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Ozone Variations Derived by a Chemical Transport Model

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Abstract The results of a comparison between monthly mean ozone column variations calculated from the chemical transport model Oslo CTM2 and those derived from solar backscatter ultraviolet (SBUV) satellite observations are presented for the period 1998–2009. Monthly mean total ozone derived from improved model simulations were used to compute monthly zonal means over 10° latitude zones over the northern and southern hemispheres. Ozone column variations from Oslo CTM2 are highly correlated with SBUV retrievals at all latitude zones. Equatorial zonal winds at 30 hPa were used as index to study the impact of quasi-biennial oscillation (QBO) on ozone. Correlations between modeled ozone and the QBO were found to be the order of +0.8 in the tropics. The impact of QBO was most pronounced at equatorial latitudes with amplitudes of +4 to −4 %. Seasonal variations in surface ozone and tropospheric ozone column calculated by the model are also presented.

Keywords Ozone · Variations · Oslo CTM2 · SBUV · QBO

1 Introduction

Ozone is an important constituent of the earth's atmosphere between 10 and 50 km height. It absorbs ultraviolet radiation from the sun, and protects the biosphere from harmful effects of ultraviolet radiation (UVB). Ozone column amounts in the atmosphere can be obtained from surface measurements and satellite observations (e.g., Harris et al. 1997, Chipperfield et al. 2007), and can be calculated by chemistry-climate and chemistry-transport models (e.g., Eyring et al. 2006, Stolarski et al. 2006, Søvde et al. 2008). The ability of models to reproduce the observed atmosphere comes from the key physical and chemical processes included in the models. Today, models are being improved to include comprehensive chemistry

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and physics of both the troposphere and the stratosphere, as it has been done for the Oslo chemical transport model (CTM2). The updated version with improved microphysics and heterogeneous chemistry and the extension of vertical layers to 60 has improved the capability to predict the distribution of ozone and precursors in the Upper Troposphere-Lower Stratosphere region, in the upper stratospheric region and in the troposphere (Søvde et al. 2008)

Eleftheratos et al. (2011) provided additional evidence of improved total ozone columns by the updated Oslo CTM2 model, by comparing monthly mean, seasonal mean, and annual mean total ozone for the period 2001–2007 with respective total ozone averages from satellite retrievals. Here, we extend the period of comparison by including simulations for the period 1998 to 2009 that includes several QBO cycles and examine whether ozone variations from improved Oslo CTM2 model simulations reproduce the well-known perturbation (QBO). Then we compare our results with respective SBUV satellite retrievals to test the consistency of the modeled ozone variations.

2 Data and Methodology

2.1 Oslo CTM2 Model

The Oslo CTM2 is a global off-line chemical transport model, driven by meteorological data from the European Centre for Medium-Range Weather Forecasts Integrated Forecast System (IFS) model. In the IFS forecasts, a spectral resolution of T319 is applied (T319 is approximately 0.5×0.5° grid resolution, longitude/latitude, with 60 vertical layers). The horizontal resolution of the Oslo CTM2 can be varied between T21 (resolution of 5.6°×5.6°, longitude/latitude), T42 (2.8°×2.8°), T63 (1.9°×1.9°), and 1°×1°, into which the IFS spectral fields are truncated. The IFS data, available as gridded data, are averaged into the model grid. Here, the T42 (2.8°×2.8°) horizontal resolution of Oslo CTM2 was used to calculate averages over 10° latitude zones.

The Oslo CTM2 has previously been applied in model/model comparisons and tested against observations (e.g., Isaksen et al. 1990; Gauss et al. 2003; Isaksen et al. 2005; Andersen et al. 2006). The global chemical transport model Oslo CTM2 has been evaluated against measurements by satellite-based instruments, ozone sondes, and aircraft (Søvde et al. 2008). All reactions and species in the Oslo CTM2 are described in detail in the study by Søvde et al. (2008). Recently, the model was used to investigate the observed record ozone decline over the Arctic during winter/spring 2011 (Balis et al. 2011; Isaksen et al. 2012; Varotsos et al. 2012).

