section.

4. Ozone depletion and wave activity

Two intriguing results have surfaced from the above analysis. First, the decrease in wave activity in the

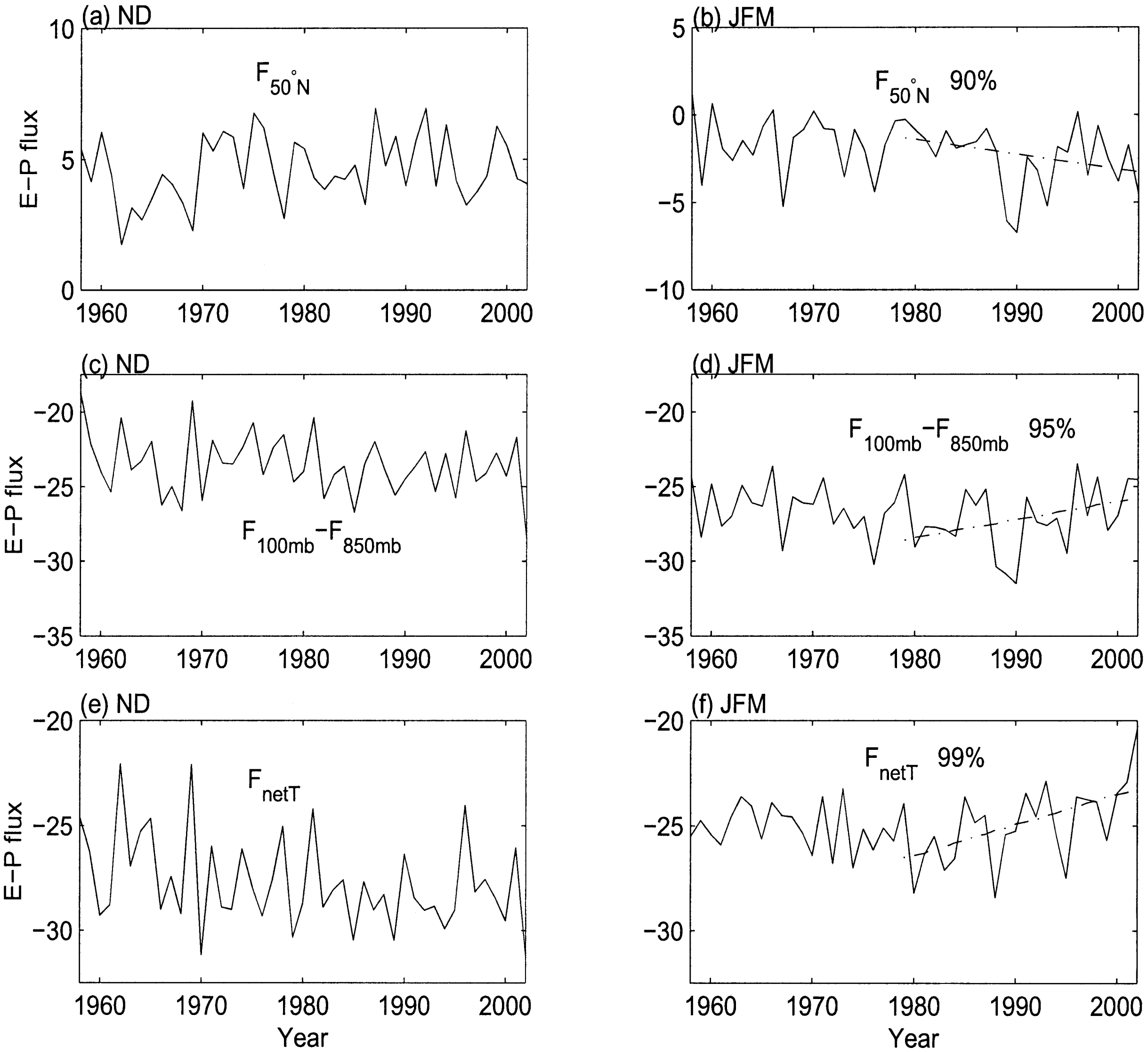

FIG. 6. The E–P flux budget in the tropospheric box. Here, $F_{50°N}$ is the total horizontal E–P fluxes vertically integrated from 850 to 100 mb at 50°N; $F_{100mb} - F_{850mb}$ is the difference of total vertical E–P fluxes, meridionally integrated from 50° to 90°N, between 100 and 850 mb; $F_{netT} = F_{100mb} - F_{850mb} - F_{50°N}$. The E–P flux unit is 10^{11} kg m s^{-2}.

stratosphere and in the vertical E–P fluxes in the troposphere are found only in late winter, and not in early winter. Second, wave activity did not decrease until the 1980s. These suggest that the systematic decrease in planetary wave activity could be related to the observed downward ozone trend in the stratospheric Arctic in late winter and springtime during the recent two or three decades.

