Very high ozone columns at northern mid-latitudes in 2010

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[1] For the year 2010, both ground- and satellite-based measurements have recorded unusually high annual mean total ozone columns over much of the Northern hemisphere. At the mid-latitude station Hohenpeissenberg (48°N, 11°E), the 2010 annual mean reached 339 Dobson Units (DU), the highest value observed since 1982, and the 8th highest in the 43 year record at Hohenpeissenberg. The 45°N to 55°N annual zonal mean exceeded 360 DU, also one of the highest values observed in the last 20 to 25 years. The 2010 annual mean was about 12 DU higher than in 2009, and almost 35 DU higher than the long-term minimum observed in 1992 and 1993. An unusually pronounced and persistent negative phase of the Arctic Oscillation and North Atlantic Oscillation in 2010, last seen in this magnitude in 1968 and 1969, and the co-incidence of northern winter 2009/2010 with the easterly wind-shear phase of the quasi biennial oscillation of stratospheric winds at the equator (QBO) have been major contributors to the high total ozone of 2010. Multiple linear regression analysis of the Hohenpeissenberg time series (since 1968) attributes about +8 DU ±2 DU (1σ) of the 2010 annual mean to the Arctic Oscillation, and about +4 DU ±1.3 DU (1σ) to the QBO. A small ozone increase since the ozone minimum of the mid 1990s might also be due to the recent decline of stratospheric chlorine and bromine.

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1. Introduction

[2] The Antarctic Ozone Hole, and the long-term depletion of stratospheric ozone by chlorine and bromine released into the stratosphere from man-made ozone depleting substances (ODS, mostly Chloro-Fluoro-Carbons, and Halons) have demonstrated that human activities can affect our environment not only locally, but over an entire continent, and even above the entire globe [*World Meteorological Organization* (*WMO*), 2007]. Fortunately, ODS production has been stopped almost completely since the early 1990s, and chlorine levels in the stratosphere have been going down since the late 1990s, i.e., for about a decade. First signs of a beginning recovery of the ozone layer have been discovered [*WMO*, 2007]. Now it is important to find out whether total ozone columns have started to recover from man-made chlorine and bromine [*Hadjinicolaou et al.*, 2005; *Kiesewetter et al.*, 2010]. This requires proper accounting for natural variations, e.g., due to the 11-year solar cycle [*WMO*, 2007], the quasi-biennial oscillation of equatorial winds (QBO) [*Baldwin et al.*, 2001], the large-scale Brewer Dobson circulation [*Dhomse et al.*, 2006], or circulation patterns like the North-Atlantic or Arctic Oscillations [e.g., *Thompson and Wallace*, 2000; *Steinbrecht et al.*, 2001].

[3] In the present letter we will not try to resolve all these questions. However, we a.) report that unusually large ozone columns were observed in 2010 over much of the Northern hemisphere, and b.) we try to estimate which main factors have contributed to this very large annual mean total ozone column in 2010.

2. Total Ozone in 2010 Compared to Previous Years

2.1. Data Sources

[4] Figure 1 shows annual means of the total ozone columns measured at Hohenpeissenberg (47.8° N, 11.0° E), by Dobson spectrometer No. 68 since 1968, joined by Brewer spectrometer No. 11 since 1984. The Brewer data are adjusted slightly to match the annual cycle of the Dobson data. The annual mean of 2010 reaches 339 DU. This is much higher than anything observed in the last 25 years. It is the first annual mean since 1991 to lie above the long-term average (red dashed line). Annual means of comparable magnitude were last observed in the early 1980s. Figure 1 shows that the 2010 annual zonal mean from 45° N to 50° N, observed by satellite instruments, is also the largest of the last 20 years.