2.2 SBUV Satellite Data

The ozone satellite data used in this study come from the SBUV (Version 8.6) merged total and profile ozone data sets for the period 1998 to 2009. The SBUV merged ozone data sets are monthly mean zonal and gridded average products constructed by merging individual SBUV/SBUV/2 (total and profile ozone) satellite data sets. The data are available at various altitude layers and the total column in Dobson units (DU) at the webpage http://acdb-ext.gsfc.nasa.gov/Data_services/merged/. Details can be found in the studies of Bhartia et al. (2004) and McPeters et al. (2011). Results of SBUV/2 ozone profile comparisons with other data sources are discussed by Petropavlovskikh et al. (2005), Nazaryan and McCormick (2005), Fioletov et al. (2006), Terao and Logan (2007)

3 Results and Discussion

Figure 1 shows the time series of zonally averaged monthly mean total ozone from Oslo CTM2 for the period 1998–2009 in comparison to respective satellite-derived ozone retrievals. The average percentage differences between the two data sets have been calculated from the following formula:

[(Model mean−Satellite mean)/Model mean]×100 %

From Fig. 1, it is evident that there are specific differences between the model and satellite-derived monthly mean total ozone. On average, the model generally underestimates total ozone over northern and southern mid-latitudes by 5.6 and 4.7 %, respectively. On the other hand, total ozone from the model is overestimated in the tropics by 1.9 %. In general, it appears that differences in columnar amounts are small in the tropics and medium over mid-latitudes but correlations are high.

Total ozone data from Oslo CTM2 have been correlated with SBUV satellite data using linear regression analysis. Model and satellite ozone columns were

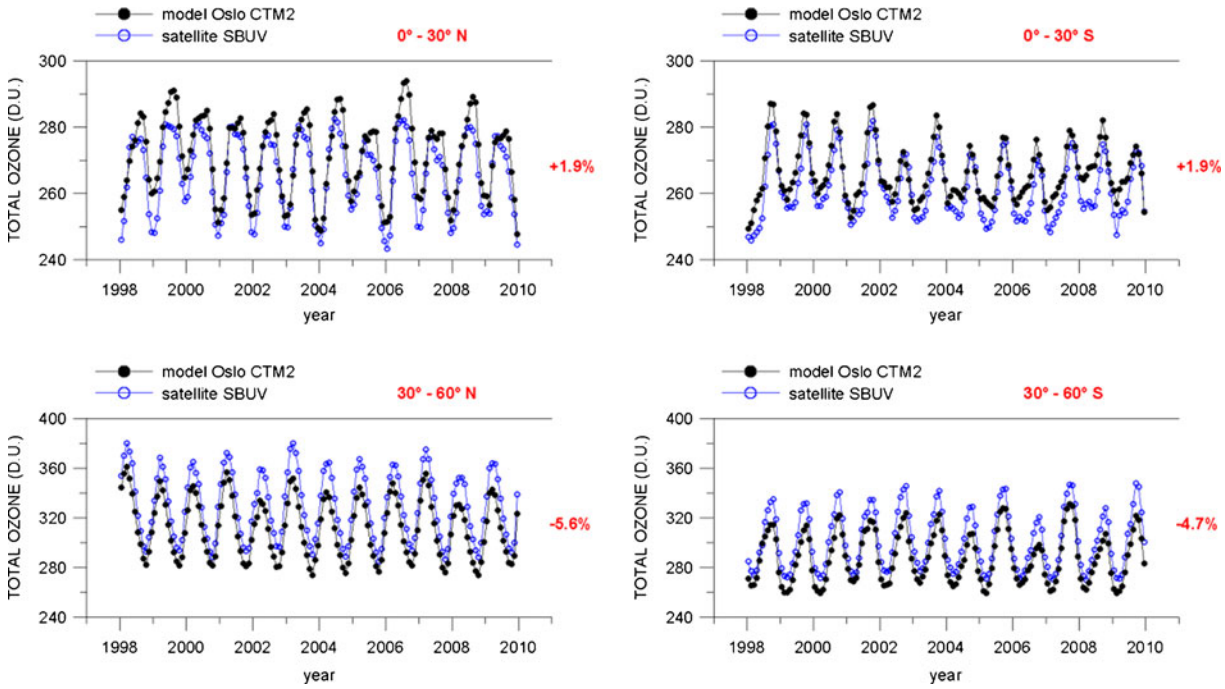

Fig. 1 Comparison of total ozone from Oslo CTM2 model calculations (*black*) and SBUV satellite retrievals (*blue*) for the period 1998–2009, and mean differences (percent) over middle and tropical latitudes

