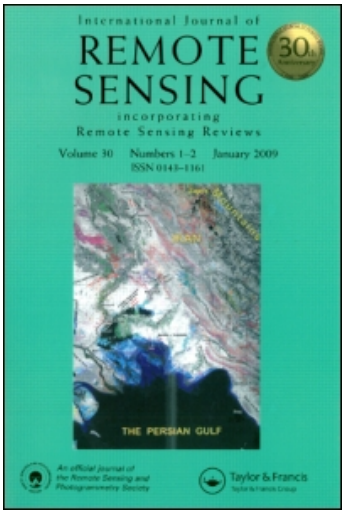

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A note on the comparison between total ozone from Oslo CTM2 and SBUV satellite data

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The results of a comparison between total ozone amounts derived from solar backscatter ultraviolet (SBUV) satellite observations and those calculated from the chemical transport model Oslo CTM2 are presented for the period 2001–2007. Monthly mean total ozone amounts from improved model simulations were used to compute monthly, seasonal and annual zonal means over 10° latitude zones, and compared with respective satellite retrievals over the northern and southern hemispheres. The results show that the improved model simulations slightly underestimate total ozone over the northern hemisphere when compared with the satellites by 1.4% on average, and slightly overestimate total ozone over the southern extra-tropics, middle and high latitudes by 1.6% on average. The mean difference between the model- and satellite-derived total ozone columns from 75°S to 75°N is estimated to be about –0.3%. A linear regression analysis between the model- and satellite-derived total ozone data shows statistically significant correlations between the two data sets at all latitude zones (about +0.8 in the tropics and more than +0.9 over all other latitudes). The annual cycle of total ozone is shown to be well reproduced by the model at all latitudes.

1. Introduction

Ozone is an important constituent of the Earth's atmosphere at a height of between 10 and 50 km. It absorbs ultraviolet radiation from the Sun and protects the biosphere from harmful effects of ultraviolet radiation. Ozone column amounts in the atmosphere can be obtained from surface measurements and satellite observations (e.g. Varotsos and Cracknell 1994, Zerefos *et al.* 1994, Chandra and Varotsos 1995, Gernandt *et al.* 1995, Varotsos *et al.* 1995, Kondratyev and Varotsos 1996, Zerefos 1997, Fioletov *et al.* 2002, Varotsos 2002, Svendby and Dahlback 2004, Chipperfield and Fioletov 2007, Kramer and Cracknell 2008), and can be calculated by chemistry-climate and chemistry-transport models (e.g. Eyring *et al.* 2006, Steinbrecht *et al.* 2006, Stolarski *et al.* 2006, Austin *et al.* 2008, 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 (Søvde *et al.* 2008).

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These models are continually being improved to include comprehensive chemistry and physics of both the troposphere and the stratosphere (e.g. Søvde *et al.* 2008 and references therein), as in the case of the Oslo chemical transport model (CTM2). To make the Oslo CTM2 model suitable for studying processes in the upper tropospheric and lower stratospheric (UTLS) region, the original tropospheric model (Stordal *et al.* 1985, Isaksen *et al.* 1990, Berntsen and Isaksen 1997, Sundet 1997) was extended to include comprehensive chemistry for the stratosphere (Gauss *et al.* 2003). 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 UTLS region, in the upper stratospheric region and in the troposphere (Søvde *et al.* 2008).

The purpose of this study was to provide additional evidence of improved simulations in total ozone columns by the updated Oslo CTM2 model, through a comparison of monthly, seasonal and annual mean total ozone, from the improved simulations for the period 2001–2007, with respective to total ozone averages from solar backscatter ultraviolet (SBUV) satellite data.