[5] The use of satellite data in Figure 1 is complicated by the fact that no consistent data set exists for the entire 1979 to 2010 time period. The "multi sensor reanalysis of total ozone" dataset (MSR) [*van der A et al.*, 2010] covers the years 1979 to 2008 only. For total ozone in 2010, SCIAMACHY, GOME2, or OMI can be used, but none of these instruments started before 2002, and they are all on slightly different levels. In Figure 1, the merged GOME, SCIAMACHY, GOME2 record (GSG record, mostly GOME2 since 2007 [*Weber et al.*, 2005; *Kiesewetter et al.*, 2010]), and the SCIAMACHY data (from http://www.temis.nl/protocols/O3global.html) are used for 2010. Both the GSG and SCIAMACHY data were shifted (by a constant offset) to match the MSR record during 2003 to 2008. In addition, all satellite data were further shifted by the average offset between the MSR record and the Hohenpeissenberg data. The final offsets are indicated in Figure 1.

[6] As Figure 1 shows, the three shifted satellite records are quite consistent over their overlap periods. They also look very similar to the Hohenpeissenberg time series. Both at Hohenpeissenberg and in the zonal mean, 2010 clearly was a remarkable year: Ozone values that high were last observed in the early 1980s, e.g., in 1982, when ozone depletion by chlorine was just starting to become visible.

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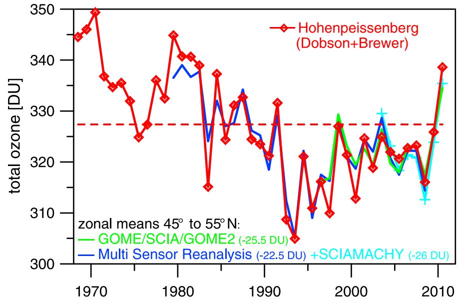

Figure 1. Red diamonds: annual mean total ozone columns observed by ground-based Brewer and Dobson spectrometer at Hohenpeissenberg (47.8° N, 11° E). Blue line: same but for the zonal mean between 45° N and 55° N from the MSR dataset [*van der A et al.*, 2010], shifted down by 22.5 DU. Light blue: same as blue line, but for SCIAMACHY data (from http://www.temis.nl/protocols/O3global.html), and shifted down by 26 DU. Green line: same, but for the combined GOME/SCIAMACHY/GOME2 record [*Weber et al.*, 2005], shifted down by 25.5 DU. The red dashed line shows the 1968 to 2010 long-term mean at Hohenpeissenberg.

What caused the high ozone in 2010, and also the large change from 2008 to 2010?

2.2. QBO Effect in 2010

[7] High values observed in winter 2009/2010 provide some clues. The January to March 2010 total ozone anomaly map, given in Figure 2, shows a belt of low total ozone in the tropics, south of 15°N, and above average total ozone in the extra-tropics, north of 20°N in the Eastern hemisphere, and north of 30°N in the Western hemisphere. This pattern is typical for the winter hemisphere during an easterly wind-shear phase of the quasi-biennial oscillation of equatorial winds (QBO), like in winter 2009/2010. It is caused by the QBO-induced secondary circulation with enhanced ascent and less ozone in the tropics, and enhanced descent and more ozone in the extra tropics [*Baldwin et al.*, 2001; *Steinbrecht et al.*, 2003].

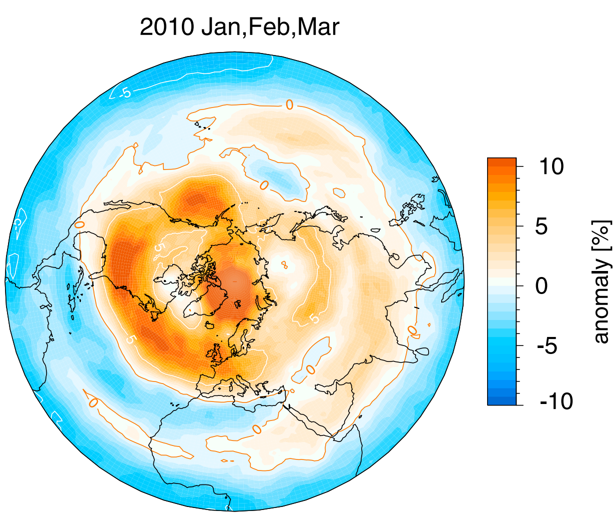

Figure 2. Total ozone anomaly (= deviation from long-term mean, in %) observed by SCIAMACHY from January to March of 2010 (data from http://www.temis.nl/protocols/O3global.html). The reference is the 1979 to 2008 long-term mean from the MSR dataset [*van der A et al.*, 2010]. The SCIAMACHY data were shifted by a constant offset at each grid-point to match the MSR data during 2003 to 2008. Polar stereographic projection from 90°N to 0°N.

