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The total ozone field separated into meteorological regimes. Part II: Northern Hemisphere mid-latitude total ozone trends

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Abstract

Previous studies have presented clear evidence that the Northern Hemisphere total ozone field can be separated into distinct regimes (tropical, midlatitude, polar, and arctic) the boundaries of which are associated with the subtropical and polar upper troposphere fronts,and in the winter, the polar vortex. This paper presents a study of total ozone variability within these regimes, from 1979–2003, using data from the TOMS instruments. The change in ozone within each regime for the period January 1979–May 1991, a period of rapid total ozone change, was studied in detail. Previous studies had observed a zonal linear trend of −3.15% per decade for the latitude band 25°–60° N. When the ozone field is separated by regime, smaller linear trends (−2.5%, −2.2%, and −1.9% per decade for the polar, midlatitude, and tropical regimes, respectively) are observed. The trend in the zonal total ozone is larger because the relative areas of the regimes also changed over this time period. The relative area of the polar regime decreased by about 15%; the tropical regime increased by about 10% over this period. The changes in the relative areas can be associated with a change of the mean latitude of the sub-tropical and polar fronts within the latitude interval 25° to 60° N. Over the period from January 1979–May 1991, both fronts moved northward by 1.1±0.2 degrees per decade. Over the entire period of the study the subtropical front moved northward at a rate of 1.1±0.1 degree per decade, while the polar front moved by only 0.5±0.1 degrees per decade.

1 Introduction

In a previous paper, Hudson et al. (2003), presented clear evidence that the Northern Hemisphere total ozone field can be separated into distinct regimes, the boundaries of which are associated with the subtropical and polar upper troposphere fronts, and in the winter, the polar vortex. These regimes were defined as: (1) the arctic regime – within the polar vortex, (2) the polar regime – between the polar front and the polar vortex, or when the latter is not present, the pole, (3) the midlatitude regime – between the subtropical and polar fronts, and (4) the tropical regime – between the equator and the subtropical front. The subtropical and polar fronts are associated with the subtropical and polar jet streams, and have mean latitudes of about 30° and 60° N, respectively. It should be noted that the mean position of the subtropical front as defined here, is not the same as the position of the maximum of the mean westerly tropospheric zonal winds, which is also sometimes referred to as the subtropical front (Bluestein, 1993). The positions of the subtropical and polar fronts defined in Hudson et al. (2003) vary on a daily basis as the Rossby waves meander about their mean latitudes. Finally, these fronts should not be confused with the cold and warm fronts associated with cyclonic flow close to the surface. Hudson et al. (2003) showed, using rawinsonde measurements, that the tropical, midlatitude, and polar regimes were identified with distinct tropopause heights over a large latitude range. In addition, in any month, a unique total ozone value and a distinct ozone profile shape could be assigned to each of these three regimes.

The definition of “mid-latitude” used in previous studies has varied. WMO (1999) and Staehelin et al. (2001) used the interval from 25° to 60° N, while Fioletov et al. (2002) and WMO (2003) used the interval from 35° to 60° N. In this paper we have chosen the latitude range from 25° to 60° N. Previous studies of the variability of total ozone and of the ozone profiles at midlatitudes (Harris et al., 1997, 1998; WMO, 1999; Staehelin et al., 2001) have centered on zonal averages over specific latitude bands. However, because the mean total ozone and the ozone profile are almost constant within a regime, a zonal average will depend on the relative areas of the respective regimes within the latitude range of the zone. Thus, for example, one can envision a long-term change in the zonal mean total ozone that is brought about by a long-term change in the relative areas of the regimes alone.

The total ozone archived data sets used in this paper are the Version 8 level-3 hierarchical data format product from the TOMS (Total Ozone Mapping Spectrometer) instruments (McPeters et al., 1996). The level-3 data set is an average ozone value on a 1-degree latitude by 1.25 degrees longitude grid. At this time three data sets are available, those from the Nimbus-7 satellite (November 1978–May 1993), the Meteor-3 satellite (August 1992 to December 1993), and the Earth Probe satellite, (September 1996–December 2003), leaving a gap in the data record between December 1994 and August 1996. Although the Nimbus-7 and Meteor-3 time periods overlap, Nimbus-7 data was used whenever available. The unit used within this paper for the total (column) ozone is the Dobson Unit (1 DU=1 m atm cm, or 2.69 10^{16} molecules cm^{-2})

This paper examines the long-term change of ozone between 1979 and 2003 within the tropical, midlatitude, polar, and arctic meteorological regimes as defined above. It is divided into four sections. In Sect. 2, the method used to define the boundaries between the regimes is presented. The results of the analysis are given in Sect. 3. The summary and conclusions of the paper are given in Sect. 4.

2 The regime boundaries

In the lower stratosphere, the photochemical lifetime of ozone is large (several weeks; Brasseur and Solomon, 1984) compared to the timescale of transport (∼1 day) (Salby and Callaghan, 1993). It is for this reason that ozone in this region, as well as total ozone, is considered to be a dynamical tracer on the timescale of a few days (Wohltmann et al., 2005).

For every day that TOMS data was available, total ozone values for the subtropical and polar boundaries were derived using the method described in Hudson et al. (2003). A contour program for these two boundary values was then used to obtain the positions of the fronts on the total ozone field for that day. This works well for any given day at the synoptic scale. The polar vortex boundary was obtained from the position of the maximum gradient in potential vorticity (PV) on the 550 K isentropic surface. This dataset was obtained from the NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) re-analysis (Kalnay et al., 1996). Figure 1a shows the TOMS total ozone field for 11 March 1990, in addition to the ozone contours representing the subtropical and polar boundaries, and the arctic boundary obtained from the PV field for this day. Figure 1b shows the one-degree zonally averaged total ozone within each regime. As noted in Hudson et al. (2003) and seen in Fig. 1b, each regime has a distinct range of ozone values that do not overlap. However, the total ozone within each regime shows that there is a small dependence (relative to the zonal data) of total ozone with latitude. This latitude dependence is greatest in the winter months, and is at a minimum in the summer months. Because trends in total ozone are of the order of few percent, small errors in the determination on the location of the upper-level trends could introduce relatively large errors in the determination of long term area trends. For that reason, the latitude dependence of total ozone must be taken into account when determining the location of the upper-level fronts for trend analysis. It should be stressed, however, that the total ozone trends within each regime are not sensitive to small errors in the determination of the exact locations of the upper-level fronts.