2. Data

2.1 The Oslo CTM2

The Oslo CTM2 is a global offline chemical transport model, driven by meteorological data from the European Centre for Medium-Range Weather Forecasts Integrated Forecast System (IFS) model. The meteorological data are given on a 3-hourly basis, produced for each day by a 36-h forecast with 12 h of spin-up, initialized from the analysis at noon (1200 Coordinated Universal Time (UTC)) the previous day (discussed by, for example, Wild *et al.* (2003), Søvde *et al.* (2008)). Using forecasts rather than analyses gives a more dynamically self-consistent data set and has been shown to give more realistic transport (e.g. Stohl *et al.* 2004, Scheele *et al.* 2005). The use of 3-hourly meteorological data instead of, for example, 6-hourly data, has been found to improve the transport further (e.g. Bregman *et al.* 2006). In the IFS model a spectral resolution of T319 is applied (T319 is approximately $0.5^\circ \times 0.5^\circ$ grid resolution, longitude/latitude, widely known by modellers). The horizontal resolution of the Oslo CTM2 can be varied between T21 (resolution of $5.6^\circ \times 5.6^\circ$, longitude/latitude), T42 ($2.8^\circ \times 2.8^\circ$), T63 ($1.9^\circ \times 1.9^\circ$) and $1^\circ \times 1^\circ$, into which the IFS spectral fields are truncated. The IFS data, available as gridded data, are averaged into the model grid. Sigma pressure hybrid coordinates are used in the vertical, extending in 40 layers from the surface up to 2 hPa (the uppermost layer mass centre is at 10 hPa). In the tropopause region the vertical resolution varies between about 0.8 km at high latitudes and about 1.2 km at low latitudes, and above 100 hPa the resolution is 20 hPa. Advective transport is calculated using the highly accurate and low diffusive second-order moments scheme (Prather 1986).

To make the Oslo CTM2 suited for studying processes in the UTLS, the original tropospheric model (Stordal *et al.* 1985, Isaksen *et al.* 1990, Berntsen and Isaksen 1997, Sundet 1997) was extended to include comprehensive chemistry for the stratosphere as well (Gauss *et al.* 2003). A heterogeneous chemistry scheme (Carslaw *et al.* 1995) and the Fast-J2 method for the calculation of photodissociation coefficients (Wild *et al.* 2000, Bian and Prather 2002) were included, and the vertical resolution was improved. The parameterizations of lightning and aircraft emissions, both important for the nitrogen budget in the UTLS, were refined. The Oslo CTM2 has now been

improved with a new scheme for microphysics and heterogeneous chemistry, to better represent the formation of polar stratospheric clouds, including denitrification and dehydration (Søvde *et al.* 2008).

The Oslo CTM2 has previously been applied in model/model comparisons and tested against observations (Isaksen *et al.* 1990, 2005, Grini *et al.* 2002, Brunner *et al.* 2003, 2005, Gauss *et al.* 2003, 2006, Isaksen 2003, Andersen *et al.* 2006). It has been evaluated against measurements by satellite-based instruments, ozonesondes and aircraft (Søvde *et al.* 2008).

The tropospheric chemistry scheme is run with a numerical time step of 15 min (5 min for $OH/HO_2/RO_2$ reactions), contains 51 species and takes into account 86 thermal reactions, 17 photolytic reactions and 2 heterogeneous reactions (which are important in the new heterogeneous chemistry). It includes hydrocarbon chemistry and has been thoroughly tested (Brunner *et al.* 2003). The stratospheric chemistry scheme is an extension of the scheme used by Stordal *et al.* (1985) for the Oslo 2-D model and was later updated to include heterogeneous chemistry (Isaksen *et al.* 1990) before it was included in the 3-D Oslo stratospheric chemical transport model (SCTM-1; Rummukainen *et al.* 1999) and the Oslo CTM2. Fifty-five species and seven families are included, and a total of 159 reactions (104 thermal, 47 photolytic and 8 heterogeneous), which are integrated with a numerical time step of 5 min. Of these species, 17 are also treated in the tropospheric scheme. The heterogeneous chemistry scheme is part of the stratospheric chemistry. The total number of species in the Oslo CTM2 amount to 97, including families. Bromine, chlorine chemistry and NOx are included. All reactions and species in the Oslo CTM2 are described in detail in the study by Søvde *et al.* (2008).

2.2 SBUV satellite data

The total ozone satellite data used in this study come from the Solar Backscatter UltraViolet Instrument (SBUV/2). Use was made of the Version 8 Zonal Profile Ozone data set for the period January 2001 to December 2007. The SBUV/2 instrument is a scanning double monochromator measuring backscattered solar radiation in 12 discrete wavelength bands ranging from 252.0 to 339.8 nm. In previous SBUV algorithms, total column ozone was retrieved using the four longest wavelengths, and then a profile was retrieved using the eight shortest wavelengths. In the version 8 algorithm released in 2004, an ozone profile is retrieved using all 12 wavelengths, and total column ozone is the integral of the profile (Bhartia *et al.* 2004). The version 8 algorithm is optimized to provide a self-consistent long-term ozone record. The SBUV/2 satellite data used here have been reprocessed with the version 8 algorithm and are available at www.cpc.ncep.noaa.gov/products/stratosphere/sbuv2to. The data are available as column ozone in Dobson Units (DU) for 13 layers. The 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) and Terao and Logan (2007).

