Total ozone variation between 50° and 60°N

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[1] The merged TOMS/SBUV ozone data for 1979–2002 are used to analyze, with a linear regression model and the other approaches, the zonal distribution of ozone variations between 50° and 60°N, the seasonal cycle and trends, and the responses to the solar cycle, quasi-biennial oscillation (QBO), El Niño–Southern Oscillation (ENSO) and Arctic Oscillation (AO). The seasonal ozone cycle shows ozone high over the north Pacific and low over the north Atlantic in winter, with a variability of 180 DU between 50° and 60°N. The maximum ozone trend obtained is over −5.3 ± 0.8%/decade at around 95°E in March. The anti-phase ozone response to the equatorial QBO is about 8 DU, with a 28-month period, in zonal average. In addition, the ozone responses to ENSO and AO are detected as 5 and 8 DU, respectively, between 95° and 190°E. The zonal inhomogeneity of ozone variations between 50° and 60°N is also discussed in this study. **Citation:** Zou, H., L. Zhou, Y. Gao, X. Chen, P. Li, C. Ji, S. Ma, and D. Gao (2005), Total ozone variation between 50° and 60°N, *Geophys. Res. Lett.*, *32*, L23812, doi:10.1029/2005GL024012.

1. Introduction

[2] Arctic ozone depletions have been investigated [*Andersen and Knudsen*, 2002], with the largest trend of $-1.04 \pm 0.39\%\text{yr}^{-1}$ occurring in March of 1978–2000 [*Bodeker et al.*, 2001]. Studies showed that the Arctic ozone depletion is related to the halogen-catalyzed chemical and photochemical processes [*Rex et al.*, 2004], the denitrification processes in polar stratospheric clouds [*Flentje et al.*, 2002] and the dynamical processes [*Randel et al.*, 2002], etc. The 50°–60°N latitude zone is a region adjacent to the Arctic, through which the Arctic ozone and ozone-destroying substances are exchanged with the lower latitudes by the atmospheric processes, e.g., the Rossby wave breaking [*Hood et al.*, 1999] and the planetary wave driven meridional transport [*Holton*, 1986; *Randel et al.*, 2002], etc. Therefore, the 50°–60°N is a critical zone for the ozone variation in the Arctic and lower latitudes. In addition, this latitude zone is better populated than the Arctic, and therefore, the ozone distribution and variation are more important to the living environment in this region.

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[3] Long-term ozone variations can be considered as responses to the natural and anthropogenic processes, including the trends, QBO, solar irradiance and ENSO, etc. [*Zerefos et al.*, 1992; *Randel and Cobb*, 1994; *Ziemke et al.*, 1997]. To study the responses comprehensively, a standard statistical model is widely applied [*World Meteorological Organization* (*WMO*), 1999]. However, the long distance between the high latitudes and the tropic regions could possibly cause weak responses to QBO and ENSO at the high latitudes in the statistical model, and more efficient approaches are required to detect these signals. Furthermore, the Arctic Oscillation (AO) is recognized as an important atmospheric process influencing the northern hemisphere high latitudes [*Thompson and Wallace*, 1998], and therefore, the possible ozone response to the AO should be included in our study.

[4] This study has been carried out to answer the above questions and analyze the meridional distribution of ozone variations, such as the seasonal cycle and trends, and responses to the solar cycle, QBO, ENSO and AO, between 50° and 60°N, using merged TOMS/SBUV ozone data for 1979–2002 with the standard statistical model and other approaches.

2. Data and Methodology

[5] The total ozone data used in this study are the TOMS/SBUV V7 merged data set, with grid resolution of 5° latitude by 10° longitude (http://code916.gsfc.nasa.gov/Data_services/merged/data/toms_sbuv.v3.78-02.5x10.v7.txt). The 10.7 cm solar flux is adopted as the solar cycle index, the Singapore (1°N, 104°E) 30 hPa zonal wind as the QBO index, the standardized surface pressure difference between Tahiti (18°S, 150°W) and Darwin (12°S, 131°E) as the Southern Oscillation Index (SOI), and the dominant pattern of non-seasonal sea-level pressure (SLP) variations north of 20°N as the AO index. A standard statistical model from *WMO* [1999] is applied in deriving the ozone trends and responses to the solar cycle. A so-called "super epoch" method [*Sitnov*, 1996] is utilized to detect the ozone responses to QBO. The detailed methodology will be described in the relevant sections.

