Interannual Variations of Total Ozone at Northern Midlatitudes Correlated with Stratospheric EP Flux and Potential Vorticity

L. L. HOOD AND B. E. SOUKHAREV

Lunar and Planetary Laboratory, The University of Arizona, Tucson, Arizona

(Manuscript received 6 October 2004, in final form 21 February 2005)

ABSTRACT

At northern midlatitudes over the 1979–2002 time period, column ozone trends are observed to have maximum negative amplitudes in February and March. Here, the portion of the observed ozone interannual variability and trends during these months that can be attributed to two specific dynamical transport processes is estimated using correlative and regression methods. In approximate agreement with a recent independent study, 18%–25% of the observed maximum negative trend is estimated to be due to long-term changes in the diabatic (Brewer–Dobson) circulation driven by global-scale changes in planetary wave [Eliassen–Palm (EP) flux] forcing. In addition, 27%–31% of the observed maximum midlatitude trend during these months is estimated to be due to long-term changes in local nonlinear synoptic wave forcing as deduced from correlated interannual variations of zonal mean ozone and Ertel’s potential vorticity. Like long-term decreases in the Brewer–Dobson circulation, this trend component reflects an overall net increase in the polar vortex strength, which is associated with increased numbers of anticyclonic, poleward-breaking Rossby waves at northern midlatitudes. Together, these components can explain approximately 50% of the observed maximum negative column ozone trend and interannual variance at northern midlatitudes in February and March. The combined empirical model also approximately simulates a leveling off or slight increase in column ozone anomalies that has been observed for some months and latitudes since the mid-1990s.

1. Introduction

It is well established that column ozone amounts at midlatitudes have been decreasing for several decades (WMO 1999, 2003). Analyses of ozonesonde data have shown that the implied ozone decreases have occurred primarily in the lower stratosphere (~15–24 km altitude) (Logan 1994; SPARC 1998). However, a detailed attribution of these decreases to specific causal mechanisms has not yet been achieved (WMO 2003). Recently, it has become clear that negative ozone trends at northern midlatitudes are not actually linear: While trends were approximately constant and strongly negative over the period from 1980 to 1993, a negligible or slightly positive trend has prevailed at many locations since that time (e.g., Fioletov et al. 2002; Steinbrecht et al. 2003). Thus, any complete interpretation of negative

ozone trends at northern midlatitudes must explain not only the overall ozone decline but also the nonlinear trends.

Possible causal mechanisms for lower-stratospheric ozone trends and interannual variability at northern midlatitudes can be divided into two general classes that are not fully independent of one another: chemical and dynamical. Chemical processes that may contribute to midlatitude ozone decreases are related to the increase in anthropogenic halogens that is known to be the main cause of ozone declines in the polar regions and in the upper stratosphere. These include direct mechanisms (chlorine activation on liquid aerosol and ice particles: e.g., Solomon et al. 1996, 1998) and indirect mechanisms (export of ozone-depleted or chlorine-enriched air from the polar vortex; e.g., Knudsen and Grooß 2000; Hauchecorne et al. 2002; Chipperfield 2003). However, chemically induced ozone losses can have dynamical feedbacks. For example, increased ozone losses in polar regions can lead to radiatively reduced temperatures, which can then accelerate the circumpolar winter vortex. On the other hand, dynamical

Corresponding author address: L. L. Hood, Space Sciences Building, The University of Arizona, 1629 E. University Blvd., Tucson, AZ 85721-0092.
E-mail: lon@lpl.arizona.edu

cal changes can influence ozone through both chemical feedbacks and direct transport. An example of chemical feedbacks is the increased Arctic chemical ozone loss that occurs during dynamically quiet conditions when the vortex is cold and isolated (Weber et al. 2003; Rex et al. 2004). These coupled feedbacks make it difficult to determine the relative contributions of dynamics and chemistry to ozone loss.

The first indication that direct dynamical transport processes may contribute to midlatitude ozone trends was an observed significant longitude dependence of *Nimbus-7* Total Ozone Mapping Spectrometer (TOMS) trends for the 1979–92 time period (Stolarski et al. 1992; Niu et al. 1992). This longitude dependence was later interpreted quantitatively as being a consequence of decadal changes in the amplitudes and phases of quasi-stationary planetary-scale Rossby waves (Hood and Zaff 1995; Peters and Entzian 1996). Although the latter mechanism does not directly affect zonally averaged ozone trends, it can significantly affect the magnitude and even the sign of column ozone trends at specific longitudes around a given latitude circle. Like zonally averaged ozone decreases at high latitudes, zonally asymmetric ozone changes occurring on interannual and longer time scales can produce significant dynamical feedbacks. These feedbacks extend well into the troposphere, especially in the North Atlantic/European region, due to coupled water vapor increases in the lower stratosphere, which cause stronger solar heating perturbations than those resulting from the ozone changes alone (Kirchner and Peters 2003).