2.3. Arctic Oscillation in 2010

[8] The second important feature in Figure 2 is a band of high total ozone extending from the Pacific Ocean over North America, and the Atlantic Ocean to Central Europe. This band is contrasted by a center of lower total ozone from Hudson Bay to Southern Greenland. Another patch of high ozone is found north of Greenland. Although the match is not perfect, this pattern of high and low total ozone corresponds to the total ozone distribution (less to the geopotential height patterns) associated with the North Atlantic Oscillation (NAO) or the Arctic Oscillation (AO) (see *Thompson and Wallace* [2000, Figure 12b] for total ozone, or *Thompson and Wallace* [2000, Figures 6b and 6d] for 50 hPa and 1000 hPa geopotential height).

[9] The 2010 total ozone anomaly pattern polewards of about 30°N coincides with an unusually pronounced negative phase of the AO and NAO, starting in December 2009 and lasting throughout most of the year 2010. According to data from the NOAA Climate Prediction Center data (www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/teleconnections.shtml), the 2010 annual means of both NAO and AO index were among the lowest on record (since 1950 and 1958, respectively). The last time such a low annual mean AO or NAO index occurred was in 1969.

[10] Winters with large negative AO indices are characterized by pronounced deflection of planetary waves towards the polar region. This means an enhanced Brewer-Dobson circulation, more ozone transport into the extra-tropics, a weakening of the polar vortex, and less polar ozone loss [*Hartmann et al.*, 2000]. In addition, an easterly QBO phase in the tropics also enhances planetary wave activity and deflection of waves into the polar region [*Baldwin et al.*, 2001].

[11] Figure 3 shows that not only the first quarter, but also the annual mean of 2010 total column ozone was well above

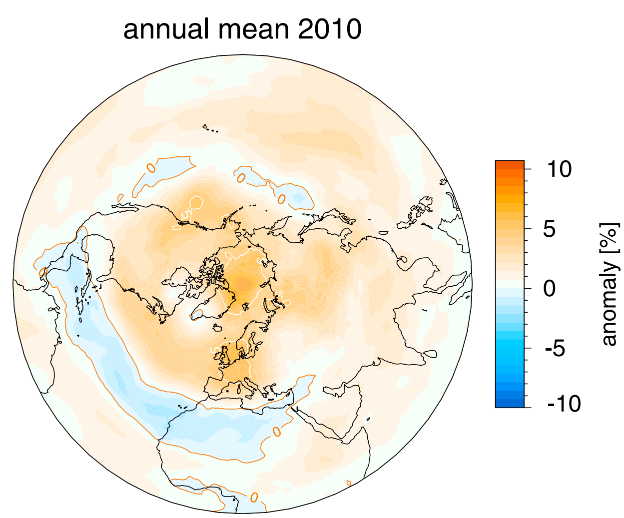

Figure 3. Same as Figure 2, but for the annual mean total ozone anomaly (in %) observed by SCIAMACHY in 2010.