A new method was developed in order to allow the boundaries to take into account any latitude dependence. The daily boundary values from Hudson et al. (2003) were used as a first guess to separate the total ozone into regimes. Next, one-degree zonal averages were calculated for each regime, as seen in Fig. 1b. New subtropical boundary values were computed by taking the average of the tropical and midlatitude total ozone at each latitude where they overlapped. Similarly, the polar boundary was calculated by taking the average of the midlatitude and polar total ozone. The new boundary values are displayed as the black stars on Fig. 1b. The total ozone field was then separated using these new latitudinally dependent boundaries. The process was then repeated with the new values. The relative area of a regime is the area of a regime divided by the total area between 25° and 60° N. Convergence was reached when the change in the relative area of each regime, from one iteration to the next, was less than 5%. The final boundaries, after iteration, are plotted on Fig. 1c. It must be stressed that these ozone boundaries were obtained on a daily basis.

Using the daily values, the mean monthly relative area was obtained for each regime, for the latitude interval 25°–60° N. The standard deviation and persistence were then calculated for each month by methods outlined in Wilks (1995). From these two values the error of the mean was estimated. Table 1 gives the mean monthly relative area, the error of the mean, and the persistence in days for the tropical, midlatitude, and polar regimes, for the period 1979–2003. The persistence is close to three days, typical of meteorological parameters.

3 Results

In the following analysis two different monthly means for the regimes are presented. First, all of the data between 25° and 60° N are used, corresponding to the zonal average between 25° and 60° N. If a pixel contains a boundary, its total ozone value and area are halved and assigned to the two regimes separated by the boundary. This data set will be labeled as the 'zero degree' data set. Next, the regions within one degree latitude and longitude of the boundaries have been excluded from the area weighting. This data set will be labeled as the one degree data set. For the linear trend analyses discussed later in the paper it is necessary to obtain the error of the mean for each data point. First, the error of the mean was estimated using the method described above. Figure 2 shows the derived error of the mean for the tropical, midlatitude and polar regimes, calculated as a percentage of the monthly mean. Linear trends will be presented only for the period from January 1979 to May 1991, the period when the chlorine loading in the stratosphere varies almost linearly with time.

Figure 3 presents the area-weighted monthly mean total ozone values obtained from the TOMS data set, for the period 1979–2003 over the latitude range 25°–60° N. The monthly means shown in Fig. 3 are derived from the zero degree data set. Figure 3a shows the monthly mean total ozone values obtained without separation into the regimes (hereinafter referred to as the "zonal data"), while Figs. 3b–e show data for the tropical, midlatitude, polar, and arctic regimes, respectively.

As expected, the monthly mean total ozone values have a strong seasonal dependence. In addition, the arctic is not seen below 60° N from about May to October. In Figs. 4a–e we have plotted the data shown in Fig. 3 after the seasonal component has been removed. This was done by subtracting the monthly mean climatology from 1979–2003. In previous studies a linear fit has been applied to the deseasonalized data between January 1979 and May 1991 (WMO, 1999; Staehelin et al., 2001). A linear fit was applied in a similar manner to the data shown in Fig. 4 in order to calculate decadal trends. The mean values for each regime and the zonal data, in addition to their trends and trend errors for the zero degree data set can be found in Table 2. The same results for the one degree data set can be found in Table 3. Within the experimental error there is no difference between the trends shown in the two tables. Looking at both Tables, it is apparent that the trend in each regime is not duplicated, nor do they match the trend in the zonal data. The trend in DU per decade for the zonal data corresponds to a percentage trend of −3.2±0.6 per decade, in excellent agreement with previous estimates (WMO, 1999; Staehelin et al., 2001). It should also be noted that not all of the fluctuations seen in the deseasonalized zonal data can be found in the data for each regime. The two strong downward fluctuations seen in the zonal data in 1985 and 1988 can be seen in the tropical regime, but not in the midlatitude or polar regime. Similarly the downward fluctuation seen in 1997 is only found in the polar regime.

The error in the trend was calculated using a Monte Carlo analysis. The error of the mean was used to obtain a normal distribution for each month. Using these distributions, 1000 new total ozone time series were created at random, and their slopes calculated. The distribution of these slopes was found to have a normal distribution and the errors shown in Tables 2 and 3 represent the errors in the trends at a 95% (2σ) confidence limit. All total ozone trends in Table 2, except that of the arctic, are statistically significant.

The trends in each of the regimes shown in Table 2 are always less than the trend for the zonal data. In order to understand this apparent anomaly we need to examine the equation for total ozone mass. Let the areas of the tropical, midlatitude, polar, and arctic regimes between 25° and 60° N be A_T, A_M, A_P, and A_A, respectively. The corresponding mean area-weighted total ozone values are defined as Ω_T, Ω_M, Ω_P, and Ω_A. Noting that Ω is the column ozone per unit area, equivalent to column mass per unit area, the total mass of ozone between 25° and 60° N, M, can be written as:

$$M = cA\Omega_O = cA_T\Omega_T + cA_M\Omega_M + cA_P\Omega_P + cA_A\Omega_A \tag{1}$$

In this equation, A is the total area between 25° and 60° N, Ω_O is the mean of the zonal data, and c is a constant of proportionality. Dividing both sides of the equation by cA we get

$$\Omega_O = R_T\Omega_T + R_M\Omega_M + R_P\Omega_P + R_A\Omega_A \tag{2}$$

Here, the R's are defined as the relative areas of the regimes. We can now examine the importance of each term on the right-hand side of Eq. (2) to the calculation of zonal total ozone.