Figure 7 shows March-mean TOMS column ozone as a function of time, together with normalized JFM-mean vertical E–P flux at 100 mb and March-mean polar temperature anomalies at 50 mb. While there are several years during which the polar ozone has poor correlations with the E–P flux and the polar temperature, the three quantities evolve consistently in general. In particular, all experienced a rapid drop in the early 1990s and tended to rebound somewhat after 1997. The correlation coefficient between the polar ozone and the polar temperature is about 0.89, suggesting a close relationship between Arctic ozone and temperatures in springtime since 1979. Arctic temperatures may not be solely determined by polar ozone because of strong planetary wave activity in the Northern Hemisphere. They can be influenced by wave dynamical heating and feedbacks involving ozone, wave fluxes, and polar temperature itself. Indeed, Fig. 7 also shows good consistencies between Arctic temperature and vertical E–P flux at 100 mb. This is unlike the case of Antarctic temperatures, which are primarily determined by polar ozone due to relatively weak wave activity. Thus, the decreasing (cooling) of Arctic temperatures can also be caused by decreasing dynamical heating and relevant feedbacks. Nevertheless, Ramaswamy et al. (1996) and Randel and Wu (1999) have argued, with evidence from GCM simulation and observations, that strong Arctic cooling is primarily a radiative response to ozone depletion.

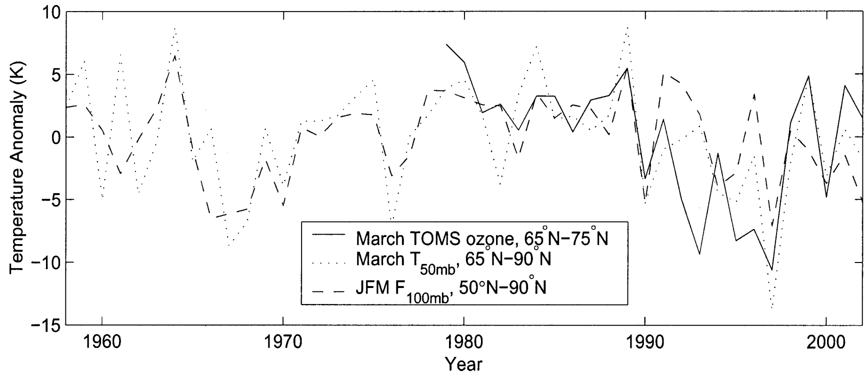

FIG. 7. Mar-mean polar temperature anomaly at 50 mb, against normalized Mar-mean TOMS total ozone and JFM-mean vertical E–P flux crossing 100 mb. For comparison, the normalized TOMS ozone is multiplied by 5, and the normalized E–P flux is multiplied by 3.5. Here, temperature and ozone are area-weighted over 65°–90°N and 65°–75°N, respectively, and E–P flux is the total amount integrated over 50°–90°N.

Figure 8 shows plots of temperatures at 30 mb, area-weighted over midlatitudes (40°–60°N) and over the polar region (65°–90°N) in February and March when sunlight returns to the polar region but generally before the breakup of the vortex. It appears that there exists a turning point around 1979 for temperatures in both the midlatitudes and the polar region. Labitzke and Naujokat (2000) have argued that the strong cooling would be swamped if one calculates the trend over the period of 1958–2002 (note that the trend over 1958–2002 is about -0.04 K yr^{-1}, but not significant). The midlatitude temperature first exhibits a weak cooling trend, about -0.05 K yr^{-1}, over 1958–79, then a strong cooling trend of about -0.12 K yr^{-1} after 1979. Both are statistically significant. The weak cooling over 1958–79 resembles the magnitude of stratospheric cooling due to the greenhouse effect. The polar temperature exhibits warming before 1979 and significant cooling, about -0.25 K yr^{-1}, after 1979. The strong cooling in the midlatitudes and the polar region over 1979–2002 is presumably due to ozone depletion in the stratosphere (Randel and Wu 1999). It is important to note that the cooling trend in the polar temperature is about twice as steep as that in the midlatitude temperature, presumably due to more severe ozone depletion in the Arctic polar region. The difference in cooling magnitudes suggests an increase of meridional temperature contrast of about 3.4 K between the polar region and midlatitudes over the past two decades. According to the thermal wind relation, the enhanced temperature contrast between midlatitudes and the polar region would lead to stronger westerly winds near the subpolar stratosphere.