Dynamical processes that may contribute to zonally averaged midlatitude ozone decreases are related to an observed strengthening and increased longevity of the wintertime Arctic vortex (Tanaka et al. 1996; Zurek et al. 1996; Pawson and Naujokat 1997), an associated weakening of the Brewer–Dobson circulation (Vaugh et al. 1999; Newman and Nash 2000), and increases in tropospheric circulation indices such as those of the Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO) (Zhou et al. 2001; Hurrell 1995; Graf et al. 1998). A trend toward more equatorward planetary wave fluxes has also been reported (Kuroda and Kodera 1999; Ohhashi and Yamazaki 1999; Baldwin and Dunkerton 1999; Hartmann et al. 2000). Finally, the total wave flux entering the stratosphere has decreased, on average, during the last few decades (Newman and Nash 2000; Randel et al. 2002). These observed trends are interrelated. For example, it has been proposed that the mean strengthening of the stratospheric polar vortex is associated with an increase in the tropospheric AO index because planetary waves at the lower edge of a westerly wind anomaly in the strato-

sphere are refracted equatorward. This is expected to produce a wave flux divergence anomaly (actually a decrease in wave flux convergence) that effectively accelerates the zonal wind at that location. Over a period of a week or more, the zonal wind anomaly could therefore propagate downward in the stratosphere, as is observed (Baldwin and Dunkerton 1999, 2001), modifying the circulation down to the surface where the AO is defined (Thompson and Wallace 1998).

As reviewed by Holton et al. (1995), the wintertime Brewer–Dobson circulation, which transports ozone to middle and higher latitudes in winter and spring, is driven in part by extratropical wave forcing. (It is also driven by the seasonal cycle in diabatic heating; see, e.g., Garcia 1987.) Evidence for a contribution to midlatitude ozone trends from a long-term weakening of the Brewer–Dobson circulation was first pointed out by Fusco and Salby (1999). This trend component represents a change in the overall abundance of ozone in the stratosphere forced by a combination of dynamical transport and photochemical production and loss. Based on correlative and regression relationships using Eliassen–Palm (EP) planetary wave flux as a measure of the wave forcing, Randel et al. (2002) have estimated that this mechanism may have caused 20%–30% of the column ozone trend at northern midlatitudes over the 1979–2000 period.

At northern midlatitudes in winter and spring, it is well known that both poleward and equatorward synoptic-scale wave-breaking events occur in the lower stratosphere (e.g., Nakamura 1994; Peters and Waugh 1996). In the NH, anticyclonic poleward wave events are characterized by northward deformations of the subtropical tropopause resulting in protrusions of ozone-poor, low potential vorticity (PV) air that extend from the tropical upper troposphere into the midlatitude lowermost stratosphere (cf. Holton et al. 1995). These poleward events are often complemented by equatorward wave events at other longitudes that generate tongues of ozone-rich stratospheric air extending into the tropical upper troposphere (Vaugh and Polvani 2000). The resulting meandering boundary between low ozone regions and higher ozone regions at northern midlatitudes has been defined as the “subtropical front” by Hudson et al. (2003).

Poleward wave events produce corresponding poleward displacements of the mean subtropical jet and midlatitude storm tracks; they are most common during winters with an enhanced polar vortex (positive Northern Annular Mode, AO, and NAO indices). During these winters, the zonal wind field at midlatitudes tends to be less cyclonic, implying greater numbers of anticyclonic wave events. When the waves break (McIntyre

and Palmer 1983, 1984), cut-off anticyclones often form and irreversible exchanges of air occur between the stratosphere and troposphere (see, e.g., Hintsä et al. 1998). However, even if the waves do not break, the monthly zonal mean ozone column at a given latitude can still be significantly modified by one or more of these nonlinear events. In some cases, the ozone column is further reduced locally during poleward wave-breaking events by southward excursions of the polar vortex and by upward deflection of the zonal flow over the associated upper-tropospheric anticyclone, causing extreme ozone minima, sometimes referred to as ozone “miniholes” (e.g., Petzoldt 1999; James et al. 2000; Hood et al. 2001; Semane et al. 2002).

There is evidence that long-term increases in poleward transient Rossby wave events in the subtropical lower stratosphere have contributed to midlatitude zonal mean ozone trends since 1979 (Hood et al. 1997, 1999; McCormack and Hood 1997; Reid et al. 2000; Appenzeller et al. 2000; Orsolini and Limpasuvan 2001; Brönnimann and Hood 2003). These increases in poleward wave events have occurred during a period of generally increasing AO index (i.e., increased negative anomalies of pressure over the polar cap and positive anomalies at low latitudes; see Fig. 1c of Gillett et al. 2002). On the basis of regression relationships between column ozone and Ertel’s PV, it has been estimated that increases in poleward wave-breaking frequency could explain as much as 40% of the zonal mean column ozone trend at northern midlatitudes during the month of February over the 1979–98 time period (Hood et al. 1999). Recent analyses of ozonesonde data also support the hypothesis that especially low monthly mean ozone amounts in the midlatitude lowermost stratosphere over Europe in winter tend to occur during years characterized by extreme ozone minima associated with poleward-breaking Rossby waves (J. Logan 2004; personal communication).

The nonlinear synoptic wave contribution to midlatitude ozone trends acts in the same direction as that due to decreases in the Brewer–Dobson circulation since both are associated with a stronger winter polar vortex. However, unlike changes in the Brewer–Dobson circulation, this trend component does not normally produce a corresponding net change in stratospheric ozone abundance. Instead, it represents primarily a rearrangement of ozone such that decreases in the ozone column in one area at one time are compensated elsewhere (cf. Fusco and Salby 1999). This is true to a first approximation provided that transport occurs on time scales short compared to the ozone photochemical lifetime. Thus, hemispherical or global column ozone averages are not strongly affected by local wave forcing. How-

ever, monthly averages of zonal-mean column ozone at northern midlatitudes, which are usually used for trend studies, are significantly affected by nonlinear wave events. It is therefore necessary to take this dynamical process into account when evaluating the origin of midlatitude ozone trends.