The monthly mean relative areas derived from the TOMS data for the tropical, midlatitude, polar, and arctic regimes, between 25° and 60° N, for the period 1979–2003, are shown in Figs. 5a–d, respectively. The zero degree data set was used for all relative area analyses. The relative area for the tropical regime shows a clear increase between 1979 and 1992, and appears to level off after 1996. The relative areas of the polar and midlatitude regimes show a clear decrease between 1979 and 1992, followed also by a leveling off. The results for the arctic show almost no trend, however data for this regime is only available in the winter months. Figures 6a–d show the same data after the seasonal component has been removed. The solid lines in Fig. 6 are a linear fit to the data between January 1979 and May 1991. The mean values, trends and trend errors for each regime can be found in Table 4. The error in the trend was obtained using a Monte Carlo analysis similar to that described above for total ozone. The regimes in which a large change in the relative area is observed are the polar and tropical regimes. Between January 1979 and May 1991, the relative area of the polar regime decreased by about 15%, while that of the tropical regime increased by about 10%.

Figure 7 presents the contribution (in DU) of each term on the right hand side of Eq. (2). It should be noted that the contribution is positive for the tropical regime. This reflects the fact that the area of the tropical regime is expanding at a faster rate than the rate of decay of its mean total ozone. The contribution of the arctic regime over this period is only 0.32 DU and shows little change with time. From January 1979 to May 1991, the polar, midlatitude and arctic regimes show net losses of 12.3, 6.2 and 0.32 DU respectively. The tropical regime shows a net gain of 8.4. The sum of these changes is a loss of 10.4 DU which agrees with the loss in the zonal ozone data of 10.8 DU over the same time period.

4 Summary and conclusions

A major conclusion of this paper is that the downward trend in total ozone of 3.2% per decade over the period 1979 to 1991, for the midlatitude zone from 25°–60° N, is due to a combination of Eq. (1) a net reduction of total ozone for each of the three regimes defined by Hudson et al. (2003), and Eq. (2) a change in the relative weighting among the regimes due to a net movement of the polar and subtropical fronts northward. Previous interpretations (Staehelin et al., 2001; Solomon et al., 1996, 1998) have concluded that this zonal total ozone trend was the result of increased homogeneous and heterogeneous chemistry in the stratosphere. However, Fusco and Salby (1999) and Graf et al. (1998) have argued that long-term, dynamical changes could be partly or largely responsible for the ozone trend. Hood et al. (1999) estimated that up to 40% of the observed mid-latitude trend could be due to changes in stratospheric dynamics. Statistical analyses have also shown that the Northern Hemisphere ozone trends are highly correlated with modes of variability of the atmospheric circulation, such as the Arctic Oscillation, accounting for about 70–80% of the long-term ozone decline (Krzyscin et al., 2001). Hadjinicolaou et al. (2002) examined the dynamically-driven long-term trend in total ozone using a three dimensional chemical transport model, the transport being derived from the European Centre for Medium-Range Weather Forecasts analysis. The conclusion of their paper is that over the period 1979 to 1998, the dynamically driven trend accounted for at least half of the observed Northern Hemisphere mid-latitude trend in total ozone averaged from December to February. Salby and Callaghan (2002) found that most (80%) of the changes in total ozone during the 1980s and 1990s were coherent with anomalous forcing of the upward Eliassen-Palm flux from the troposphere and the quasi-biennial oscillation. The remaining 20% was almost entirely accounted for by including aerosol and chlorine forcing. Koch et al. (2002) conclude that in the lower stratosphere, dynamical transport processes dominate the day-to-day as well as the interannual variability of mid-latitude ozone.

If we ascribe that portion of the trend arising from changes in the total ozone within each regime to ‘chemistry’, and that portion arising from the movement of the fronts to ‘dynamics’, then we can make a crude estimate of the relative role of the two. Equation (2) can be differentiated with respect to time to yield:

$$\frac{d\Omega}{dt}=\frac{d\Omega_T}{dt}R_T+\frac{dR_T}{dt}\Omega_T+\frac{d\Omega_M}{dt}R_M+\frac{dR_M}{dt}\Omega_M+\frac{d\Omega_P}{dt}R_P+\frac{dR_P}{dt}\Omega_P+\frac{d\Omega_A}{dt}R_A+\frac{dR_A}{dt}\Omega_A \quad (3)$$

The variation of total ozone with time for each regime is represented by two terms, one in which the total ozone is fixed and the area changes (dynamics), and the other in which the area remains constant but the total ozone value changes (chemistry). The results for each of the terms shown in Eq. (3) are given in Table 5. The mean values and slopes used to calculate each term in Eq. (3) can be found in Tables 2 and 4. The sum of the terms when the area remains constant is −7.23 DU and the sum when the total ozone remains constant is −3.18 DU. The total is −10.41 DU, very close to the zonal trend of −10.84. Thus, from this analysis, we would conclude that about 30% of the observed total ozone trend between January 1979 and May 1991 is due to dynamics, and 70% due to chemistry. However, this analysis does not take into account the possibility that some of the dynamical forcing of the frontal movement might arise from changes in the total ozone within the regimes.