In HT, we have argued that upward planetary wave propagation is very sensitive to the strength of westerly winds at subpolar latitudes. When high-latitude westerly winds are strengthened, it leads to enhanced equatorward wave refraction. The tendency for wave refraction can be evaluated by studying the trends in the index of refraction. Figure 9 shows the time series of squared refraction indices for wavenumber 1 in ND and FM. Note that the refraction indices are averaged over 55°–65°N, which is the most important channel for upward planetary wave propagation. Panels (a), (c), (e), and (g) show refraction indices at 50, 100, 200, and 400 mb for ND. These indices do not show significant tendencies in early winter over the 45 years. This is consistent with

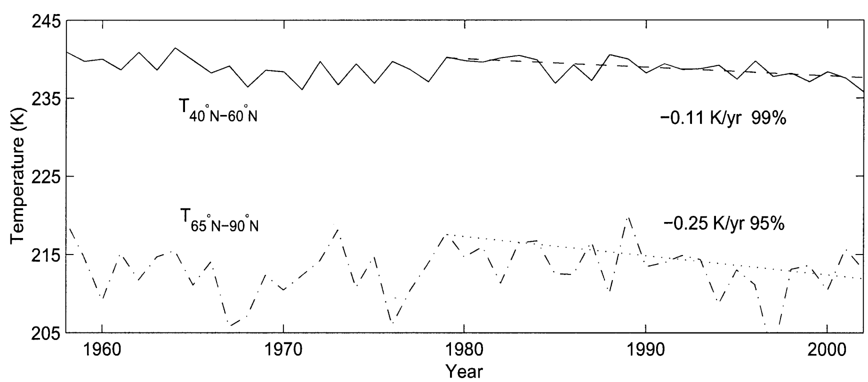

FIG. 8. Midlatitude temperature at 30 mb, area-weighted over 40°–60°N, against polar temperature at 30 mb, area-weighted over 65°–90°N, during FM.