To date, three-dimensional model simulations have not yet definitively determined the relative contributions of dynamical and chemical processes to ozone trends at northern midlatitudes. Hadjinicolaou et al. (2002) reported a 20-yr integration of the SLIMCAT chemical transport model forced by observational meteorological analyses (European Centre for Medium-Range Weather Forecasts) in which interannual chemical (halogen) forcing was intentionally held constant. Results showed a downward trend in midlatitude ozone and the model successfully simulated a large fraction of the observed ozone interannual variability, especially during the winter season (see their Figs. 2, 4, and 5). It was concluded that at least half of the observed NH midlatitude column ozone trend averaged over December to February from 1979 to 1998 could be accounted for solely by changes in the meteorology. They presented correlative evidence that the model ozone trend was related, at least in part, to changes in the Brewer–Dobson circulation and to changes in the NAO index. They also noted that very low midlatitude ozone during some years was influenced by injection of tropical, upper-tropospheric air into the midlatitude lowermost stratosphere, as evidenced by correspondingly low values of Ertel’s PV at middle latitudes.

On the other hand, Chipperfield (2003) reported a 20-yr integration of the same SLIMCAT model (but including detailed chemistry and resulting feedbacks) for cases with and without the inclusion of halogen loading and time-dependent aerosol. For most months and latitudes, the run with halogen loading and aerosol data yielded a better agreement with observed ozone time series. It was therefore concluded that halogen-related trends dominated the modeled ozone decrease at all latitudes, including northern midlatitudes. The partial contradiction between results of Hadjinicolaou et al. (2002) and Chipperfield (2003) was discussed by the latter author but was not clearly resolved.

It is important to quantify the effective dynamical transport contribution to ozone interannual variability and trends at northern midlatitudes so that the direct chemical contribution can be more accurately estimated. Although some component of observed circulation changes at NH midlatitudes may be attributable to feedback effects of ozone changes, model simulations to date indicate that other mechanisms [natural climate variability, greenhouse gas forcing (GHG) forcing] are

more likely to be dominant contributors to these circulation changes (e.g., Graf et al. 1998; Gillett et al. 2002). Thus, to some extent, dynamical and direct chemical contributions are separable. If so, an observational assessment of the effective contribution of circulation changes to ozone interannual variability and trends could be valuable.

In this paper, empirical (correlative and regression) methods are applied to investigate further the two primary dynamical mechanisms that have been proposed as significant contributors to column ozone trends at northern midlatitudes. In section 2, the dependences on season and latitude of assumed linear trends in column ozone are first reestimated for the 1979–2002 time period based on an updated merged satellite total ozone record. Example plots of ozone interannual and long-term variability are also given for northern midlatitudes in winter when the largest negative trends are observed. In section 3, interannual variability of the Eliassen–Palm planetary wave flux in the NH is investigated further, and correlations with interannual total ozone changes during specific months at northern midlatitudes are determined. For comparison with previous estimates, the results are applied to predict the component of interannual ozone variability at northern midlatitudes in winter that can be attributed to wave-induced changes in the Brewer–Dobson circulation. In section 4, correlations are determined between monthly zonal mean wintertime ozone decreases at northern midlatitudes and corresponding decreases in zonally averaged Ertel’s PV. In agreement with earlier work, this correlation is interpreted as being a consequence of interannual variations in the number and amplitude of northward excursions of upper-tropospheric air into the midlatitude lowermost stratosphere during nonlinear synoptic wave events. The independence of interannual PV deviations from EP flux interannual deviations is then investigated, and mean sensitivities of zonal-mean column ozone to PV deviations on the 350-K surface are estimated as a function of latitude and month during the northern winter. These sensitivities are applied to calculate model-predicted time series of February zonal mean column ozone at northern midlatitudes for comparison with that predicted on the basis of EP flux alone. Finally, both EP flux deviations and 350-K PV deviations are included in a single regression model to predict the total contribution of both dynamical mechanisms to ozone interannual variability in February and March. In addition, the relative contributions of these two dynamical mechanisms to zonal-mean ozone trends at northern midlatitudes are estimated for January, February, and March. Conclusions are summarized in section 5.

FIG. 1. Linear column ozone trends from 1979 to 2002 (% decade⁻¹) based on a standard multiple regression statistical analysis of the TOMS/SBUV data record calibrated as described by Stolarski et al. (2000). Shaded areas are significant at the 95% confidence level.

2. Ozone interannual variability and trends at northern midlatitudes

We consider here an updated version (version 8) of the merged satellite column ozone dataset prepared originally at the NASA Goddard Space Flight Center (Stolarski et al. 2000). This dataset combines the *Nimbus-7* and Earth Probe TOMS data, the *Nimbus-7* Solar Backscattered Ultraviolet (SBUV), and NOAA satellites, *NOAA-9*, *-11*, and *-14*, SBUV/2 data (available online at http://code916.gsfc.nasa.gov/Data_services/merged/). The dataset is more continuous with fewer gaps (e.g., the SBUV data were used to fill in a period during 1995 and 1996 when there were no TOMS measurements) and has been adjusted using operational overlap periods to minimize differences in calibration between the various instruments. It covers the period 1979–2002 (24 yr).