3. Results and Discussion

3.1. Seasonal Cycle

[6] Averaging the total ozone between 50° and 60°N for 1979–2002 gives the seasonal cycle for each 10 degrees longitude (Figure 1). The total ozone between 50° and 60°N decreases from the late winter and early spring (February and March) to the late autumn and early winter (October and November), and increases during winter. The ozone maximum is located in the east Siberia section (130°–

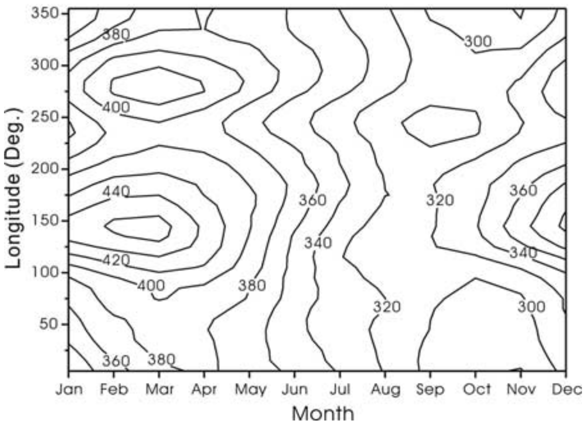

Figure 1. Seasonal cycle of total ozone between 50° and 60°N, with contour interval 20 DU.

155°E) and the minimum in the north Atlantic section (335°–15°E), in all the seasons. The highest total ozone (above 460 DU) is centered at 140°E in March, and the lowest (below 280 DU) at 0° in November, resulting in variability above 180 DU. In addition, the second highest ozone (430–440 DU) is found at 275°E in March and the second lowest (290–300 DU) at 225°E in September. The zonal mean ozone at these latitudes has the maximum (412 DU) in March and minimum (306 DU) in September, with a variability 106 DU. The winter zonal ozone distribution agrees with the patterns derived from the observations and dynamical model by *Hood and Zaff* [1995], who attribute the ozone distribution to the influence of stationary wave 1 and 2. However, the delayed appearance of the ozone maximum in the early spring (March) may imply impacts from the other dynamical and chemical processes on the ozone distribution between 50° and 60°N.

3.2. Trends

[7] The standard statistical model [*WMO*, 1999], which includes the seasonal cycle, trends, solar cycle and QBO, is applied to retrieve the monthly ozone trends between 50° and 60°N for 1979–2002 (Figure 2). The ozone decreases between 50° and 60°N in all seasons. The maximum decrease is found in spring and the minimum in summer. The strongest decrease (over −3.0%/decade or −12.0 DU/decade) occurs between 75° and 125°E from February to April, with a center (−5.3 ± 0.8%/decade or −23.5 ± 3.3 DU/decade) at 95°E in March. The zonal averaged ozone trend results in a maximum decrease of −2.6 ± 0.6%/decade (−11.0 ± 2.5 DU/decade) in March and a minimum of −0.8 ± 0.3%/decade (−2.7 ± 1.0 DU/decade) in August. The seasonal variation of zonal averaged trend agrees with the trends at this latitude zone derived by *Randel and Wu* [1999, Figure 5] from 1979–1997 TOMS data. However, the rate of decrease in our study is much weaker than in their results. For example, the zonal averaged maximum decrease in March is only half of Randel and Wu's (over −24.0 DU/decade). The weakened ozone decrease might imply an ozone recovery between 50° and 60°N with our longer data series. Since the polar vortex has an asymmetric expansion toward low latitudes in the eastern hemisphere [*WMO*, 2003], and more ozone depleting regimes inside of the Arctic region are impacting the 50°–60°N ozone trends, the large ozone decrease at 95°E in March could be related to the spatial expansion of the polar vortex.