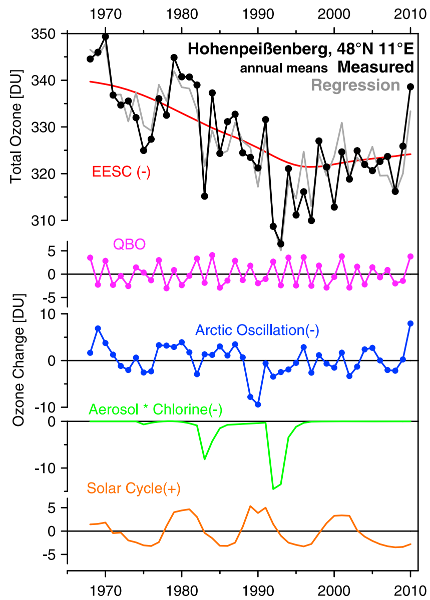

Figure 4. Observed annual mean total ozone at Hohenpeissenberg, and magnitude of contributing factors obtained by multiple linear regression. Black: annual mean total ozone observed at Hohenpeissenberg (47.8° N, 11° E). Gray: corresponding result of multiple linear regression. Red: ozone variation attributed to Effective Equivalent Stratospheric Chlorine (EESC). Ozone variation attributed to the QBO (magenta), to the Arctic Oscillation (AO, blue), to enhanced stratospheric aerosol (green), and to the 11-year solar cycle (orange).

the 1979 to 2010 long-term mean over much of the Northern hemisphere. Polewards of 20°N, the geographic distribution of the annual mean deviation is less pronounced, but otherwise similar to the January to March anomaly (Figure 2). This is expected, because the negative AO phase lasted throughout much of the year, and because winter/spring ozone anomalies usually persist, but weaken throughout summer and fall [*Fioletov and Shepherd*, 2003]. Compared to the beginning of the year, however, the tropical band of low ozone is less pronounced. This is attributed to the switch of the QBO from easterly to westerly shear after May 2010, resulting in higher ozone in the tropics in the second half of 2010.

3. Multiple Linear Regression Analysis of the Hohenpeissenberg Record

[12] Multiple linear regression is a standard tool to quantitatively attribute observed total ozone variations to different natural and anthropogenic influences [e.g., *Steinbrecht et al.*, 2001, 2003; *WMO*, 2007]. The Hohenpeissenberg total ozone time series is represented by a sum of proxy time series accounting for ozone variations due to effective equivalent stratospheric chlorine (EESC, http://acdb-ext.gsfc.nasa.gov/Data_services/automailer/index.html); due to the QBO (zonal winds at 30 and 10 hPa, http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/index.html); due to the 11-year solar cycle, here solar radio flux at 10.7 cm wavelength (ftp://ftp.ngdc.noaa.gov/STP/ SOLAR_DATA/SOLAR_RADIO/FLUX/Penticton_Observed/monthly/); due to ozone destruction enhanced by volcanic aerosol, here stratospheric aerosol optical depth at 550 nm (http://data.giss.nasa.gov/modelforce/strataer/), multiplied by the stratospheric chlorine content; and related to the AO index (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/teleconnections.shtml).

[13] Here the regression is applied to annual mean data, obtained by averaging monthly mean values. For the QBO and AO terms, the monthly means were weighted by the climatological total ozone variance at Hohenpeissenberg, i.e., highest weight was given to Februaries, and lowest weight to Julies. This weighting improves the regression results, because it helps to account for the seasonal variation of QBO and AO influences on mid-latitude total ozone. The correlation between observed annual means and regression results is high ($R = 0.92$), and auto-correlation of the residuals is small (0.11 for lag 1). The predictor time series are not perfectly orthogonal, but correlations between them are usually small, less than 0.1 to 0.2, except for the EESC and AO term (correlation 0.32). Very similar results are obtained when some years are excluded from the regression, or when not all terms, or other terms, e.g., piecewise linear trends from 1968 to 1996, and from 1997 to 2010, are included in the regression.

[14] The regressed time series (gray line in Figure 4) very closely follows the observations (black line). The long-term ozone variation attributed to man-made chlorine and bromine (EESC) is given by the red line in Figure 4. The decline of ozone from the 1960s to the mid-1990s is clearly visible. Since then chlorine has turned around, and a small increase of ozone is expected. The red line in Figure 4 assumes that ozone follows the prescribed shape of the EESC curve exactly. In this case, the ozone increase related to EESC decline since 1997 would amount to +3 DU ±1 DU (1σ). A similar increase, however, is also suggested by tests with other regression proxies, e.g., piecewise linear trends.