To provide a brief overview of long-term variations in the merged TOMS–SBUV record, a standard multiple-regression statistical model was applied, including terms representing variability associated with the equatorial quasi-biennial wind oscillation (QBO), the 11-yr solar cycle, and assumed linear trends. A contour map of the resulting monthly linear trend regression coefficients (in percent per decade) is shown in Fig. 1. Shaded areas indicate where trends are significant at the 2σ (95% confidence) level. For recent detailed analyses of total ozone interannual variability and trends, see Fioletov et al. (2002) and Steinbrecht et al. (2003). An examination of Fig. 1 shows that, in the NH, maximum linear trends occur at northern midlatitudes (about 40° to 45°N) in winter (February). Trends are also rela-

tively large in the Arctic spring but, because of lack of backscattered sunlight during the polar night, these trends are not clearly shown in Fig. 1.

To illustrate the interannual and decadal variability of ozone for the month and latitudes where ozone linear trends are largest, Fig. 2 plots monthly zonal mean ozone for February at latitudes ranging from 30° to 60°N. Interannual variability associated with the QBO is evident. In addition, a relatively large minimum occurs in 1993; this minimum follows the 15 June 1991 eruption of Mt. Pinatubo and is caused mainly by the chemical and/or dynamical effects of this aerosol injection event (Hadjinicolaou et al. 1997; Stenchikov et al. 2002; Rozanov et al. 2002). At the latitudes plotted in Fig. 2, the modified circulation (positive phase of the AO in winter during the QBO west phase) is a partial cause of the negative ozone anomaly in 1993 (G. Stenchikov 2004, private communication). At 40°N where the trend maximizes, the trend is mostly linear but is less steep (the linear trend coefficient becomes less negative) toward the end of the record. At 60°N, however, the last part of the record has no detectable trend and a possible slight upturn appears during the last seven years. As noted, for example, by Fioletov et al. (2002), the latter upturn appears to occur too rapidly to represent a recovery from chemically induced ozone depletion associated with reduced anthropogenic halogen emissions. Rather, natural climate variability with its effects on stratospheric circulation is a more likely explanation.

3. Ozone changes correlated with stratospheric EP flux

Fusco and Salby (1999) first demonstrated a correlation between hemispherically averaged upward EP flux at 100 hPa during January and the increase of extratropically averaged total ozone during the same month for the 1979–93 time period. Randel et al. (2002) extended their analysis to 2000 and found similar correlations between upward EP flux in January (averaged over the 40°–70°N latitude band) and the change in ozone during the same month at northern midlatitudes. The 40°–70°N band was used by them because EP flux maximizes within this latitude range and nearly identical results were obtained using averages over the entire hemisphere. This is considered to be a reasonable measure of the strength of the overall Brewer–Dobson circulation, which influences ozone at all latitudes in the winter hemisphere. We note that it may also be a useful proxy for wave breaking and, hence, quasi-horizontal mixing, another ozone transport mechanism, at midlatitudes.

FIG. 2. Time series of merged TOMS/SBUV ozone monthly zonal means for February at a series of latitudes in the Northern Hemisphere.

Here we extend by two years the analysis of Randel et al. (2002) and investigate further the application of EP flux data to predict interannual variability of northern midlatitude ozone in winter. Specifically, values of the zonally averaged meridional eddy heat flux, $\overline{v'T'}$, which is approximately proportional to the vertical component of the EP flux, are calculated at 100 hPa based on National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data (Kalnay et al. 1996).

Figure 3 shows examples of correlations between monthly averaged 100-hPa EP flux (averaged over the 40°–70°N latitude band) and the change in ozone at 45°N during the same month (i.e., the difference between zonal mean column ozone on the last of the month and that on the first of the month, hereafter

FIG. 3. Correlation between ozone tendencies at 45°N (solid line) and of the 100-hPa eddy heat flux (proportional to the vertical component of the EP flux) averaged over the 40°–70°N latitude band. The ozone tendencies were calculated from daily TOMS and NOAA SBUV/2 data as described in the text.

referred to as “ozone tendency”). The top panel of the figure is comparable to Fig. 7 of Randel et al. (2002) except for the addition of two years of data. The correlation coefficient (R) is seen to be strongest for the month of January (0.56) and is also significant for February (0.44) but becomes statistically insignificant (−0.12) in March. The 95% confidence level is $R = 0.43$. Correlation coefficients for other months and latitudes (not given here) show that correlations are insignificant at the 95% level at all latitudes except for the months of January through March. In January, significant correlations are obtained at 40°, 45°, and 50°N; in February, significant correlations are obtained at 45° and 50°N; in March, significant correlations are obtained only at 55°N. On this basis, we expect that the midlatitude ozone buildup in January and February would be significantly influenced by interannual variations in the Brewer–Dobson circulation (as measured

by the EP flux). Small negative trends are also evident in the January and February EP flux time series (dashed line in the top two panels of Fig. 3). A corresponding contribution to the ozone trend during these months is therefore expected.