The relative areas discussed above can be used to calculate the mean latitude of the subtropical and polar fronts for the latitude range from 25° to 60° N. A linear fit of

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the resulting mean latitudes from 1979 to 2003 yields a mean latitude shift northward of about 1.0 degree per decade for the subtropical front, and 0.5 degrees per decade for the polar front. It should be noted that significant portions of the polar regime, and therefore the polar front, are located above 60 N at certain times of the year, and parts of the subtropical front are frequently found above 60° N in the summer months. Hence these estimates cannot be representative of the entire front. When the period of study was limited to January 1979 to May 1991, then the trend for the subtropical front was 1.1 degrees per decade and the polar front was 1.2 degrees per decade. In a recent article, Fu et al. (2006) present an analysis of global measurements of atmospheric temperature based on satellite-borne microwave sounding unit (MSU) data. They conclude that the jet streams moved northward approximately 1 degree over the period from 1979 to 2005, in essential agreement with our findings.

As shown above, the change in the zonal total ozone at mid-latitudes (25°–60° N) is a combination of changes in total ozone within each regime, and changes in the relative areas of the regimes brought about by a net northward movement of the subtropical and polar fronts. There is considerable interest in how the mean mid-latitude total ozone will change in the future as the amount of chlorine compounds in the stratosphere decreases as a result of the Montreal protocol. The most important factor in making an accurate estimate of when and how mid-latitude total ozone will return to a pre-1979 value is the understanding of the mechanisms responsible for the movement of the ozone fronts.

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Table 1. Mean relative area, error of the mean, and persistence

Month	Tropical Regime Mean area	Error of the mean	Persistence (Days)	Midlatitude Regime Mean area	Error of the mean	Persistence (Days)	Polar Regime Mean area	Error of the mean	Persistence (Days)
JAN	0.39	0.017	2.8	0.43	0.021	3.8	0.16	0.014	4.5
FEB	0.37	0.017	3.4	0.43	0.02	3.9	0.17	0.012	3.4
MAR	0.35	0.016	3	0.45	0.02	3.8	0.18	0.016	4.6
APR	0.32	0.017	3.4	0.48	0.019	4.1	0.19	0.014	4
MAY	0.28	0.016	3.5	0.51	0.021	4	0.21	0.012	3.4
JUN	0.32	0.018	4.1	0.5	0.019	4.4	0.18	0.011	3.4
JUL	0.34	0.017	3.1	0.52	0.02	3.6	0.14	0.011	3.8
AUG	0.35	0.019	3.3	0.55	0.018	3.2	0.11	0.007	2.5
SEP	0.4	0.023	3.4	0.49	0.023	3.6	0.11	0.008	2.6
OCT	0.42	0.018	2.5	0.44	0.019	2.9	0.11	0.007	2.7
NOV	0.43	0.019	2.9	0.42	0.019	3.1	0.12	0.008	3.4
DEC	0.39	0.017	2.8	0.43	0.018	3	0.14	0.014	4.5

Table 2. Mean total ozone values and trends for zero-degree data set

Regime	Mean (DU)	Trend per decade (DU)[a]	Trend per decade (percent)[a]
Tropical	285.6	−5.3±1.0	−1.9±0.4
Midlatitude	331.5	−7.6±1.4	−2.2±0.4
Polar	394.34	−10.6±3.1	−2.5±0.7
Arctic	215.0	−5.2±9.0	−1.5±1.2
Zonal	325.9	−10.8±2.0	−3.2±0.6

[a] All trends calculated from January 1979 to May 1991.

Table 3. Mean total ozone values and trends for one-degree data set

Regime	Mean (DU)	Trend per decade (DU)[a]	Trend per decade (percent)[a]
Tropical	279.6	−4.8±1.0	−1.8±0.4
Midlatitude	333.3	−6.9±1.9	−2.0±0.4
Polar	404.4	−10.1±3.3	−2.3±0.8
Arctic	194.6	−6.3±11.0	−1.8±2.6

[a] All trends calculated from January 1979 to May 1991

Table 4. Mean relative areas and trends

Regime	Mean	Trend per decade (x10^{-3})[a]
Tropical	0.345	3.6±0.9
Midlatitude	0.481	−0.9±1.0
Polar	0.158	−2.6±0.6
Arctic	0.0153	−0.0009±0.24

[a] All trends calculated from January 1979 to May 1991

Table 5. Terms in Eq. (3)

Regime	$\Omega dA/dt$[a]	$Ad\Omega/dt$[a]
Tropical	10.34	−1.82
Midlatitude	−3.11	−3.65
Polar	−10.41	−1.68
Arctic	−0.002	−0.08
Total	−3.18	−7.23