[15] The magenta curve in Figure 4 shows the inter-annual variation attributed to the QBO. QBO related ozone variations typically amount to ±2 to ±4 DU. Note the slowly growing and shrinking amplitude, as the QBO goes in and out of phase with the annual cycle. For 2010, +4 DU ±1.3 DU (1σ) of the high annual mean are attributed to the QBO.

[16] The blue line gives the ozone variation attributed to the Arctic Oscillation (AO). A high AO index, e.g., in 1989 and 1990, means low total ozone over the Atlantic, Central Europe, Hohenpeissenberg, and the zonal mean. A low AO index, in contrast, means high total ozone. The lowest AO index values occurred in 1969 and 2010, and in these years total ozone was unusually high at Hohenpeissenberg (and in the zonal mean in 2010). For 2010, the regression attributes +8 DU ±2 DU (1σ) of the high annual mean to the pronounced negative phase of the Arctic Oscillation.

[17] There was no enhanced stratospheric aerosol loading in 2010, so we do not expect an effect, but the inclusion of the aerosol term helps to explain the pronounced ozone minimum after the Mt. Pinatubo eruption in the early 1990s. The 11-year solar cycle was still near its' minimum in 2010. Otherwise, total ozone in 2010 might have been even higher. A similar QBO and AO constellation near solar

maximum, e.g., in 2015, would probably have resulted in 5 to 8 DU more total ozone than in 2010.

4. Conclusions

[18] The year 2010 brought the largest annual mean total ozone columns observed at Northern mid-latitudes for the last 25 years. At Hohenpeissenberg, 339 DU were registered for the annual mean, the largest value since 1982. Larger values have been observed only before 1982. Unusually large values were also observed for the 45°N to 55°N zonal mean, and, in fact, over much of the Northern hemisphere polewards of 30°N.

[19] The high annual mean total ozone of 2010 is attributed to the unusually pronounced negative phase of the AO (and NAO), and the easterly wind-shear phase of the QBO during northern winter 2009/2010. Both AO and NAO were in their negative phase since December 2009 and over much of 2010. The 2010 annual mean of the AO and NAO indices was by far the lowest of the last decades. 1969 was the last time, that such a low annual mean index occurred for the AO or NAO. A good match between Northern winter and an easterly wind-shear phase of the QBO occurs more often, roughly every 2 to 3 years.

[20] Multiple linear regression analysis applied to the 43 year Hohenpeissenberg annual mean total ozone record indicates, that of the +12 DU total ozone anomaly of 2010, about +8 DU are attributable to the negative phase of the AO, and about +4 DU are attributable to the QBO phase. Compared to the period of maximum stratospheric chlorine loading around 1997, the decline of chlorine should have also contributed a few Dobson Units to the high total ozone of 2010. The close correspondence between ground-based data at Hohenpeissenberg and larger scale satellite data, e.g., the 45°N to 55°N zonal mean in Figure 1, indicates that comparable numbers are valid for a good part of the Northern mid-latitudes. Multiple linear regression analysis of satellite data confirms this.

[21] Our analysis is largely based on empirical relations between total ozone and major influence factors. We have not really addressed ozone anomalies in the polar cap, which may require other influence factors or a different approach. We also have not looked into detailed processes, and have not considered possible feedbacks between changing ozone, changing climate, and large scale circulation modes like the AO [*Thompson and Wallace*, 2000; *Hadjinicolaou et al.*, 2005; *Kiesewetter et al.*, 2010]. These might be important: The decadal shifts of the AO from negative regime in the late 1960s to positive regime in the 1990s, and back to negative regime in recent years (blue curve in Figure 4), for example, go hand in hand with the chemical decline and beginning increase of ozone (red curve in Figure 4). Because the AO is a leading mode of northern hemispheric climate variability, and couples between stratosphere and troposphere [*Thompson and Wallace*, 2000; *Hartmann et al.*, 2000], we wonder if stratospheric ozone changes might have contributed on long time-scales to these changes in the AO regime. 2010 has highlighted shorter term aspects of the AO-ozone connection, but all aspects of this connection deserve further investigations.

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