In this study, total ozone was calculated by summing the profile ozone data for all 13 layers.

3. Results and discussion

Figure 1(*a*) shows the latitudinal distribution of zonally averaged annual mean total ozone from Oslo CTM2 calculations for the period 2001–2007 in comparison with

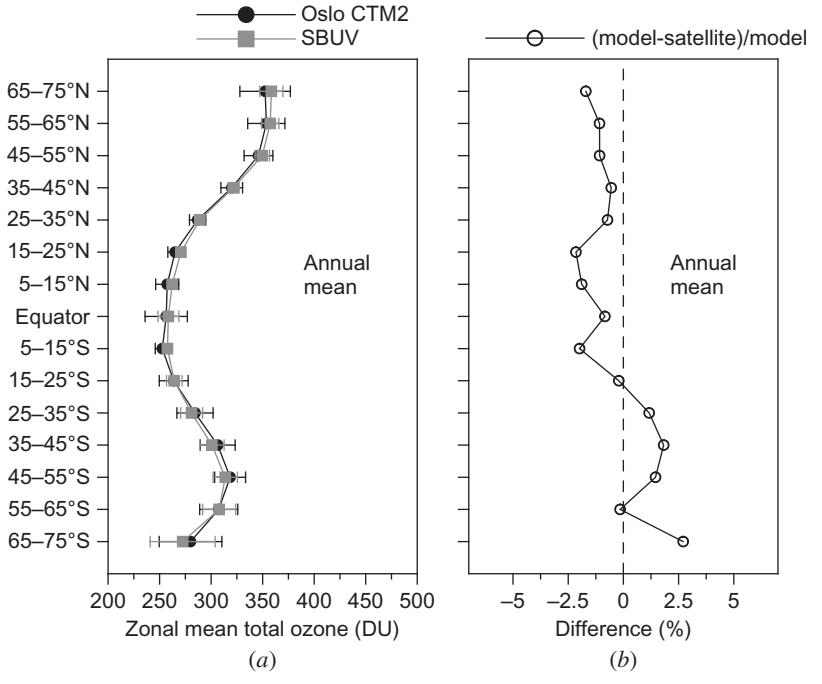

Figure 1. (*a*) Comparison between annual mean total ozone (DU) from Oslo CTM2 calculations and SBUV satellite data for the period 2001–2007. Error bars show the standard deviation (2σ) from each mean. (*b*) The respective differences are shown as percentages.

total ozone from SBUV satellite observations. Figure 1(*b*) shows the respective differences between the two data sets as a percentage, calculated as [(model value – satellite value)/model value] × 100%. From figure 1 it is evident that there are specific differences between the model- and satellite-derived annual mean total ozone. The model generally underestimates total ozone over the northern hemisphere by 1.4%, over the tropics by 0.8% and over the southern subtopics by 1.1%. However, over the southern extra-tropics, middle and high latitudes, total ozone from the model is overestimated by 1.5, 0.7 and 2.7%, respectively. Table 1 summarizes the mean differences between the model- and satellite-derived total ozone columns at each 10° latitude zone: the mean differences are less than ±2.7%.

Figure 2 shows the comparison between the model and satellite total ozone amounts for each season (December-January-February (DJF), March-April-May (MAM), June-July-August (JJA) and September-October-November (SON)), together with the respective differences as a percentage. Again there is good agreement between the latitudinal distributions of seasonally averaged total ozone from the model calculations and the satellite data. In wintertime, the highest differences between the model and the satellite data are found over the southern tropical latitudes where the model underestimates total ozone by 4.6% (figure 2(*b*)). In the northern hemisphere, however, the wintertime simulated total ozone shows excellent agreement with the satellite observations (differences less than about 1%). In springtime, differences between model and satellite-derived total ozone do not exceed ±3% (figure 2(*d*)), and in the summer a mean difference of about –6.5% in total ozone is observed between the latitudes 55°S and 65°S (figure 2(*f*)). In autumn, the highest

Table 1. Comparison between annual mean total ozone (in DU) from Oslo CTM2 calculations and SBUV satellite data for the period 2001–2007, averaged for each 10° latitude zone.