3.3. 11-Year Solar Cycle

[8] The 11-year cycle in the solar irradiance has important impacts on the ozone variation [*Zerefos et al.*, 1997], and therefore should be included, as a predictor, in a statistical model for ozone variation. Figure 3 presents the ozone responses to the solar cycle derived from the statistical model [*WMO*, 1999] using the trends and solar cycle as predictors. The solar cycle used in this study is a 3-year smoothed 10.7 cm solar flux. The 50°–60°N ozone responses are in-phase with the solar cycle. Three longitude sections, 30°–60°E, 150°–200°E and 250°–360°E, have strong ozone responses (over 8 DU). The maximum ozone response is over 12 DU (more than 4% of total ozone) between 260° and 320°E. The zonal averaged ozone response is about 9 DU (around 2.5% of total ozone). However, the weakest ozone response is lower than 4 DU between 75° and 125°E. As discussed in the above section, the Arctic vortex expansion towards low latitudes in the eastern hemisphere brings polar air masses to this longitude section with less impact from the solar irradiance, especially in the polar winter. Therefore, the weakest ozone response

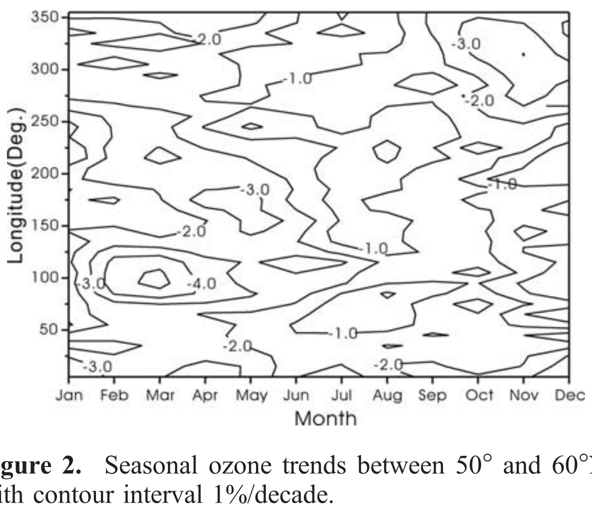

Figure 2. Seasonal ozone trends between 50° and 60°N, with contour interval 1%/decade.

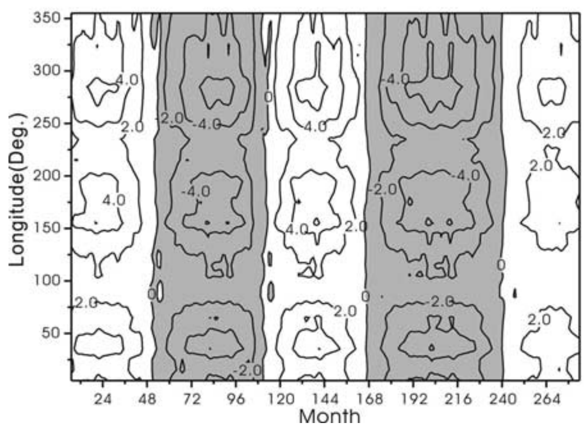

Figure 3. Ozone responses to solar cycle between 50° and 60°N, with contour interval 2 DU and the negative areas are shaded.

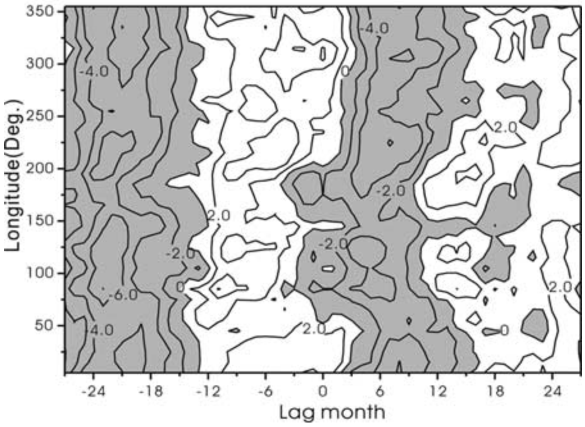

Figure 4. Ozone response to the equatorial QBO, with contour interval 2 DU and the negative areas are shaded.

to the solar cycle occurring between 75° and 125°E could be caused by the vortex expansion.