For the purpose of estimating the contribution of EP flux variations to interannual midlatitude ozone variations in winter, regression relationships between monthly mean EP flux and the column ozone tendency were first derived from data such as that shown in Fig. 3. Figure 4 compares the observed zonal mean ozone time series for February at 45°N with a model time series calculated by integrating over time the ozone tendency estimated from the eddy heat flux data of January and February of each year. Specifically, following Randel et al. (2002), the ozone anomalies are calculated from

$$O_3(t) = \int_{\text{January}}^{\text{February}} \frac{\Delta O_3}{\Delta t} dt, \quad (1)$$

where monthly $\Delta O_3/\Delta t$ is estimated from observed monthly averages of daily anomalies in $\overline{v'T'}$ using empirical correlations between these two quantities (e.g., Fig. 3). Again following Randel et al. (2002), the ozone anomalies are assumed to be zero at the beginning of January for each year. The predicted ozone anomalies are then added to the long-term mean ozone value for February to produce the time series shown in the figure. Both the observed ozone (solid line) and the model-predicted ozone (dashed line) exhibit a downward trend. The overall correlation coefficient is $R = 0.43$, implying that approximately 20% of the interannual variability is explained by the model based on EP flux anomalies. If both time series are detrended, the correlation coefficient is reduced further to 0.31.

FIG. 4. Comparison of observed and empirically estimated column ozone when only the mean 40°–70°N EP flux is considered as a predictor variable. For the empirically estimated time series, the ozone anomaly on 1 Jan of each year was assumed to be zero.

4. Ozone changes correlated with Ertel's potential vorticity

As reviewed previously (Hood et al. 1999), a number of earlier studies have indicated a probable important role for local synoptic-scale planetary wave processes in contributing to midlatitude ozone trends (Randel and Cobb 1994; Chandra et al. 1996; Hood et al. 1997; Jadin and Diansky 1997; Steinbrecht et al. 1998). Several studies have attempted to estimate empirically the contribution of such processes to column ozone trends using lower-stratospheric (~ 100 hPa) temperature and geopotential height data as effective proxies (Chandra et al. 1996; Hood et al. 1997). As discussed by Randel et al. (2002), estimation of dynamical contributions is relatively straightforward on short-term (synoptic) time scales. However, such estimation becomes more complicated on interannual and longer time scales because of nonnegligible dynamical feedbacks of ozone changes. For example, trends in 50–100-hPa temperature are observed at northern midlatitudes that can be modeled as resulting, at least in part, from the radiative effects of chemically induced ozone depletion (e.g., Ramaswamy et al. 1996). Hence, the interpretation of the inferred dynamical contributions to ozone trends is somewhat ambiguous when using lower-stratospheric temperature and geopotential height as dynamical proxies.

As an alternate approach to estimating the contribution of local synoptic wave forcing to midlatitude ozone trends, one may employ as an effective dynamical proxy Ertel's PV on isentropic surfaces that connect the tropical upper troposphere with the midlatitude lowermost stratosphere (Hood et al. 1999). It has been established empirically that maximum correlations (~ 0.6) between PV and total ozone at northern midlatitudes occur above the mean tropopause at pressures of 200–300 hPa, corresponding to potential temperature surfaces in the range from ~ 330 to 350 K (Vaughan and Price 1991; see especially Fig. 3 of Ziemke et al. 1997). Ertel's PV, which for inviscid, adiabatic motion is conserved, has several advantages for the purpose of estimating the influence of short-term dynamical processes on column ozone trends. First, the appropriate isentropic surfaces (330–350 K) lie at a significantly lower level (200–250 hPa or 10–12-km altitude at middle latitudes) than where decadal lower-stratospheric temperature trends are observed. Therefore, long-term differences in this quantity primarily reflect differences in dynamical transport occurring on short time scales during different winters, for example, differences in the number and amplitudes of poleward synoptic wave events. Since ozone is also approximately conserved on

lower-stratospheric isentropic surfaces on synoptic wave time scales, differences in PV can be used as a first estimate for the change in ozone to be expected from transport effects alone. Second, comparisons of daily and monthly PV maps with column ozone maps allow an identification of the basic physical cause of the associated ozone trend contributions. As shown, for example, in Fig. 5 [reproduced from Hood et al. (1997) and Peters et al. (1995)], an especially large poleward-breaking event occurred in early February of 1990, resulting in an extreme ozone minimum at northern midlatitudes. Events of this type, occurring with increased frequency or amplitude during a given month, can significantly reduce the monthly zonal mean column ozone value for that year, thereby influencing ozone interannual variability and trends.

To indicate the possible role of nonlinear local wave forcing in producing interannual variability of ozone at northern midlatitudes, Fig. 6 compares daily zonal means of TOMS ozone and 350-K PV at 50°N for two winters: 1980/81 (a high-ozone year) and 1989/90 (a low-ozone year). As seen in the top panel, daily ozone amounts at this latitude were much lower during the 1989/90 winter than during the 1980/81 winter. As can be seen from Fig. 3, only a small part of this difference can be attributed to differences in nonlocal wave forcing of the Brewer–Dobson circulation since the February and March average eddy heat flux was not significantly higher during the 1980/81 winter than during the 1989/90 winter. However, as shown in the lower panel, daily zonal mean PV values at this latitude were significantly lower during February through April of 1990 than during the same months of 1981.