used to compute monthly zonal means per 10° latitude zones. The time series obtained have been pre-whitened to remove the annual cycle by subtracting from each month the long-term monthly mean of the 12-year period of record. The correlation analysis of model calculations with satellite retrievals was performed using the obtained deseasonalized time series for the period 1998–2009. Figure 2 shows the total ozone anomalies (in percent of the mean) from Oslo CTM2 model calculations and SBUV satellite retrievals at different latitudes zones (60–70° N, 50–60° N, 40–50° N, 30–40° N, 20–30° N, 10–20° N, 0–10° N, the equator, 10–20° S, 20–30° S, 30–40° S, 40–50° S, 50–60° S, and 60–70° S). The correlation coefficients between the two data sets at these latitude zones are summarized in Table 1.

As can be seen from Fig. 2, there is very good agreement between the Oslo CTM2 model and SBUV satellite ozone anomalies throughout the whole period of record. The correlation coefficients are highly significant at all latitude zones (Table 1). The dotted line in the middle of Fig. 2 shows the variations in the zonally averaged winds at 30 hPa taken from over the equator, as index of the QBO. The QBO index was obtained from the Climate Prediction Centre of NOAA at http://www.cpc.ncep.noaa.gov/data/indices/. The general features of the QBO in total ozone has been examined in several studies dating back to 1964 (e.g., Zerefos 1983 and references therein). They include a QBO in total ozone at the equator (between 5° N and 5° S) which is nearly in-phase with the QBO in 50-hPa temperature. The out-of-phase relation between the equatorial QBO and the middle latitude QBO is also easily seen in both hemispheres (Zerefos 1983). These features are evident in both Oslo CTM2 model and SBUV satellite data sets. It is noted that when the QBO is in its west phase, the global total ozone is positively correlated with the solar cycle; the opposite holds for the east phase of the QBO (Varotsos 1989).

Next, we have calculated the amplitude of QBO in total ozone, [i.e., (max–min)/2], which is presented in Fig. 3 in DU (left side) and in percent of the zonal mean (right side). In the tropics, the differences in amplitudes between the modeled and satellite-derived total ozone are up to 2 %. Over the southern extra tropics, the difference is about 0.5 %, increasing over northern extra tropics to about 1 % of the mean. Over the northern and southern sub-tropics (10°–20°) the differences are zero.

The highly significant correlations between the modeled and satellite-derived ozone variations, as described above, allowed looking at variations in ozone at lower altitudes as well. In the boundary layer, ozone is

