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Summertime total ozone variations over middle and polar latitudes

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[1] The statistical relationship between springtime and summertime ozone over middle and polar latitudes is analyzed using zonally averaged total ozone data. Short-term variations in springtime midlatitude ozone demonstrate only a modest correlation with springtime polar ozone variations. However by early summer, ozone variations throughout the extratropics are highly correlated. Analysis of correlation functions indicates that springtime midlatitude ozone, not polar ozone, is the best predictor for summertime polar ozone. Long-term total ozone trends at middle and high latitudes are also different for spring and nearly identical for summer. About 39% of the observed southern midlatitude ozone decline in December can be attributed to the polar ozone depletion up to November. In the Northern Hemisphere, the corresponding contribution is about 15%, but the error bars are too large to make an accurate estimate.
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1. Introduction

[2] A long-term ozone decline over middle and polar latitudes of the Northern and Southern Hemispheres is now well established. The strongest decline over northern midlatitudes is observed during winter-spring (~4%), with summer-autumn decreases approximately half as large. In contrast, there is no clear seasonal cycle in the ozone trend over southern midlatitudes where the decline is about 6% [*World Meteorological Organization* (*WMO*), 2003]. *Fioletov and Shepherd* [2003, hereinafter referred to as F&S] showed that the winter-spring ozone trend at Northern Hemisphere (NH) midlatitudes together with the natural ozone decline through the seasonal cycle are enough to explain the NH midlatitude summertime trends. However, in the Southern Hemisphere (SH) midlatitudes the summertime ozone decline is stronger than can be explained by this mechanism.

[3] Low temperatures and the isolation of stratospheric air in the polar vortex in winter-spring create unique conditions that cause the very strong springtime ozone depletion seen in the Antarctic, and in some years in the Arctic. After the breakup of the vortex, ozone-depleted polar air is mixed into midlatitudes. Several studies [e.g., *Knudsen and Grooß*, 2000; *Chipperfield*, 2003; *Ajtić et al.*, 2004] have demonstrated that this "dilution" effect contributes to the long-term decline in midlatitude ozone in the late spring and summer, although the quantification of this contribution is still a challenge.

[4] A 25-year record of reliable total ozone measurements makes it possible to analyze the link between springtime and summertime ozone variations over middle and polar latitudes directly from the ozone data. In this study, we use the F&S approach to quantify the statistical relationship between short-term ozone variations at middle and polar latitudes, and from this relationship analyze the contribution of springtime polar ozone depletion to the summertime midlatitude ozone decline.

2. Data Set and Analysis Method

[5] The merged satellite data set used here is prepared by NASA and combines version 8 of the TOMS and SBUV data [*Frith et al.*, 2004]. The data set provides a nearly continuous time series of zonal monthly mean total ozone values for the period from November 1978 to December 2003, with coverage up to 80°N from March to September in the NH and up to 80°S from October to March in the SH. The data for August–September 1995 and May–June 1996 are missing. Estimates of zonal monthly mean total ozone from ground-based measurements were used to fill the gaps [*Fioletov et al.*, 2002]. Following the F&S approach, we analyze the short-term and long-term variations separately. Over 1978–2003, the long-term ozone decline is not a linear function of time. Thus, the effective equivalent stratospheric chlorine (EESC) [*WMO*, 2003] was used as a proxy for the long-term trend. EESC was a nearly linear function of time during the 1980s. We scale the EESC loading to be one unit per year during the 1980s, so that the trend coefficient can be expressed in DU per year during the 1980s. On that scale, a 1 DU/year trend yields a maximum decline of ~17 DU in the late 1990s. For all latitude belts, data for each month of the year were fitted by the EESC trend function. The estimated trends were then subtracted from the data. We refer to data with the trend subtracted as "detrended" data.

3. Short-Term Variations

[6] Area weighted total ozone values for the entire midlatitude and polar region (35°–80°) are shown in Figure 1. It is evident that late-spring short-term total ozone variations are highly correlated with summer variations in both hemispheres. Thus, springtime 35°–80° ozone can be used as a predictor for summertime ozone integrated over the same wide latitudinal belt.