[a] All trends calculated from January 1979 to May 1991

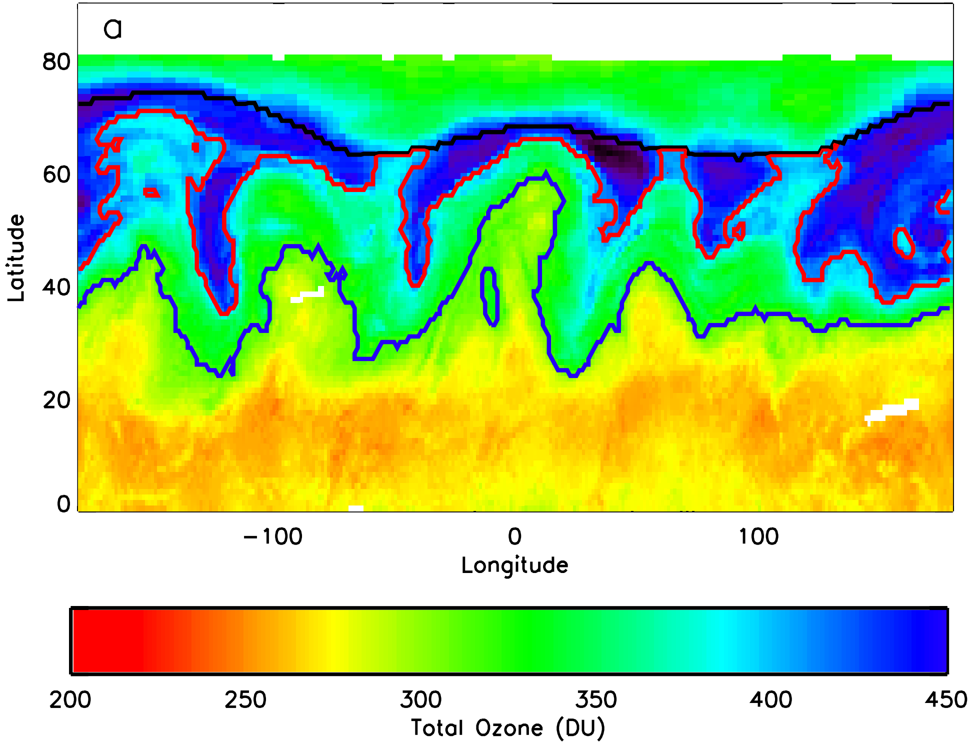

Fig. 1. **(a)** TOMS total ozone field for 11 March 1990. The subtropical (blue line), polar (red line), and polar vortex (black line) boundaries derived by Hudson et al. (2003) are also plotted.

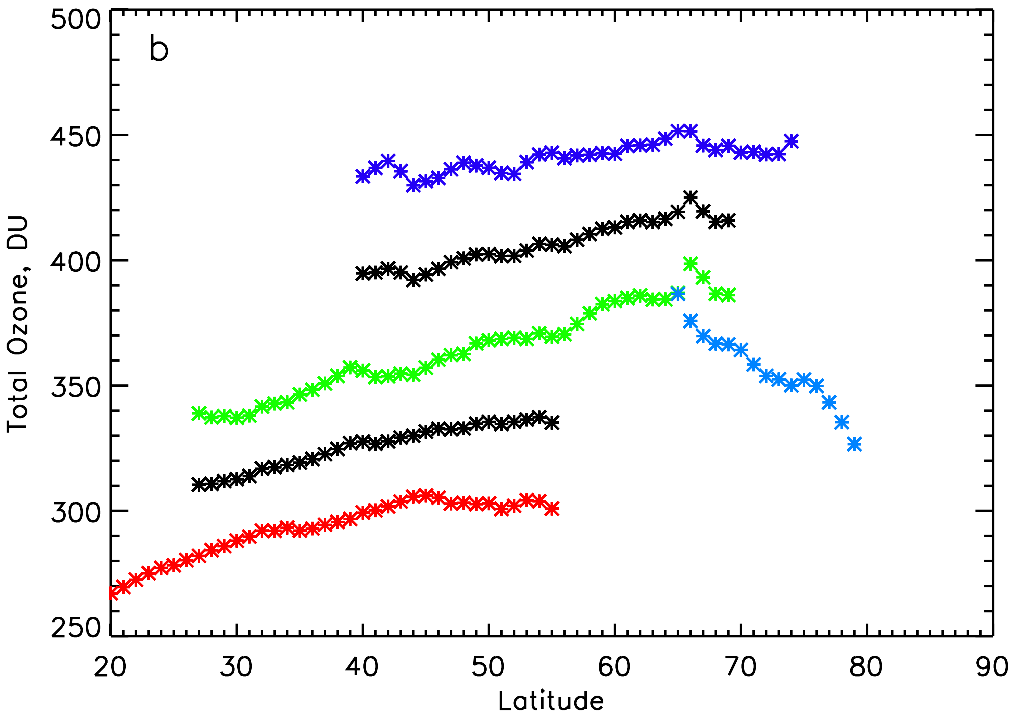

Fig. 1. (b) The one-degree zonally averaged total ozone within the tropical (red stars), midlatitude (green stars), polar (blue stars), and arctic (light blue stars) regimes. The new boundary values calculated by taking the average of neighboring regimes are shown as black stars.

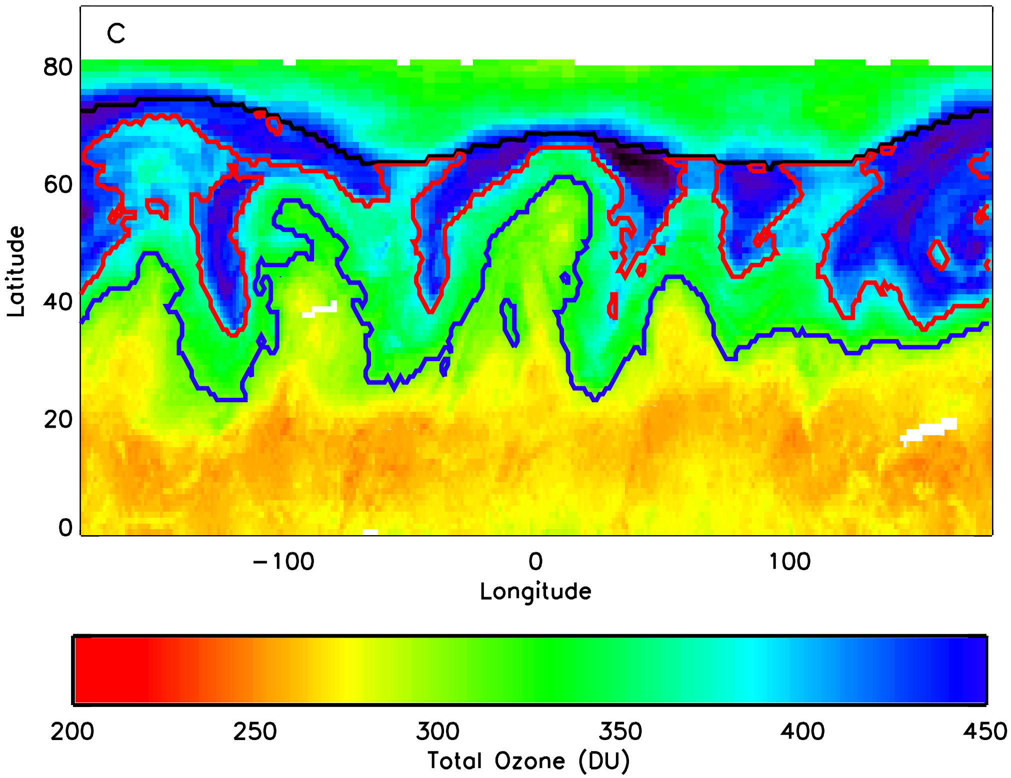

Fig. 1. (c) Same as (a), except with the boundaries after the iteration procedure described in the text.