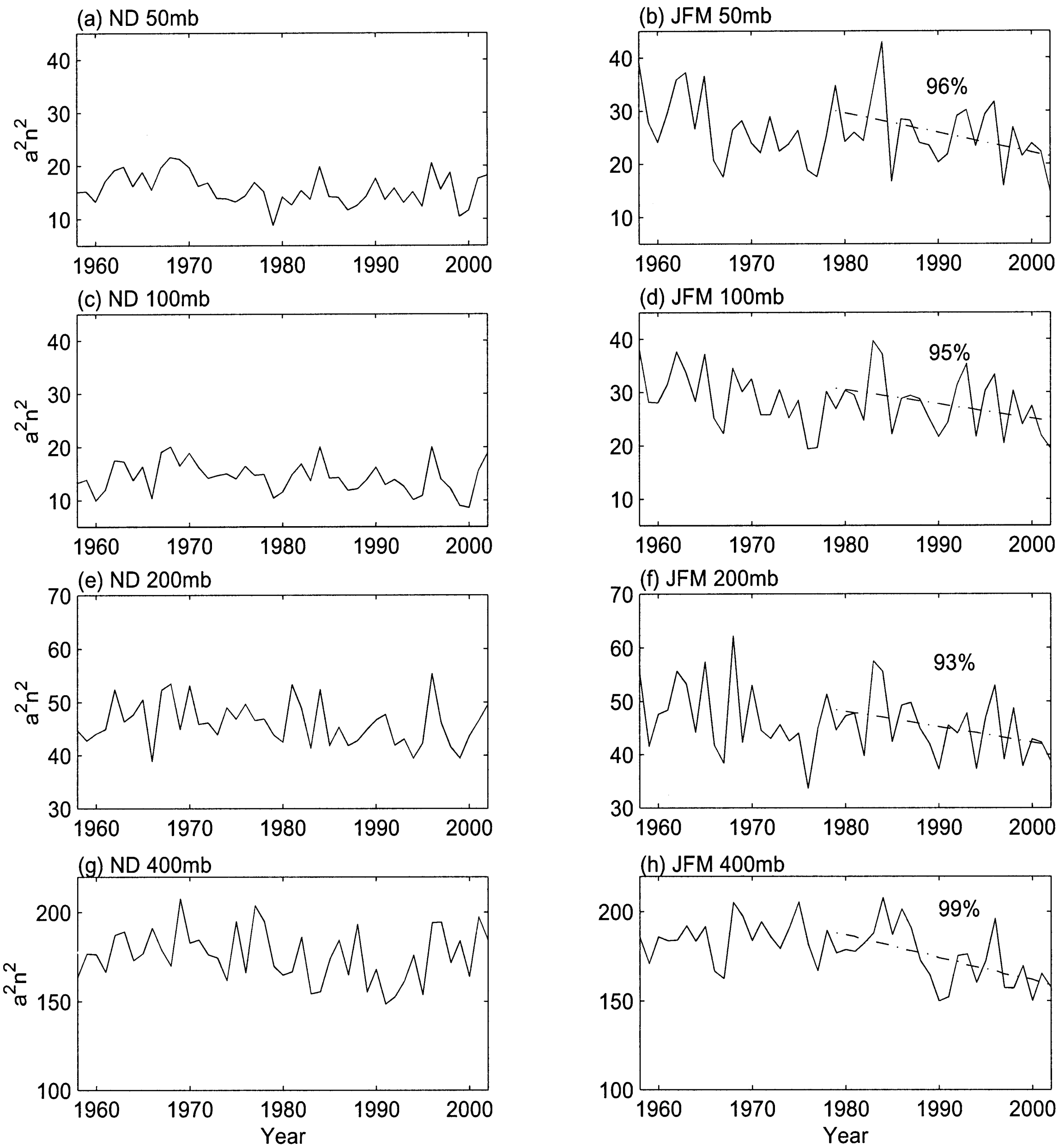

FIG. 9. Wavenumber-1 refraction index square at different levels. Note that the refraction index squared is averaged over 55°–65°N and multiplied by earth's radius square, a^2. The unit of a^2n^2 is m^2.

the observation of no significant changes in early-winter wave activity. In contrast, refraction indices at all four levels in FM show negative trends. The indices evolve differently from one level to another prior to 1979, but have become more consistent and decreased since then. The negative trends in the indices at 50, 100, and 400 mb are all statistically significant, while the significance level of the trend at 200 mb is slightly below 95%. The decrease in the refraction indices is consistent with the enhanced temperature contrast in Fig. 8. In fact, the correlation between the refraction index at 50 mb and the polar temperature at 50 mb is about 0.44 (larger than 0.39 required for statistical significance), suggesting a consistency of trends in the refraction indices and the Arctic cooling. According to the linear wave theory (Andrews et al. 1987), smaller indices of refraction in the subpolar region implies that planetary waves tend to be refracted away from high latitudes. This is consistent with the results of increasing equatorward horizontal E–P fluxes and decreasing upward vertical E–P fluxes in section 3b.

Note that strengthened subpolar westerly winds are not limited to the stratosphere. Observations have shown that strengthened subpolar zonal winds extend from the stratosphere to near the surface, with a maximum in the stratosphere (Thompson et al. 2000). When the subpolar winds in the lower stratosphere become stronger, the winds tend to suppress upward wave propagation and refract waves away from high latitudes over a large vertical extent, since planetary-scale waves have rather large vertical wavelengths. This leads to decreases in wave activity not only in the high-latitude stratosphere but also in the high-latitude upper troposphere. As a result, westerly winds in the high-latitude troposphere have also become stronger.

It is generally thought that, as wave activity is reduced, it would lead to both less dynamical heating and less ozone transport from midlatitudes into the Arctic; the polar vortex is thus getting colder and stronger, which in turn causes more ozone depletion and more reduction in wave activity. Such a process forms a positive feedback cycle: ozone depletion $\rightarrow$ colder and stronger polar vortex $\rightarrow$ reduced wave activity $\rightarrow$ less dynamical heating and less ozone transport $\rightarrow$ much colder and stronger polar vortex $\rightarrow$ more ozone depletion. According to such an interpretation, the reduction in wave activity is initialized by the ozone depletion, which started in the 1980s and has been acting as the external forcing, while less ozone transport from midlatitudes into the Arctic due to the reduction in wave activity, observed by Coy et al. (1997), Fusco and Salby (1999), and Randel et al. (2002), is only a part of the positive feedback cycle. Randel et al. (2002) have estimated that interannual changes in E–P flux contribute about 20%–40% of observed trends in column ozone over 40°–60°N during the past two decades.