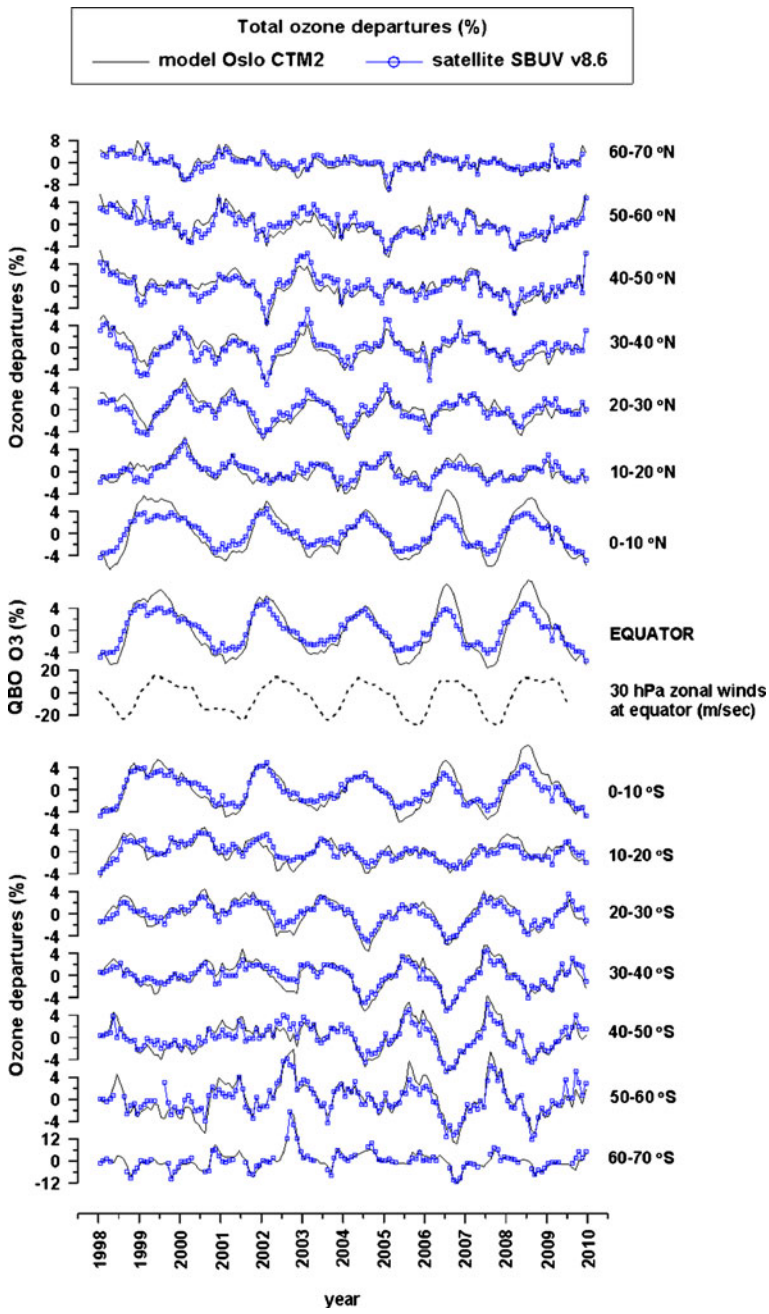

Fig. 2 Comparison between deseasonalized ozone anomalies (percent) from Oslo CTM2 model calculations (*solid line*) and SBUV satellite retrievals (*circles*) for the period 1998–2009. The *dotted line* shows the zonal winds at the equator at 30 hPa (meter per second) as index of the QBO

of high importance because it serves as an indicator of air quality. In the troposphere, it affects the atmospheric environment through radiative and chemical processes. With the Oslo CTM2, we were able to look at variations in both surface and tropospheric ozone. We have analyzed the seasonal variability of tropospheric ozone columns and surface ozone concentrations as calculated by the model. Here, we do not compare with satellite observations as we have done in the case of total ozone or with ground-based measurements. We just present the annual variations of surface and tropospheric ozone as calculated by the model, and refer to chapter 7 (Surface Ozone) of the World Data Centre for Greenhouse Gases (WDCGG) no. 36 report (WMO 2012) as a reference for discussion of seasonal variations from ground-truth measurements. A detailed comparison with data from ground-based stations is planned to be performed in a future study.

Table 1 Correlation coefficients, *R*, between deseasonalized total ozone from Oslo CTM2 model calculations and SBUV satellite retrievals in the period 1998–2009. *P* is the probability that *R* is zero

	R	Number of data	*P* value
60–70° N	0.86	143	<0.0001
50–60° N	0.86	144	<0.0001
40–50° N	0.85	144	<0.0001
30–40° N	0.85	144	<0.0001
20–30° N	0.84	144	<0.0001
10–20° N	0.82	144	<0.0001
0–10° N	0.94	144	<0.0001
Equator	0.94	144	<0.0001
0–10° S	0.92	144	<0.0001
10–20° S	0.81	144	<0.0001
20–30° S	0.92	144	<0.0001
30–40° S	0.92	144	<0.0001
40–50° S	0.91	144	<0.0001
50–60° S	0.90	140	<0.0001
60–70° S	0.95	106	<0.0001