3.4. Quasi-Biennial Oscillation (QBO)

[9] QBO is a global atmospheric phenomenon with important impact on the ozone variation [*Holton and Tan*, 1980]. The monthly ozone anomalies for each 10 degrees longitude between 50° and 60°N are obtained by subtracting the seasonal cycle, trends and solar cycle (retrieved from the WMO statistical model) from the total ozone and applying a 7-month smoothing. Since the atmospheric QBO itself is not a strictly periodic process, to examine clearly the ozone responses between 50° and 60°N to the equatorial QBO, a superimposed epoch method [*Sitnov*, 1996] is applied. In this method, key-0 months of tropical QBO are defined as the months when the QBO shifts its phase from easterly to westerly. Therefore, the QBO periods are defined by easterly and westerly months on both sides of the key-0 months. To analyze the ozone responses to QBO, the monthly ozone anomalies are averaged in each lag month (lags up to ±27 months) from QBO key-0 months. The mean ozone anomalies (with lag to the key-0 months of tropical QBO) between 50° and 60°N are plotted in Figure 4. The figure shows an anti-phase ozone response to the tropic QBO, i.e., the ozone anomalies have positive values in the QBO easterly phase, and *vice versa*. The zonal averaged ozone response to QBO is 8 DU (about 2.3% of total ozone) with a period 28 months. The ozone response to QBO between 50° and 60°N varies from 4 to 12 DU. The negative ozone anomalies appear from lag months 3 to 15 at most longitudes, except two longitudinal sections in lag months −3 to 12 between 70° and 200°E, and the positive ozone anomalies start from lag month −13 at all the longitudes. Therefore, the QBO-related ozone variation between 50° and 60°N has the period of 28 months, with exception of 25 months in two sections between 70° and 200°E. Because the Arctic polar vortex is related to the equatorial QBO [*Holton and Tan*, 1980], the inhomogeneous ozone responses (about 10 DU) to QBO in the longitude section between 75° and 125°E could be related to the low-latitude-ward expansion of the polar vortex discussed above. Another inhomogeneous ozone QBO response (8 DU) between 150° and 200°E may be related to other dynamic processes, such as the Aleutian low.

3.5. El Niño–Southern Oscillation (ENSO) and Arctic Oscillation (AO)

[10] ENSO is a well-known long-term internal oscillation in the global atmospheric system with a significant impact on the ozone variation [*Randel and Cobb*, 1994]. AO is a dominant climate pattern connecting the Arctic and middle latitudes in the Northern Hemisphere, and is closely related to the atmospheric ozone concentrations [*Thompson and Wallace*, 1998]. The responses of ozone variation between 50° and 60°N to ENSO and AO are the focus of in this study. Since 50°–60°N is north of the tropic regions, the ENSO signal in the ozone variation appears rather weak as determined by the standard statistical model [*Ziemke et al.*, 1997]. Therefore, in this study, the monthly ozone anomalies are retrieved by removing the seasonal cycle, trends, solar cycle and QBO (obtained in the above standard statistical model) from the total ozone, and thereafter, grouped according to the positive and negative phases of ENSO and AO indices.

[11] Figure 5 (top) shows the zonal distribution of ozone responses to the phases of ENSO index (SOI). An in-phase ozone response to ENSO, i.e., the positive ozone anomalies are associated with the positive SOI, and vice versa, are detected in this figure. However, the response is obviously inhomogeneous between 50° and 60°N, detectable between 70° and 200°E, and negligible between 265°–315°E and 35°–65°E. The responding strength, defined as the absolute difference between the ozone responses to the positive and negative ENSO phases, is significant and over 4 DU (1.1% of total ozone) between 90° and 190°E, with a maximum of 5.7 DU (1.6% of total ozone) at 105°E (see Figure 5 (bottom)).

[12] Figure 5 (middle) shows the ozone responses to the AO index between 50° and 60°N. Anti-phase responses of