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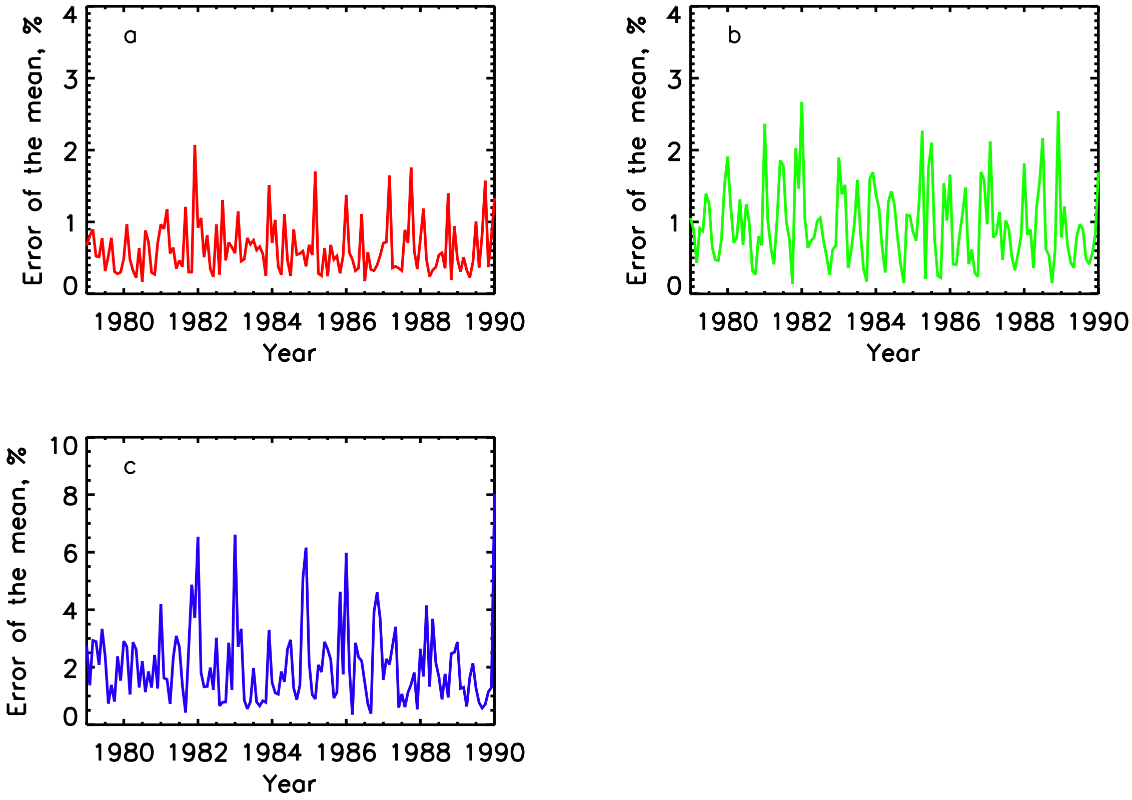

Fig. 2. The derived error of the mean for the **(a)** tropical, **(b)** midlatitude, and **(c)** polar regimes, calculated as a percentage of the monthly mean for 25°–60° N, 1980–1990.