[7] There is in fact a high correlation between 35°–80° springtime ozone and summertime ozone variations at both middle and high latitudes, as is demonstrated by Figure 2 where normalized (i.e. divided by their standard deviation) detrended 35°–80° springtime and 35°–60° and 60°–80°

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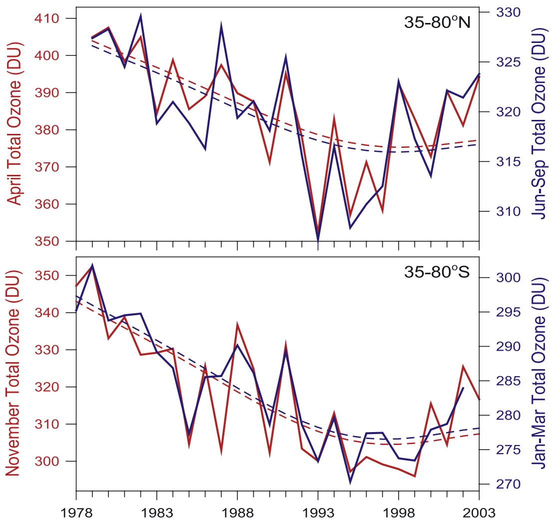

Figure 1. Total ozone values for different latitudinal belts and different time periods, as indicated. The dashed lines represent the best fit to the long-term trend function which is based on the effective equivalent stratospheric chlorine.

summertime ozone are plotted. The correlation coefficients describing the link between springtime and summertime total ozone for different latitudinal belts are shown in Table 1. There are particularly high cross-correlations between springtime ozone at midlatitudes (35°–60°N and S) and summertime ozone at polar latitudes (60°–80°N and S). These correlation coefficients are higher than those between springtime and summertime polar ozone. Thus midlatitude rather than polar springtime ozone is the best predictor for summertime polar ozone. This reflects the much greater area

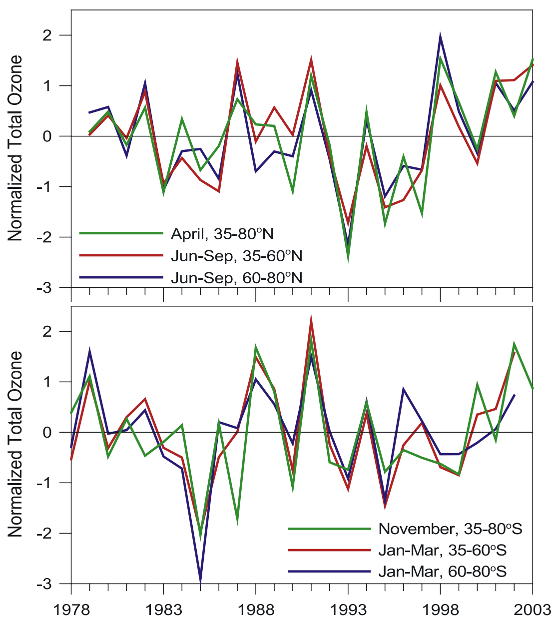

Figure 2. Normalized detrended (see text) total ozone values for different latitudinal belts and time periods, as indicated. A high correlation exists between 35°–80° springtime ozone and summertime ozone variations at both middle and high latitudes.

Table 1. Correlation Coefficients Between April and June–September Ozone Values in the NH and Between November and January–March in the SH for Different Belts[a]

Month/Season, Belt	Correlation Coefficient 35°–60°	60°–80°
NH, June–September		
April, 35°–60°N	0.87	0.88
April, 60°–80°N	0.65	0.74
April, 35°–80°N	0.87	0.89
June–September, 35°–60°N	1.00	0.88
SH, January–March		
November, 35°–60°S	0.79	0.82
November, 60°–80°S	0.67	0.49
November, 35°–80°S	0.82	0.71
January–March, 35°–60°S	1.00	0.86

[a]Detrended data were used.

of the 35°–60° belt compared to the 60°–80° belt, leading to a greater contribution of the former to the overall 35°–80° summertime ozone anomaly—even in the SH.

[8] There is also a good agreement between summertime midlatitude normalized ozone and summertime polar ozone in both hemispheres (Figure 2). The cross correlations between detrended total ozone values at different 5-degree latitude bands for different months are shown in Figure 3. Correlation coefficients of 0.7 and higher can be seen in June from 35° to 80° N. A similar pattern can be seen in the SH in January, although the correlation coefficients there are slightly lower. Thus, in summer, ozone variations as a function of latitude are uniform. The implication is that once the vortex breaks down, ozone is rapidly mixed throughout the extratropics. In contrast, the cross correlations between middle and high latitudes are relatively low during winter and early spring in each hemisphere. The switch to a uniform distribution of ozone variations in summer occurs between April and June in the NH and between November and January in the SH.