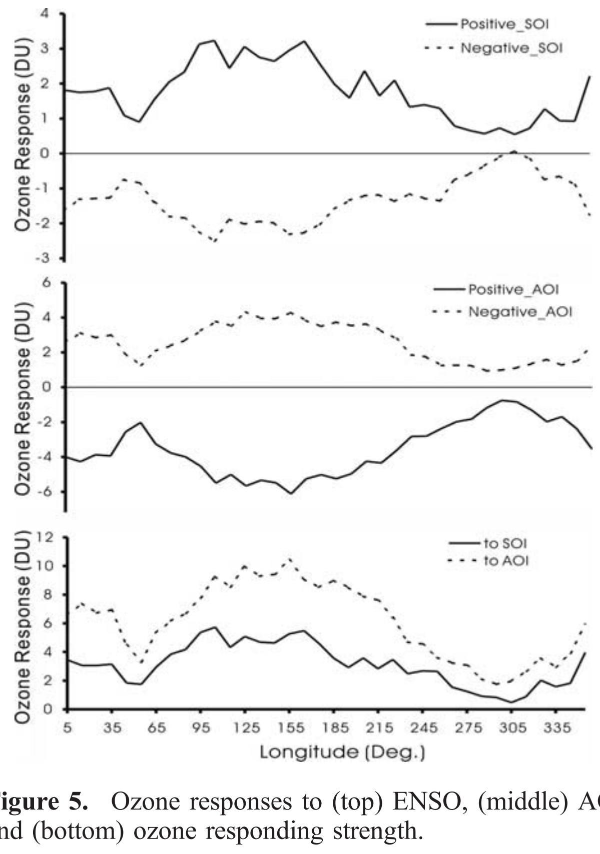

Figure 5. Ozone responses to (top) ENSO, (middle) AO, and (bottom) ozone responding strength.

total ozone to AO are found between 50° and 60°N, i.e., positive/negative ozone anomalies occur in negative/positive the AO phases. Similar to the ENSO events, the ozone responses to the AO are inhomogeneously distributed between 50° and 60°N. The responding strength is significant and over 8 DU (2.0% of total ozone) between 95° and 200°E, with a maximum response of 10.4 DU (2.7% of total ozone) at 155°E (Figure 5 (bottom)). The second maximum response of over 6 DU between 0 and 40°E is also significant.

[13] From the above analysis, the 50°–60°N ozone responses to ENSO and AO are significant between 95° and 190°E, with a great zonal inhomogeneity. Since ENSO originates in the equatorial Pacific region, the strong ozone response to ENSO in the eastern hemisphere is reasonable when atmospheric baroclinicity is considered. The AO has two major oscillation structures in both the directions of the pole to Siberia-Pacific and the pole to Atlantic [*Baldwin et al.*, 1994], and therefore, the ozone responses to the AO between 50° and 60°N could be significant in the 95°–200°E and 0–40°E sections.

4. Summary

[14] The ozone variations at 50°–60°N in 1979–2002 analyzed in this study can be summarized as the following:

[15] 1) The ozone is maximum over eastern Siberia (130°–155°E) in March and minimum over the North Atlantic (335°–15°E) in November, with a seasonal variability above 180 DU. This can be related to the planetary wave dynamics, as demonstrated by *Hood and Zaff* [1995];

[16] 2) The total ozone decreases along the latitude zone in all the seasons, with a maximum rate of decrease of −5.3 ± 0.8%/decade at 95°E in March. The ozone decrease is inhomogeneously distributed between 50° and 60°N, with the largest decrease occurring between 75° and 125°E from February to April. This may be related to the polar vortex expansion towards this longitude section;

[17] 3) An in-phase ozone response to the solar cycle is detected as above 9 DU, equivalent to 2.5% of total ozone, in zonal average, with the maximum being over 12 DU, equivalent to 5% of total ozone, at 275°E. The ozone response to the solar cycle is the weakest between 75° and 125°E, which may also be related to the polar vortex expansion to this section;

[18] 4) An anti-phase ozone response to the equatorial QBO is found to be 8 DU in zonal average, equivalent to 2.3% of total ozone, with a period of 28 months. The response between 70° and 200°E is significantly shifted from the other longitude sections, with a period of 25 months and an obvious phase shift. The inhomogeneous ozone response between 75° and 125°E can be related to the polar vortex expansion toward this section, and the other inhomogeneous response between 150° and 200°E may be related to different dynamic processes;

[19] 5) The ozone responses to ENSO and AO are significant between 95° and 190°E and 50° and 60°N, with strengths of 5 and 8 DU (1.4% and 2.0% of total ozone), in-phase and anti-phase, respectively. The inhomogeneous ozone responses along the latitudes can be related to the origination and structure of ENSO and AO.

[20] In a conclusion, the inhomogeneity of long-term ozone variations between 50° and 60°N is clearly showed in all the aspects discussed above. This inhomogeneity could be introduced by the dynamical processes in the Arctic and tropic regions. The longitudinal zone 95°–125°E between 50° and 60°N, in which ozone responds to both the Arctic and tropic forcing, might be a critical region linking the Arctic ozone to that over the lower latitudes.

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