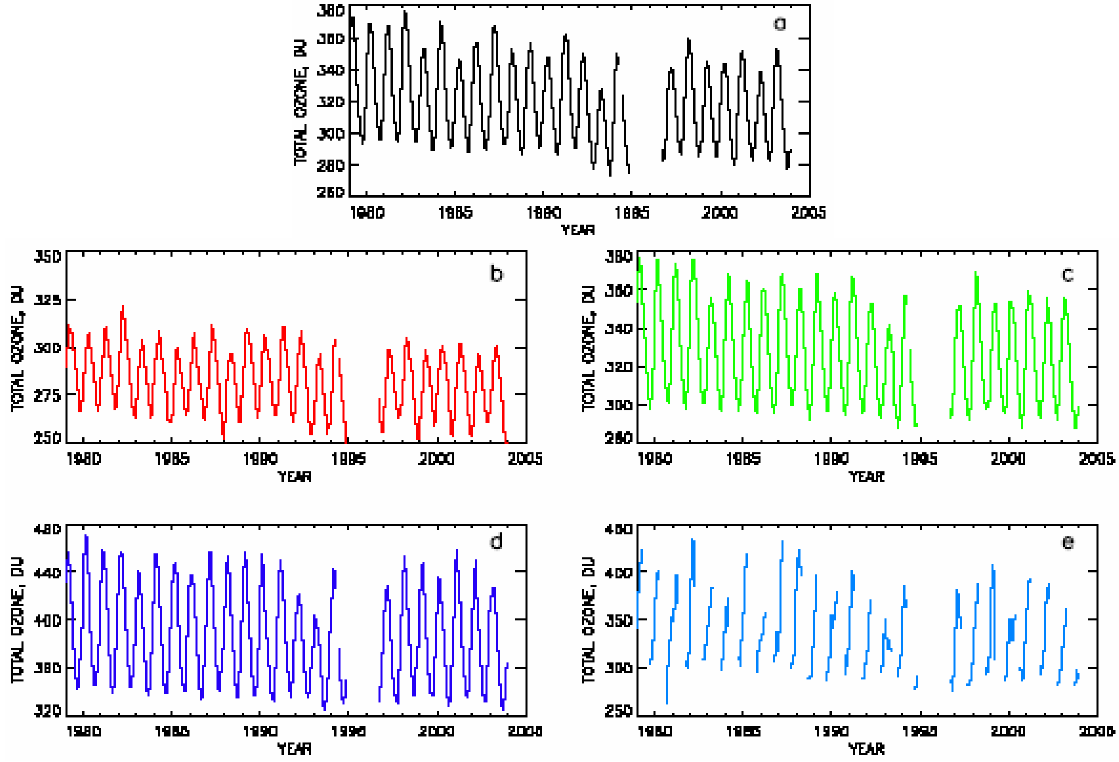

Fig. 3. Monthly mean total ozone values for the **(a)** zonal data, **(b)** tropical regime,**(c)** mid-latitude regime, **(d)** polar regime, and **(e)** arctic regime for 25°–60° N, 1979–2003. Note the different scales.

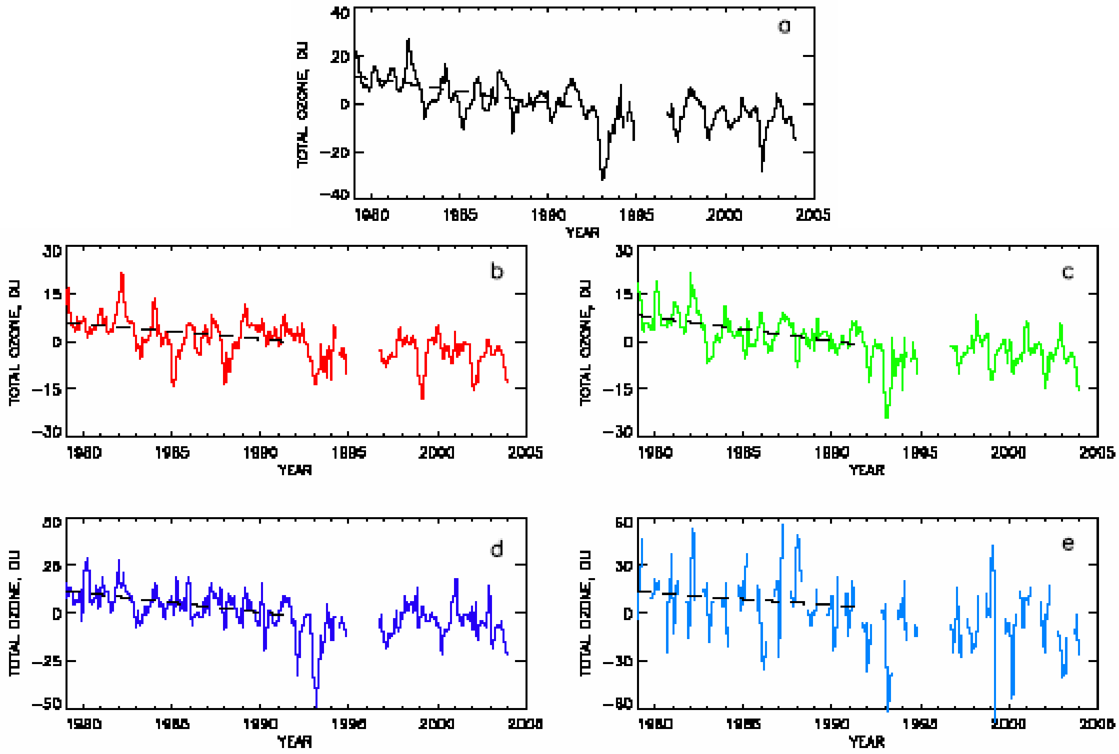

Fig. 4. Same as Fig. 3, except the monthly climatology has been removed. The black dashed line is the linear fit to the data between January 1979–May 1991. Note the different scales.

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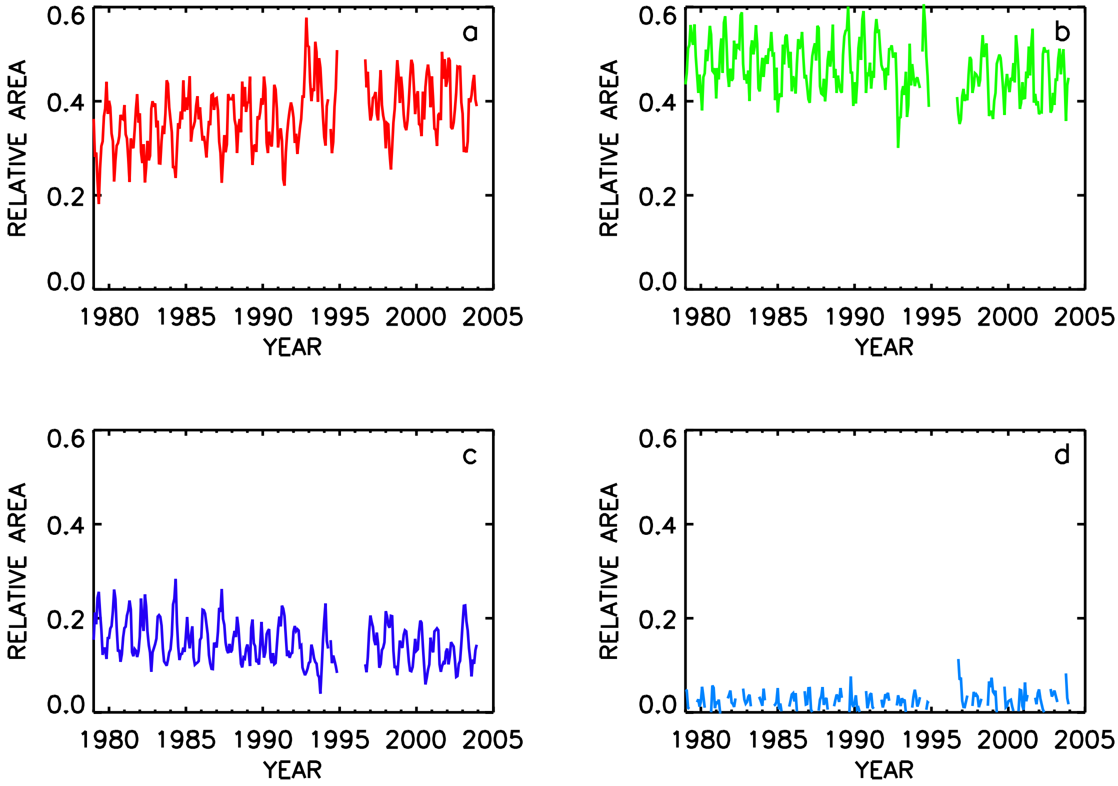