The annual cycles of surface and tropospheric ozone simulated by the model averaged for each 30° latitudinal zone are presented in Fig. 4. Shown are monthly mean anomalies from the long-term annual mean, calculated by subtracting the long-term annual mean from each long-term monthly mean [i.e., January mean (1998–2011)− Annual mean (1998–2011)]. It appears that the seasonal variability of surface ozone from the model resembles the respective one reported in Fig. 7.1 of the WDCGG report (not shown), with the latitudinal mean mole fractions being elevated in spring in most latitudinal zones. It should be mentioned here that the stations reporting the mole fraction of surface ozone in WDCGG are few in number and unevenly distributed around the globe, and that the majority of those stations is located in Europe. Therefore, it is not strange if there are differences between our figure and Fig. 7.1 of the WDCGG report. However, our analysis restricts us to provide quantitative results from the comparison of the annual cycles, and only qualitative estimates can be inferred with caution.

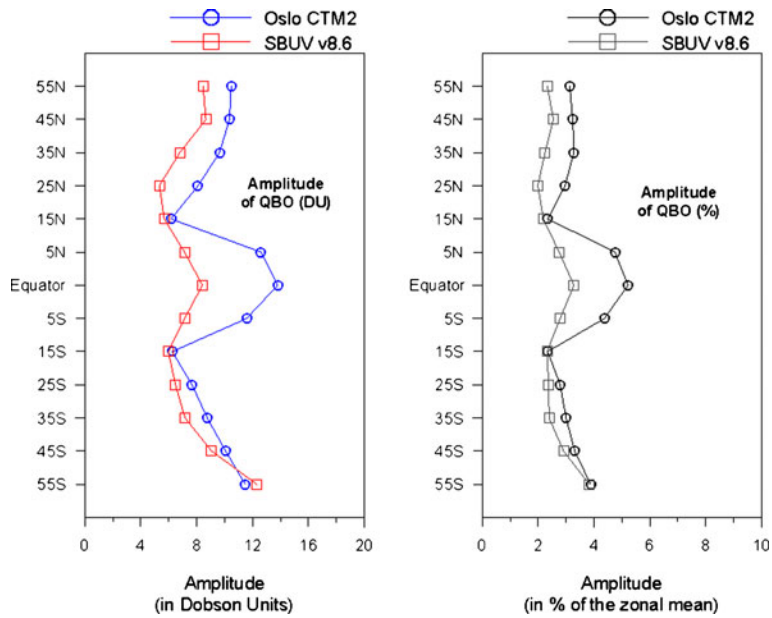

Fig. 3 Amplitude of QBO in total ozone in the period 1998–2009 based on model calculations (Oslo CTM2) and satellite retrievals (SBUV)