4. Long-Term Variations

[9] If short-term summertime ozone variations are homogeneous in latitude, it is expected that there should also be good agreement in long-term summertime ozone variations between middle and high latitudes. Figure 4 (top) shows that the magnitudes of the summer trends over middle and polar latitudes are nearly identical, while the springtime trends are quite different.

[10] If springtime ozone anomalies persist through summer, this means that springtime ozone trends imply summertime trends. Indeed, F&S demonstrated that the observed summertime ozone trends over NH midlatitudes can be entirely explained from the springtime trends there, implying that there is no need to invoke anomalous summertime ozone chemistry to explain the summertime trends. However, the same mechanism is not enough to account for the observed summertime trends in the SH (F&S, Figure 5). The estimates of summertime trends from springtime trends work better in the SH if the entire area between 35° and 80° S is considered (Figure 4 (bottom)). This can be interpreted as implying that springtime polar ozone depletion in the

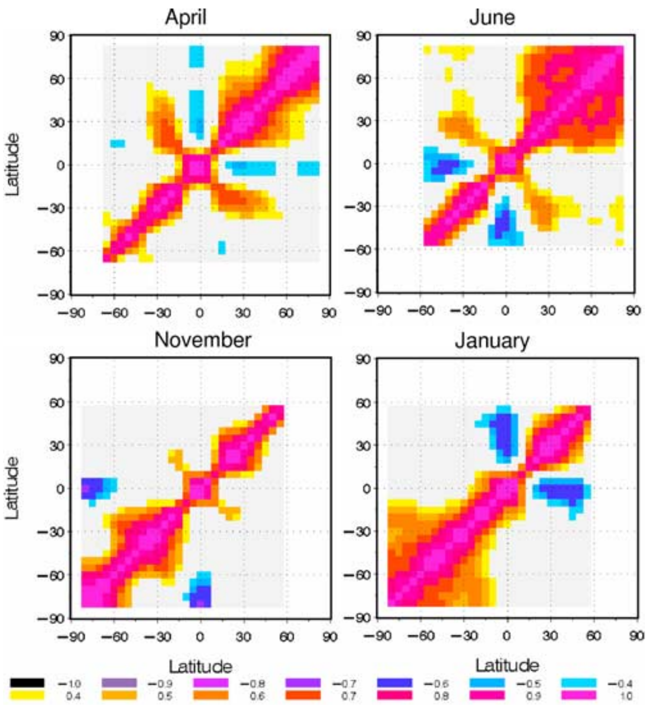

Figure 3. Correlation coefficients between detrended zonal mean total ozone values for 5-degree wide belts for different months of the year. Values along the diagonal represent correlations of latitude belts with themselves and are 1.0. Areas with no data are shown in white. Correlation coefficients between −0.4 and 0.4 are not statistically significant (95% confidence level) and are shown in gray. The figure demonstrates significant correlation between summer total ozone values at all latitudes from about 30° to 80° in both hemispheres. With few exceptions, all correlation coefficients there are above 0.75 in the NH and 0.65 in the SH. Correlations between midlatitude and polar ozone in spring are below the significance level in both hemispheres. Negative correlations between equatorial and midlatitude ozone in winter and spring are likely related to the QBO.

Antarctic contributes to the summertime ozone trend over SH midlatitudes.

[11] Midlatitude ozone in a late-spring/summer month (M_m) can be expressed as a linear combination of November (SH) or April (NH) polar (P_s) and midlatitude (M_s) ozone:

$$M_m = a_0 + a_1 M_s + a_2 P_s, \qquad (1)$$

where the unknown coefficients a_0, a_1 and a_2 are estimated from the data. For the detrended data discussed here, $a_0 = 0$. Table 2 contains the coefficient estimates. The regression coefficients reflect the contribution of November (SH) or April (NH) ozone anomalies in middle or polar latitudes to midlatitude ozone anomalies in subsequent months, in absolute units. For example, a 1 DU anomaly in the Antarctic in November implies a 0.12 DU anomaly in December over 35°–60°S. Applying these regression coefficients for detrended data to the midlatitude and polar trends in November (SH) and April (NH), one can estimate the contribution of the two regions to the summertime midlatitude trends. It is a rather crude estimate because the record is short. The results of the estimation are similar to those for the entire 35°–80° belts (Figure 4 (bottom)). Similarly, multiplying the standard deviations of these coefficients by the trend values, one can calculate the standard errors of the estimated trends.