5. Summary

We have studied the decadal trends in planetary wave activity or E–P fluxes in the high-latitude Northern Hemisphere. It was found that in JFM wave activity in the stratosphere and vertical E–P fluxes in the troposphere have been largely reduced and exhibit statistically significant downward trends from 1979 to 2002, while equatorward horizontal E–P fluxes in the troposphere have been considerably increased. The following evidence appears to argue that the reduction in wave activity is likely caused by stratospheric ozone depletion in the Arctic.

1) Timing: The reduction in wave activity occurs only in late winter. In contrast, there are no statistically significant changes in wave activity in early winter. The negative trends in late-winter wave activity start in the 1980s. Before 1979, wave activity in late winter has no statistically significant trend (slightly increasing). The timing, both seasonal and decadal, is consistent with the observed downward ozone trend in the stratospheric Arctic in recent decades.
2) Refraction index: The indices of refraction have been altered in the high-latitude Northern Hemisphere during late winter, exhibiting significant negative trends over 1979–2002. The decrease in the refraction index is consistent with the strong cooling in the stratospheric Arctic and the observed strengthened westerly jet near the subpolar stratosphere. It is the strengthened westerly winds that refract planetary waves away from high latitudes toward low latitudes. The observed 130% increase in the equatorward wave E–P fluxes in the troposphere are more than sufficient to accounts for the 30% reduction in vertical E–P fluxes from the troposphere into the stratosphere.

According to our interpretation, ozone depletion in the stratospheric Arctic is likely the external forcing that initiated the cooling and a systematic reduction in planetary wave activity, while the observed reduction in ozone transport from midlatitudes into the Arctic and reduced dynamical heating in the polar region are a result of positive feedback. How to quantify the effect of the positive feedback is a problem for future studies. We would like to further point out that we have not ruled out the possibility that some other external forcing reduced the wave flux into the stratosphere, which then caused stratospheric cooling and ozone depletion. More numerical model studies are needed.

If it turns out to be true that the wave activity decline was caused by ozone-induced cooling, it then suggests a plausible mechanism for the stratosphere to influence tropospheric climate, specifically, the observed late-winter warming over high-latitude Northern Hemisphere continents during the recent two or three decades (Hurrell 1995; Thompson et al. 2000). Our results show that the decline in vertical E–P fluxes extends all the way from the stratosphere to near the surface. Vertical E–P fluxes at 850 mb have been reduced by about 10% over the 24 years. The wave E–P flux convergence in the high-latitude troposphere has decreased by about 14%. Consistent with the interpretation of high-latitude warming in the context of AO by Wallace and Thompson (2002), the reduction in wave activity can lead to strengthened westerly winds at high latitudes, which blow warm oceanic air over high-latitude continents and possibly cause warming.

The proposed mechanism through which ozone depletion can induce planetary wave activity decline is probably the same as that for aerosol-induced wave activity decrease following volcano eruptions. Rind et al. (1992), Robock and Mao (1992), and Graf et al. (1993) noticed that the stratospheric polar vortex became abnormally strong and cold in winters right after major volcano eruptions. It was also argued that the sharp decrease of wave activity, Arctic ozone, and temperature in 1994 might be due to the effect of volcanic aerosols from the Mount Pinatubo eruption (Kirchner et al. 1999). However, since the radiative effect of volcanic aerosols is most active during polar night and major volcanic eruptions do not happen frequently, it appears unlikely that the effect of volcanic eruptions are responsible for the long-term trend in wave activity in springtime found here. Simulations by Shindell et al. (2001a) suggest that the effect of volcanic aerosols is not as important as that of ozone depletion.

There have been GCM simulations supporting the proposed mechanism of possible ozone-induced decrease in planetary wave activity and surface climate (Graf et al. 1998; Volodin and Galin 1998, 1999; Shindell et al. 2001a). In a more recent simulation work on the European Little Ice Age during the Maunder Minimum, Shindell et al. (2001b) demonstrated the importance of ozone in translating a small reduction in solar emission into a significant increase in planetary wave activity and a decrease in regional temperature on the surface. However, these simulation results are either too weak when compared to observations or not reproduced in other GCM simulations. Further simulation studies are necessary to test the proposed mechanism.

A problem that remains is the decrease of wave activity in January as shown in Fig. 3c (not statistically significant). It seems to be difficult to interpret such a decrease with the proposed mechanism since major ozone depletion in the Arctic usually starts in February when sunlight returns to the Arctic. Nevertheless, this does not necessarily contradict the mechanism of ozone depletion because the Arctic polar vortex is not always confined to the dark, polar cap region as it is in the Antarctic. When the vortex shifts out of the polar night region, chemical ozone depletion can also take place in January, as suggested by Randel and Wu (1999).

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