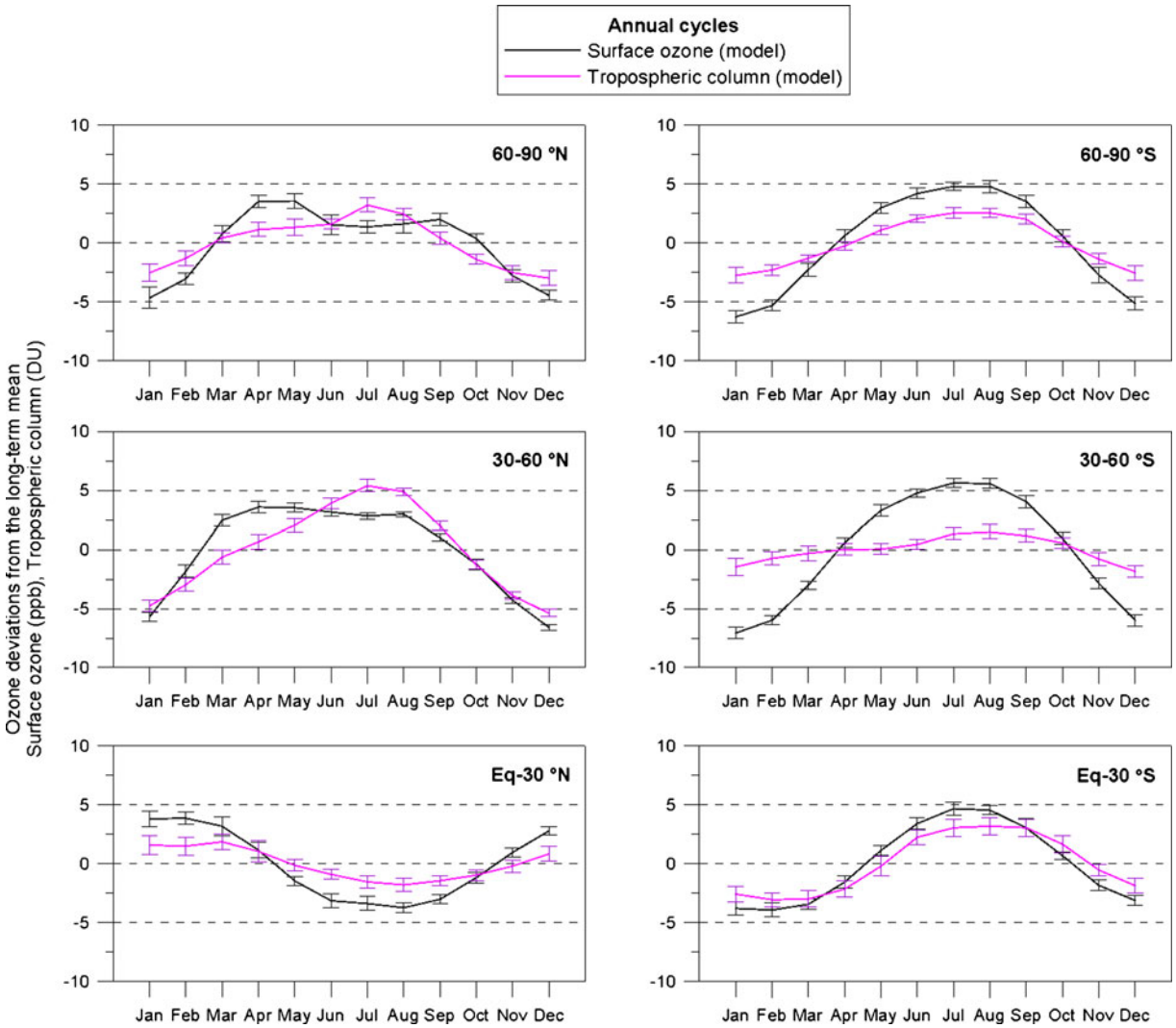

Fig. 4 Annual cycles of surface and tropospheric ozone by Oslo CTM2 model calculations for the period 1998–2009 averaged over 30° latitude zones

3.1 Conclusions

This study analyzed monthly averaged total ozone amounts from improved Oslo CTM2 model simulations for the period 1998–2009, and compared them with respective total ozone columns from SBUV satellite data. Total ozone columns from improved Oslo CTM2 model calculations compared well with the satellite data and the differences ranged between +2 % in the tropics and −6 % over middle latitudes. Comparison of monthly mean total ozone anomalies from the model with satellite retrievals using linear regression analysis, showed statistically significant correlation coefficients between the two data sets at all latitude zones (correlations of +0.94 between 10° N and 10° S, +0.80 over 10–60° N, and +0.87 over 10–60° S). Correlations between modeled ozone and the QBO were found to be the order of +0.8 in the tropics. The impact of QBO was most pronounced at equatorial latitudes with amplitudes of +4 to −4 %.

In summary, model results reproduced global observed ozone column well. Multi-year analysis gave good agreement between modeled and satellite-derived ozone column variations, and also revealed large-scale impact of the QBO on the ozone column. These findings provide significant level of confidence when studying interannual variations of ozone columns with the Oslo CTM2 model.

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