Figure 7 compares the February mean ozone and 350-K PV distributions for a midlatitude low-ozone winter (1989/90) to those for a high-ozone winter (1990/91). As seen in Fig. 3, the 1990/91 winter (like the 1980/81 winter) is characterized by eddy heat fluxes that are not significantly higher than those of the 1989/90 winter. The lower panels in Figs. 7a and 7b show the differences between the February 1990 and the February 1991 ozone and 350-K PV distributions, respectively. By comparing these lower panels, it is seen that the reduced ozone values at middle latitudes during February of 1990 are associated with reduced PV values in the same geographic regions. Examinations of daily ozone and PV maps confirm that the reduced PV values of February 1990 are caused mainly by several large poleward wave breaking events in the subtropical and midlatitude lower stratosphere (e.g., Fig. 5). As is typical for these events, most occurred in the Atlantic–European sector (see, e.g., Hood et al. 1999).

As indicated in Fig. 8, zonally averaged column

FIG. 5. Example of a large poleward wave-breaking event occurring during early February 1990. On the ozone plots, contours of 280 DU or less are highlighted in red [1 Dobson unit (DU) = 2.69×10^{16} molecules cm^{-2}]. On the PV plots, the 2.5 unit contour (representing the approximate location of the tropopause) is highlighted in blue. Stratospheric air with PV ≥ 5 units is indicated by shading. PV is in units of $10^{-6} \text{ m}^2 \text{ K s}^{-1} \text{ kg}^{-1}$. Reproduced from Hood et al. (1997) and Peters et al. (1995).

FIG. 6. Decreases in daily zonal mean Ertel's PV occurring in Feb and Mar of 1990 during a winter when ozone was anomalously low compared to Feb and Mar 1981 when ozone and PV were anomalously high. (See the text.)

ozone and 350-K PV are significantly correlated at northern midlatitudes during the winter season. Although depending significantly on latitude, correlation coefficients are generally somewhat higher than those obtained for ozone tendencies versus EP flux and are significant during more months (November through March) at northern midlatitudes. Since the observed interannual PV variations are dominantly caused by year-to-year differences in local synoptic wave forcing, these correlations allow the possibility of estimating the resulting contribution to column ozone interannual variability and trends. It would then be possible to add this contribution to that of nonlocal planetary wave forcing of the Brewer–Dobson circulation in order to estimate the total contribution of these two dynamical processes to column ozone trends. However, a prerequisite for such an application is that the interannual zonal mean PV variations should be independent of interannual EP flux variations, that is, ozone changes caused by changes in the Brewer–Dobson circulation

should be separate and independent of ozone changes caused by year-to-year differences in local synoptic wave forcing. Evidence that this is the case is shown in Fig. 9, which plots at a series of latitudes the seasonal course of the correlation between 350-K PV and 100-hPa 40°–70°N average eddy heat flux. During the northern winter, correlations are weak and insignificant at all latitudes of interest.

To allow empirical estimates of the contribution of local synoptic wave forcing to column ozone trends at northern midlatitudes, mean sensitivities (mean regression slopes) were determined for the monthly mean TOMS/SBUV ozone response to a change in monthly mean PV on the 350-K surface. To increase the sample number for each latitude, regression slopes were estimated using monthly ozone and 350-K PV data at each of 12 longitudes. Means and 2σ errors were then calculated from the resulting 12 slope estimates. The resulting sensitivities are plotted in Fig. 10 in units of DU/PVU ($1 \text{ PVU} = 10^{-6} \text{ m}^2 \text{ K s}^{-1} \text{ kg}^{-1}$) as a function of latitude for the months of January through March. These sensitivities compare favorably with those estimated previously by Hood et al. (1999) for 330-K PV in February and March.

In the same format as Fig. 4, Fig. 11 shows a comparison of observed zonal mean column ozone at 45°N in February to values predicted by regression relationships between 350-K PV and column ozone at this latitude and for this month. Specifically, the interannual zonal mean ozone anomalies ΔO_3 were calculated from

$$\Delta O_3 = m \Delta PV_{350}, \quad (2)$$

where m is the longitudinally averaged sensitivity (Fig. 10) and ΔPV_{350} is the zonal-mean deviation of the 350-K PV at the same latitude during the same month. The overall correlation coefficient (0.55) is somewhat higher than that obtained using the EP flux data (Fig. 4) and indicates that the regression model can explain approximately 30% of the interannual variability. It should be noted that a regression model analogous to (2) can also be applied to individual longitudes using sensitivities and PV deviations for each longitude; the resulting predicted ozone anomalies can then be averaged over longitude. However, results do not differ significantly from that obtained using (2) with zonally averaged sensitivities and zonal-mean PV deviations.

Finally, since the 350-K PV and 100-hPa 40° to 70°N mean EP fluxes are not significantly correlated, the contributions predicted by (1) and (2) can be combined linearly to yield an estimate for the total contribution of these two dynamical mechanisms to ozone interannual variability and trends. Results are shown in Figs. 12a,b for February and March at 45°N. [Note that the March

FIG. 7. (a) (top) Ozone distribution in Feb 1990 (a low-ozone year), (center) the distribution in Feb 1991 (a high-ozone year), and (bottom) the difference (high-ozone year minus low-ozone year). (b) As in (a) but for 350-K PV.