[12] The estimated trend is nearly identical to the observed trend for 35°–60°N, as noted by F&S. The contribution of springtime polar ozone depletion to summertime trends is not statistically significant in the NH. The largest contribution of the April NH polar ozone trend can be seen in the May ozone trend (15%), but the error is large, ±20% (2σ). This reflects the fact that strong Arctic ozone depletion has only occurred in a relatively small number of years; and even in those years, only half the depletion appears to be chemical [*WMO*, 2003]. The situation is quite different in the SH, where polar ozone depletion is much stronger and more regular than in the NH, and is essentially all chemical. The effect of this polar depletion on midlatitude ozone can be estimated directly from the ozone data. The SH December observed midlatitude trend agrees with the estimated trend, and 39% ± 10% (2σ) of this trend can be "explained" by the Antarctic ozone depletion achieved by November. According to Table 2, a sizable fraction of the ozone trend in January–March can also be attributed to the Antarctic depletion achieved by November, although the error bars are large and the estimated trends tend to underestimate the observed decline.

[13] Similar regression calculations for the polar regions demonstrate that in May (NH) and December (SH), more than half the observed variability and trends is related to polar ozone in the preceding month. However, by midsummer the contribution of midlatitude springtime ozone variations exceeds two thirds.

[14] The relative influence of polar and midlatitude springtime trends to summertime trends over both regions is clearly illustrated by the top panels of Figure 4. The black curves are the area-weighted averages of the blue and red ones. In the NH, the Arctic ozone trend makes little difference relative to the midlatitude trend, and the midlatitude trend therefore reflects the seasonal cycle (F&S). In the SH, however, the Antarctic ozone trend makes a substantial contribution relative to the midlatitude trend. Thus, while the trend over 35°–80°S reflects the seasonal cycle, the midlatitude trend is roughly constant throughout the year.

5. Summary and Discussion

[15] Analysis of zonally averaged total ozone data shows that summertime short-term ozone variations at middle and high latitudes are highly correlated, and the long-term declines are nearly identical. Springtime variations demonstrate lower correlations between middle and polar latitudes, and the trends are substantially different. The switch from springtime to summertime ozone "regimes" occurs between April and June in the NH and between November and January in the SH.

[16] F&S demonstrated that long-term trends over NH midlatitudes are in line with interannual variability: the trend magnitudes in the summer months are related to the