2001–2007	Annual mean total ozone (in DU)		
Latitude zone	Oslo CTM2	SBUV	Mean difference (%)
65–75°N	352.4	358.4	–1.7
55–65°N	353.6	357.4	–1.1
45–55°N	345.9	349.6	–1.1
35–45°N	320.0	321.7	–0.5
25–35°N	286.9	289.0	–0.7
15–25°N	265.0	270.7	–2.1
5–15°N	257.4	262.2	–1.9
Equator	256.4	258.5	–0.8
5–15°S	252.6	257.6	–2.0
15–25°S	263.7	264.2	–0.2
25–35°S	284.4	281.0	+1.2
35–45°S	306.4	300.8	+1.8
45–55°S	318.4	313.7	+1.5
55–65°S	307.4	307.8	–0.1
65–75°S	280.0	272.4	+2.7

differences between the model and satellite data are found over the tropics of the northern hemisphere, where the model underestimates total ozone by about 4.5% (figure 2(*h*)).

In addition to the seasonal comparisons described above, total ozone data from the Oslo CTM2 were compared with SBUV satellite retrievals on a monthly basis, using linear regression analysis. Figure 3 shows scatter plots between the Oslo CTM2- and SBUV satellite-derived monthly mean total ozone, over different latitude zones: (*a*) northern extra-tropics (25–45°N), (*b*) northern middle latitudes (45–65°N), (*c*) northern high latitudes (65–75°N), (*d*) northern tropics (5–25°N), (*e*) equator (5°S–5°N), (*f*) southern tropics (5–25°S), (*g*) southern extra-tropics (25–45°S), (*h*) southern middle latitudes (45–65°S), (*i*) southern high latitudes (65–75°S). The correlation analysis was performed using monthly mean data from the two data sets for the period 2001–2007. As can be inferred from the scatter plots and from the slopes of the regression lines, there are statistically significant correlations between the two data sets at all latitudes. The highest correlation coefficients are found over the extra-tropics, over middle and high latitudes and in both hemispheres (correlations greater than +0.9). Over the tropics the correlation coefficients are estimated to be about +0.8. All correlation coefficients are statistically significant at the 99% confidence level.

Part of the strong correlations shown in figure 3 can be attributed to the annual cycle of total ozone, which is presented in figure 4 for (*a*) the Oslo CTM2 calculations and (*b*) the SBUV satellite data. There is excellent agreement between the annual cycles of the two data sets, indicating the close correspondence between the model simulations and the satellite total ozone retrievals. Good comparison also exists between the latitudinal distributions of the amplitudes of the annual cycles, calculated as [(maximum value – minimum value)/2] as a percentage of the zonal mean, as shown in figure 4(*c*). Over the tropics the differences in the amplitude of the annual cycle are up to 2%. Over the north and south middle latitudes the differences are less than ± 2%, increasing over high latitudes.