Fig. 5. Monthly mean relative areas of the **(a)** tropical regime, **(b)** midlatitude regime, **(c)** polar regime, and **(d)** arctic regime for 25° –60° N, 1979–2003.

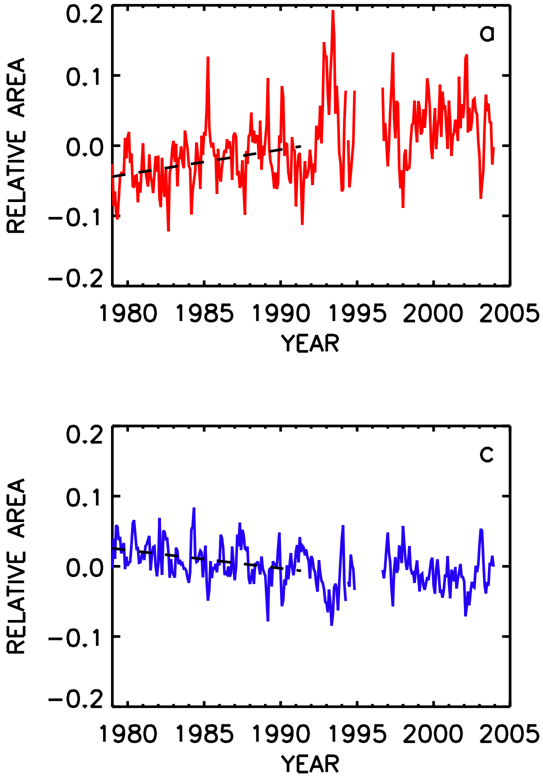

Fig. 6. Same as Fig. 5, except the monthly climatology has been removed. The black dashed line is the linear fit to the data between January 1979–May 1991.

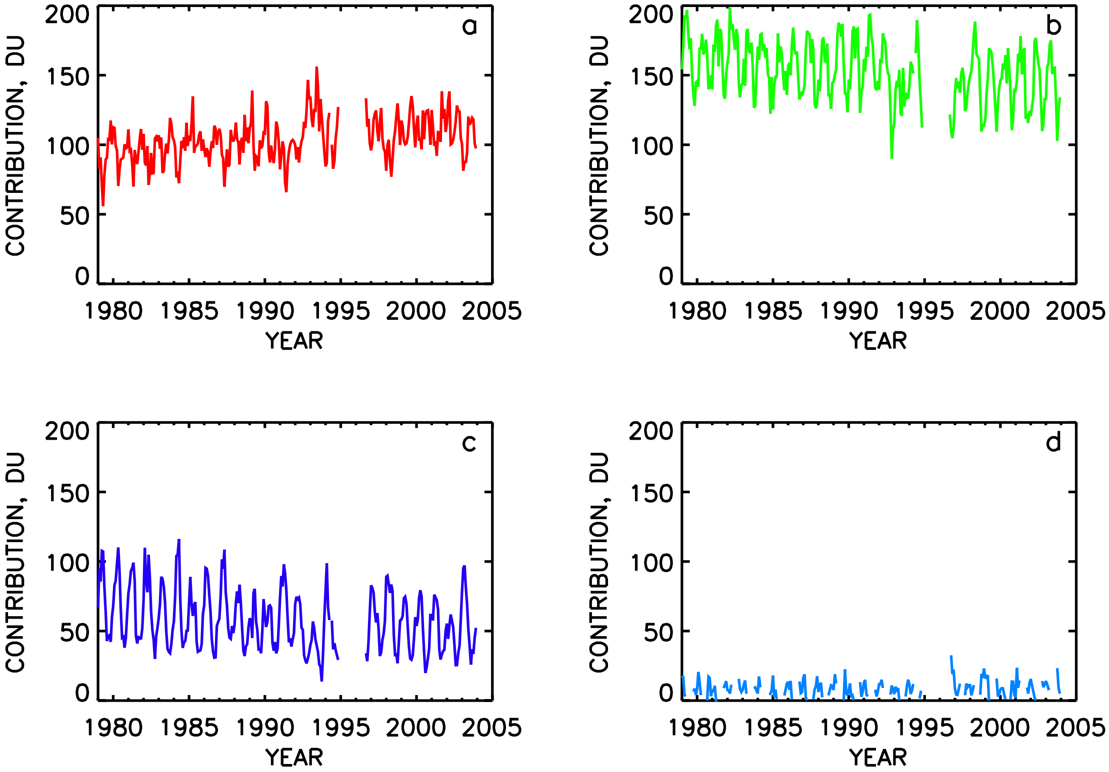

Fig. 7. Monthly mean mass contribution (in DU) by the **(a)** tropical regime, **(b)** midlatitude regime, **(c)** polar regime, and **(d)** arctic regime for 25°–60° N, 1979–2003.