FIG. 8. Correlation between monthly zonal mean TOMS/SBUV ozone (solid line) and 350-K PV (dashed line) at 45°N for three winter months.

contribution from changes in the Brewer–Dobson circulation are calculated from (1) by integrating over the January to March period.] The correlation coefficients (0.67 and 0.65) are higher than obtained using either

FIG. 9. Seasonal course of the correlation between 350-K zonal mean PV at a series of NH latitudes and 100-hPa eddy heat flux averaged over the 40°–70°N latitude band. The dashed lines indicate minimum correlations for statistical significance at the 95% confidence level.

FIG. 10. Mean sensitivities (in DU/PV units) and 2σ errors for monthly mean TOMS/SBUV ozone to a change in monthly mean 350-K PV. (See the text for further explanation.)

the EP flux data alone [Eq. (1)] or the 350-K PV data alone [Eq. (2)]. Almost half of the interannual variability is explained by the combined regression model. At 50°N the correlation coefficients are as high as 0.70 in February and March. Figure 12b also provides some evidence that the upturn in column ozone amounts that is seen for some months at northern midlatitudes beginning in about 1993 is at least partially simulated by the dynamical transport empirical model. The ozone increase from 1994 to 2002 is approximately simulated. A major feature in the observed ozone time series that is not adequately simulated by the dynamical transport

FIG. 11. Comparison of observed and empirically estimated column ozone at 45°N for the month of Feb when only 350-K PV is considered as a predictor variable. (Same format as in Fig. 4.)

empirical model is the depth of the 1993 ozone minimum. As noted above, this extreme minimum closely follows the Mt. Pinatubo volcanic aerosol injection event originating in June 1991 and is caused mainly by the resulting effects on stratospheric circulation at NH midlatitudes (along with a direct chemical contribution). In addition, the minimum is especially large in 1993 because it occurred at a time when the equatorial wind QBO was in its westerly phase. At such times, an induced meridional circulation anomaly exists characterized by adiabatic ascent in the extratropics and descent in the Tropics (e.g., Plumb and Bell 1982). Since the dynamical transport model does not explicitly include the QBO, it is possible that the increased extratropical ascent at this time combined with direct chemical losses on Pinatubo aerosol are sufficient to explain the depth of the anomaly. A more detailed examination of this minimum should be the subject of future work. It may be possible, for example, to apply a regression model that also includes a QBO term to improve upon the simulations shown in Fig. 12. However, such a modification would be allowed only if it can be shown that the PV and EP flux interannual variations are not significantly correlated with the QBO.

Shown in Fig. 13 are (assumed linear) trends plotted as a function of latitude for several different winter time periods calculated for (i) the observed ozone time series (heavy solid line), (ii) the ozone time series predicted by the empirical model including only forcing by the Brewer–Dobson circulation (short dashed line), (iii) that predicted by the model including only local synoptic wave forcing (long dashed line), and (iv) that predicted by the model including both the Brewer–Dobson circulation forcing and local synoptic wave forcing (thin solid line). Figure 13a shows results for January; Fig. 13b shows results for February, Fig. 13c shows results for March, and Fig. 13d shows results for the average of January, February, and March. These

FIG. 12. (a) Comparison of observed and empirically estimated column ozone at 45°N for the month of Feb when both EP flux averaged over the 40°–70°N latitude band and 350-K PV are considered as predictor variables. (Same format as in Figs. 4 and 11.) (b) As in (a) but for the month of Mar.

trends are calculated using the same standard multiple regression statistical model (including QBO and solar cycle terms) that was employed in the production of Fig. 1. In January, the model-predicted trends account for only a fraction of the observed trends at most latitudes. The largest contribution is found at 50°N where the model accounts for about 25% of the trend during this month. In February and March, the model-predicted trends account for a larger fraction of the observed trend. At 50°N the total model-predicted trend accounts for about 50% of the observed trend in February and ~60% of the observed trend in March (Figs. 13b,c). The trend contributions shown in Fig. 13 are comparable to the percent of variance (~50%) explained by the combined regression model as seen in Fig. 12. Both interannual and long-term variability components are partially simulated by the model. The residual trend not explained by the model could be attributed to increasing chlorine loading during the 1980s, incompleteness of the dynamical transport regression model (see section 5), or both.

As discussed in more detail in the introduction, local

FIG. 13. Linear column ozone trends for (a) Jan, (b) Feb, (c) Mar, and (d) the Jan, Feb, and Mar mean calculated using a standard multiple regression statistical analysis for both observed TOMS/SBUV ozone and three empirical model-predicted time series. The filled circles indicate the observed linear trend coefficients and 2σ errors as a function of latitude. The open circles indicate the trend coefficients for the model time series when both EP flux and 350-K PV are considered as predictor variables. The long-dashed lines indicate trend coefficients for the model time series when only 350-K PV is considered. The short-dashed lines indicate the same coefficients for model time series when only EP flux is considered as a predictor variable.

synoptic wave forcing does not generally change the absolute abundance of ozone in the stratosphere but, instead, consists primarily of a rearrangement of ozone such that increases in the ozone column in one area are compensated elsewhere. Some evidence that this is the case is shown in Fig. 14. Plotted here are February mean column ozone and 350-K PV at two latitudes (45° and 10°N) and at a single longitude (215°E). It is seen that decreases of ozone and PV at 45°N are often accompanied by increases at 10°N . This suggests that local wave forcing events in the subtropics that inject low PV air into the midlatitude lowermost stratosphere are often accompanied by equatorward-breaking waves that transport high PV air from the midlatitude stratosphere into the tropical upper troposphere. A similar, but weaker, inverse correlation can also be found using zonal mean data. Interestingly, Fig. 1 shows a statistically significant positive ozone trend in February near a latitude of 10°N with an amplitude of about $+1.7\%$ per decade. A possible interpretation is that this positive

trend is a consequence of increased equatorward breaking waves at this latitude in the latter part of the time record. A long-term decrease in EP flux absorption could also produce an ozone increase at low latitudes relative to high latitudes because of the overturning Brewer–Dobson circulation (see, e.g., Fig. 5 of Fusco and Salby 1999). Therefore, it is also possible that this positive trend in the Tropics in February is a consequence of both the EP flux decrease and an increase in equatorward-breaking waves.