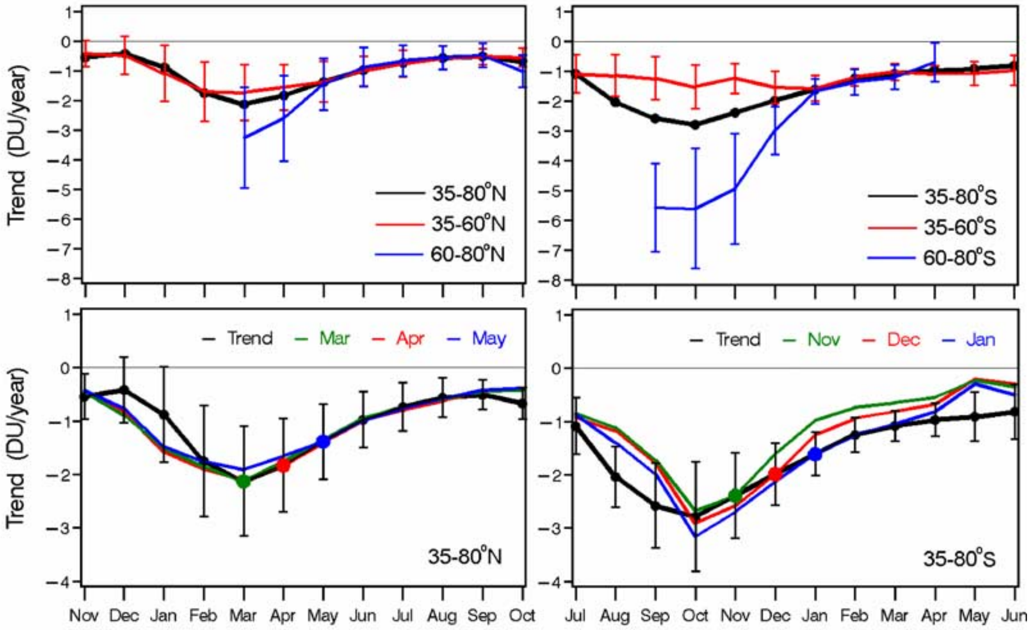

Figure 4. (top) The observed total ozone trends for 35°–60° (red), 60°–80° (blue), and 35°–80° (black) latitudinal belts for the Northern (left) and Southern (right) Hemispheres. (bottom) The observed ozone trends for 35°–80°N and S (black line), and the trends estimated from the March, April, and May trends for the NH (November, December, and January trends for the SH) and regression coefficients estimated from detrended data. The error bars represent the 95% confidence intervals.

trend in April in the same way as the corresponding monthly anomalies are related to the April anomaly in the detrended data. However, the same approach did not work for SH midlatitudes. By considering the entire 35°–80° belt, it is shown here that long-term trends in SH ozone are in line with interannual variability. This suggests that the discrepancy found by F&S for SH midlatitudes was due to transport. Indeed, regression analysis of springtime and summertime ozone variations over middle and polar latitudes demonstrates that a large fraction (39% ± 10% (2σ)) of the observed summertime ozone decline in southern midlatitudes is related to polar ozone depletion in spring.

[17] These results are consistent with previous estimates. The 3D model calculation of *Chipperfield* [2003] suggests that 30–50% of the SH midlatitude ozone decline is due to polar ozone destruction on polar stratospheric clouds. *Ajtić et al.* [2004] used a trajectory analysis technique and found that about 18 DU of ozone was depleted over SH midlatitudes in the summers of 1998–2000 due to dilution from the ozone hole, which represents about 90% of the observed depletion over midlatitudes. This is about twice as much as the linear regression method discussed in this study gives for December (85 DU long-term decline in 1998–2000 in November at 60–80°S times the coefficient of 0.12 from Table 2). However, *Ajtić et al.* [2004] state that their method

Table 2. The Coefficients for the Regression Equation (1) That "Predicts" Midlatitude (35°–60°) Ozone in Late Spring and Summer From Midlatitude and Polar (60°–80°) Ozone in April (NH) and November (SH) for Detrended Data, and Midlatitude Total Ozone Trends in DU/Year Observed and Estimated From the Regression Equation With and Without Polar Ozone[a]

	Regression Coefficients for the Model Including Polar O_3 (2σ)		Observed Trend,	Estimated Trend (Without Polar O_3),	Estimated Trend (With Polar O_3),	Estimated Contribution to Midlatitude Trend, DU/Year		% of Polar O_3 in the Estimated //
Month	Midlat. O_3	Polar O_3	DU/Year	DU/Year	DU/Year	Midlat. O_3	Polar O_3	Observed Trend
				Northern Hemisphere				
May	0.71 (0.18)	0.08 (0.10)	−1.36	−1.30	−1.32	−1.11	−0.21	16//15
June	0.50 (0.17)	0.06 (0.09)	−1.01	−0.91	−0.94	−0.78	−0.16	16//15
July	0.47 (0.20)	0.01 (0.10)	−0.76	−0.76	−0.76	−0.73	−0.03	3//3
August	0.37 (0.20)	0.01 (0.10)	−0.56	−0.61	−0.60	−0.58	−0.03	4//4
				Southern Hemisphere				
December	0.72 (0.12)	0.12 (0.03)	−1.53	−1.15	−1.50	−0.90	−0.59	40//39
January	0.47 (0.22)	0.09 (0.06)	−1.57	−0.77	−1.03	−0.58	−0.45	43//28
February	0.30 (0.16)	0.06 (0.04)	−1.19	−0.51	−0.67	−0.38	−0.30	43//25
March	0.34 (0.14)	0.05 (0.04)	−1.01	−0.53	−0.67	−0.42	−0.25	37//24

[a]The effective equivalent stratospheric chlorine curve was used as a proxy for the trend function.

overestimates the effect since photochemical recovery along the trajectories is ignored. Also, the method estimates the number of "destroyed" molecules moved into midlatitudes from October to January, but the number of ozone molecules also declines over midlatitudes during that period due to the natural seasonal cycle of ozone. It is important to distinguish the long-term ozone decline from the seasonal loss.

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