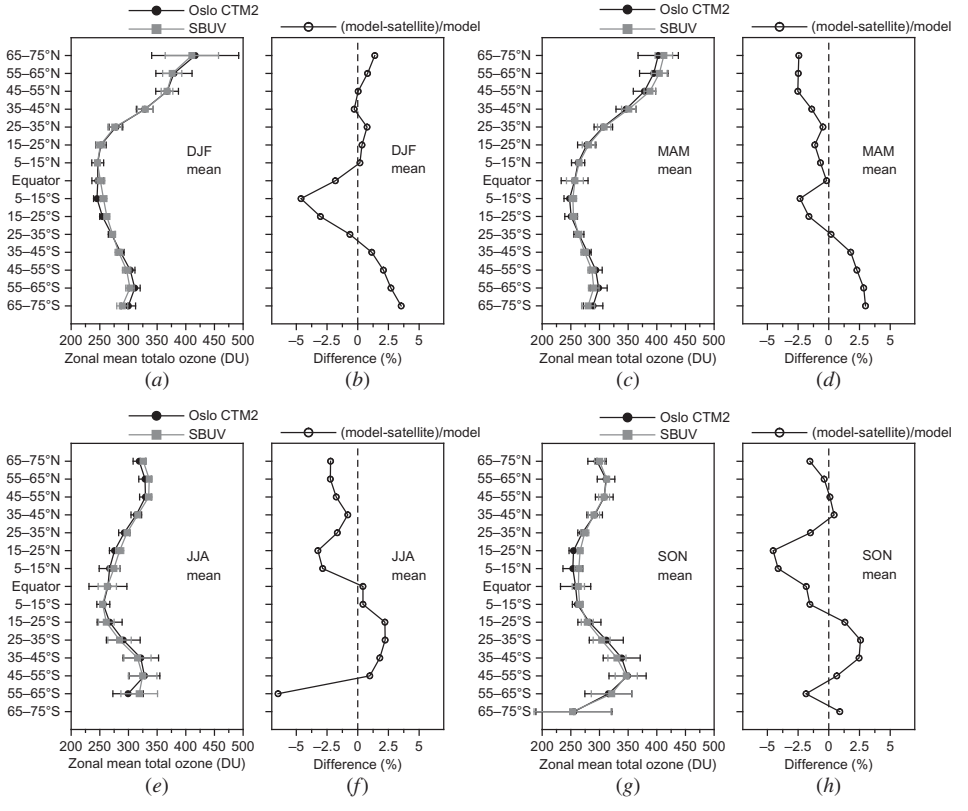

Figure 2. Comparison between total ozone (DU) from Oslo CTM2 calculation and SBUV satellite data for the period 2001–2007 for different seasons: (*a*)-(*b*) DJF, (*c*)-(*d*) MAM, (*e*)-(*f*) JJA and (*g*)-(*h*) SON.

4. Summary

This study analysed annually and seasonal averaged total ozone amounts from improved Oslo CTM2 simulations for the period 2001–2007, and compared them with respective total ozone columns from SBUV satellite data. The main results can be summarized as follows:

- Global total ozone amounts from the Oslo CTM2 calculations show good agreement with respective total ozone amounts retrieved from the SBUV satellite data set.
- Oslo CTM2 simulations slightly underestimate the total ozone over the northern hemisphere by about 1.4% on average, and slightly overestimate the total ozone over the southern extra-tropics, middle and high latitudes by about 1.6% on average. The mean difference between the model- and satellite-derived total ozone columns over 75° S to 75° N gives an underestimation of total ozone from the model by about –0.3%.
- Monthly mean total ozone from the model was also compared with satellite retrievals using linear regression analysis. The results show statistically significant correlations between the two data sets at all latitudes (correlation coefficients of +0.8 over the tropics, and greater than +0.9 over all other latitudes).
- The latitudinal distribution of the seasonal variations of zonally averaged total ozone from the model agrees well with the respective distribution of zonally averaged total ozone from the satellite observations.