5. Conclusions and discussion

In this paper, an attempt has been made to apply empirical (correlative and regression) methods in order to estimate the contribution of two dynamical processes to column ozone interannual variability at northern midlatitudes. Both nonlocal EP flux variations (implying variations in the Brewer–Dobson circulation) and local PV variations (implying local synoptic wave forc-

FIG. 14. Time series of the February mean TOMS/SBUV ozone (solid line) and 350-K PV (dashed line) at a longitude of 215°E for (top) 45°N and (bottom) 10°N. (See the text.)

ing) were found to contribute significantly to observed trends and interannual variability. As seen in Fig. 13, the former process is estimated to contribute 18%–25% to observed maximum negative ozone trends in February near 40° to 50°N, while the latter process is estimated to contribute 27%–31% to these trends. Northern Hemisphere EP flux variations and local midlatitude PV variations are not statistically correlated with one another, so it has been assumed here that their contributions can be linearly summed. Therefore, the total contribution of these processes to northern midlatitude ozone trends in winter is estimated to be approximately 50%. This empirical estimate is in reasonable agreement with the chemical transport model experiments of Hadjinicolaou et al. (2002). As seen most clearly in Fig. 12b, the combined empirical model is also able to simulate approximately the change in trend that has occurred since 1993–95 for some months at some latitudes. As reviewed in the introduction, decreases in EP flux wave forcing and increases in the frequency of anticyclonic, poleward-breaking Rossby waves that lead to PV decreases at northern midlatitudes in winter are both consistent with observed long-term net increases

in polar vortex strength and longevity as well as increases in the AO and NAO indices.

Although a significant portion of the remaining trend is undoubtedly caused by direct chemical losses, it is also possible that the empirical dynamical model adopted here is incomplete so that the dynamical contribution to ozone trends has been underestimated. In particular, while PV accounts for total ozone variations forced by horizontal transport, it does not account adequately for variations induced by vertical transport. Vertical transport typically accompanies horizontal transport during synoptic wave events, especially those that lead to extreme ozone minima. Specifically, horizontally transported air masses are often lifted adiabatically and cool as they flow over a local tropospheric high pressure system. This lifting and expansion process implies a divergence of the flow so that potential temperature surface converge in pressure space and the total ozone column decreases because the ozone-rich lower stratosphere contributes a smaller fraction of the total column. It is therefore possible that future empirical models should include adiabatic temperature changes near the 30-hPa level where the best correlation of temperature decreases associated with extreme ozone minima are observed (e.g., Hood et al. 2001).

The cause(s), natural or anthropogenic, of observed decadal changes in stratospheric circulation remain unclear. Observed long-term circulation changes in the Southern Hemisphere may have been produced by polar ozone depletion in the Antarctic spring (Thompson and Solomon 2002; Gillett and Thompson 2003) and/or increased greenhouse gas (GHG) forcing (Marshall et al. 2004). A similar influence of ozone depletion in the NH, in the direction of enhancing the AO and NAO indices, is also expected; however, the reduced amplitude of Arctic ozone depletion makes detection of this influence more difficult in the NH against the background of natural variability (e.g., Graf et al. 1998; Gillett et al. 2002). Several authors have reported numerical model simulations indicating that increased GHG emissions, which heat the tropical upper troposphere and cool the polar lower stratosphere in late fall and early winter, could produce a long-term strengthening of the northern polar vortex (e.g., Perlwitz and Graf 1995; Kodera et al. 1996; Shindell et al. 1998, 1999, 2001; Perlwitz et al. 2000). In addition, long-term trends in the polar vortex and tropospheric AO could be enhanced further by GHG-forced decreases in the tropospheric meridional temperature gradient (Stenchikov et al. 2002). The latter is caused by polar amplification of warming resulting from albedo–snow–sea effects and leads to a decrease in wave activity flux into the strato-

sphere, allowing the polar vortex to increase in strength. On the other hand, other model simulations of the effect of *future* increases in GHG forcing predict an increase in overall generation of planetary waves leading to a weaker NH polar vortex (for a review, see Austin et al. (2003)). Therefore, it must be concluded that the origin of observed changes in stratospheric circulation over the past few decades is not yet well understood.

Acknowledgments. The TOMS/SBUV ozone processing team (led by R. Stolarski and R. McPeters) at the NASA Goddard Space Flight Center provided the column ozone data used in this work. The NCEP–NCAR reanalysis data team at the NCEP Climate prediction Center provided the data used to calculate EP fluxes and 350-K potential vorticity. Comments on an earlier version of the manuscript by W. J. Randel and three anonymous reviewers are appreciated. This work was supported by a grant from the NASA Atmospheric Chemistry Modeling and Analysis Program.

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