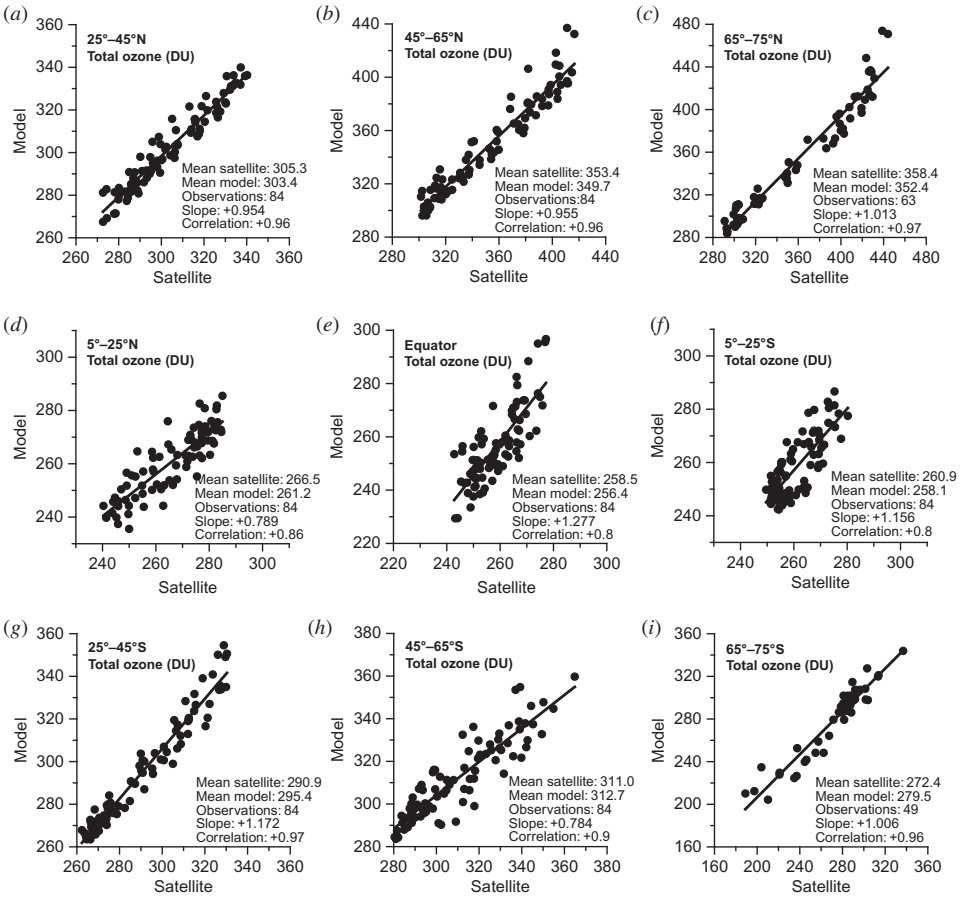

Figure 3. Scatter diagrams between monthly mean total ozone from Oslo CTM2 calculations and SBUV satellite data for the period 2001–2007, for different latitude zones: (*a*) northern extra-tropics (25–45°N), (*b*) northern middle latitudes (45–65°N), (*c*) northern high latitudes (65–75°N), (*d*) northern tropics (5–25°N), (*e*) equator (5° S–5°N), (*f*) southern tropics (5–25°S), (*g*) southern extra-tropics (25–45°S), (*h*) southern middle latitudes (45–65°S), (*i*) southern high latitudes (65–75°S).

- Good agreement also exists between the latitudinal distributions of the amplitudes of the annual cycles in total ozone from model and satellite data. Over the tropics differences of up to 2% in the amplitude of the annual cycle are observed. Correspondingly, over the north and south middle latitudes the differences are less than ± 2%, increasing over high latitudes.
- In general, the zonal mean total ozone columns from the improved Oslo CTM2 simulations compare well with the SBUV satellite data. The differences are within ±2.7%.

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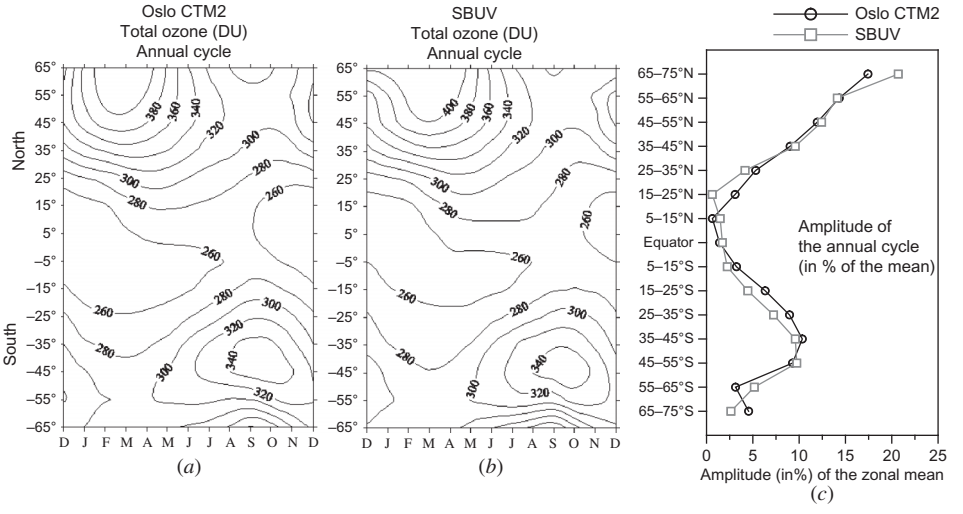

Figure 4. Comparison between the latitudinal distribution of the annual cycles of total ozone from (*a*) Oslo CTM2 calculations and (*b*) SBUV satellite data. (*c*) Comparison between the amplitudes of the annual cycles per latitude zone as a percentage of the zonal mean.

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