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The use of QBO, ENSO and NAO perturbations in the evaluation of GOME-2/MetopA total ozone measurements

Kostas Eleftheratos[1,2], Christos S. Zerefos[2,3,4,5], Dimitris S. Balis[6], Maria-Elissavet Koukouli[6], John Kapsomenakis[3], Diego G. Loyola[7], Pieter Valks[7], Melanie Coldewey-Egbers[7], Christophe Lerot[8], Stacey M. Frith[9], Amund Søvde Haslerud[10], Ivar S. A. Isaksen[10,11], Seppo Hassinen[12]

[1]Laboratory of Climatology and Atmospheric Environment, Faculty of Geology and Geoenvironment, National and Kapodistrian University of Athens, Greece
[2]Biomedical Research Foundation of the Academy of Athens, Athens, Greece
[3]Research Centre for Atmospheric Physics and Climatology, Academy of Athens, Athens, Greece
[4]Mariolopoulos-Kanaginis Foundation for the Environmental Sciences, Athens, Greece
[5]Navarino Environmental Observatory (N.E.O.), Messinia, Greece
[6]Laboratory of Atmospheric Physics, Department of Physics, Aristotle University of Thessaloniki, Greece
[7]Institut für Methodik der Fernerkundung (IMF), Deutsches Zentrum für Luft- und Raumfahrt (DLR), Oberpfaffenhofen, Germany
[8]Royal Belgian Institute for Space Aeronomy (BIRA), Brussels, Belgium
[9]Science Systems and Applications, Inc., Lanham, MD, USA
[10]Cicero Center for International Climate Research, Oslo, Norway
[11]Department of Geosciences, University of Oslo, Oslo, Norway
[12]Finnish Meteorological Institute, Helsinki, Finland

Correspondence to: Kostas Eleftheratos (kelef@geol.uoa.gr)

Abstract. In this work we present evidence that quasi cyclical perturbations in total ozone (Quasi Biennial Oscillation (QBO), El Nino Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO)) can be used as independent proxies in validating Global Ozone Monitoring Experiment-2 aboard MetopA (GOME-2A) satellite total ozone data, using ground-based measurements, other satellite data and chemical transport model calculations. The analysis is performed in the frame of the validation strategy on longer time scales within the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), Satellite Application Facility on Atmospheric Composition Monitoring (AC SAF) project, and covers the period 2007-2016. In general, we find that GOME-2A total ozone data depict the QBO/ENSO/NAO natural fluctuations in concurrence with co-located Solar Backscatter Ultraviolet Radiometer (SBUV), GOME-type Total Ozone Essential Climate Variable (GTO-ECV) and ground-based (GB) observations. Total ozone from GOME-2A is well correlated with the QBO (highest correlation in the tropics of +0.8) in agreement with SBUV, GTO-ECV and GB data which also give the highest correlation in the tropics. The differences between deseazonalised GOME-2A and GB total ozone in the tropics are within ±1%. These differences were tested further as to their correlations with the QBO. The differences had practically no QBO signal, providing an independent test of the stability of the long-term variability of the satellite data. Correlations between GOME-2A total ozone and the Southern Oscillation Index (SOI) were studied over the tropical Pacific Ocean after removing seasonal and QBO related variability. Correlations between ozone and SOI are the order of +0.6, in consistency with SBUV and GB observations. Differences between GOME-2A and GB measurements at the station of Samoa (American Samoa; 14.25^{o} S, 170.6^{o} W) are within ±1.5%. We also studied the impact of NAO on total ozone in the northern mid-latitudes in winter. We find very good agreement between GOME-2A and GB

observations over Canada and Europe as to their NAO-related variability, with mean differences reaching the ±1% levels. The agreement and small differences which were found between the independently produced total ozone data sets as to the influence of QBO, ENSO and NAO show the importance of these climatological proxies as additional tool for monitoring the long-term stability of satellite-ground truth biases.

1 Introduction

Ozone is an important gas of the Earth's atmosphere. In the stratosphere, ozone is considered as *good ozone* because it absorbs ultraviolet-B radiation from the Sun thus it protects the biosphere from a large part of the Sun's harmful radiation (e.g. Eleftheratos et al., 2012; Hegglin et al., 2015). In the lower atmosphere and near the surface, natural ozone has an equally important beneficial role because it initiates the chemical removal of air pollutants from the atmosphere such as carbon monoxide, nitrogen oxides and methane. Above natural levels however, ozone is considered as *bad ozone* because it can harm humans, plants and animals. In addition, increases in tropospheric ozone lead to a warming of the Earth's surface because ozone is a greenhouse gas (Hegglin et al., 2015).

Ozone in the atmosphere can be measured by ground-based instruments, by balloons, aircraft and satellites and can be calculated by chemical transport model (CTM) simulations. Measurements by satellites from space provide ozone profiles and column amounts over nearly the entire globe on a daily basis (e.g. WMO, 2014). The three Global Ozone Monitoring Experiment-2 (GOME-2) instruments carried on Metop platforms A, B and C serve this purpose. The first was launched in 2006, the second in 2012 and the last one will be launched in 2018. The three GOME-2 instruments will provide unique long-term data sets of more than 15 years (2007-2024) related to atmospheric composition and surface ultraviolet radiation using consistent retrieval techniques (Hassinen et al., 2016). The GOME-2 off-line data is set to make a significant contribution towards climate and atmospheric research while providing near real-time data for use in weather forecasting and air quality forecasting applications (Hassinen et al., 2016).

Validation of satellite ozone measurements is performed with ground-based (GB) measurements as well as other satellite instruments (Hassinen et al., 2016). Validation of GOME-2A total ozone for the period 2007-2011 was performed by Loyola et al. (2011) and Koukouli et al. (2012). It was found that GOME-2 total ozone data agree at the ±1% level with GB measurements and other satellite data sets (Hassinen et al., 2016). The consistency between GOME-2A and GOME-2B total ozone columns, including a validation with GB measurements, was presented by Hao et al. (2014). An updated time series of the differences between GOME-2A and GOME-2B with GB observations can be found in Hassinen et al. (2016). The long-term stability of the two satellite instruments was also noted in that study. Both satellites are consistent over the Northern Hemisphere with negligible latitudinal dependence, while over the Southern Hemisphere there is a systematic difference of 1% between the two satellite instruments (Hassinen et al., 2016).

Chiou et al. (2014) compared zonal mean total column ozone inferred from three independent multi-year data records, namely, SBUV (v8.6) total ozone, GOME-type Total Ozone Essential Climate Variable (GTO-ECV) and GB total ozone for the period 1996-2011. Their analyses were conducted for the latitudinal zones of 0-30^{o} S, 0-30^{o}

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N, 50-30^o S, and 30-60^o N. It was found that, on average, the differences in monthly zonal mean total ozone vary between -0.3 and 0.8% and are well within 1%. In that study it was concluded that despite the differences in the satellite sensors and retrievals methods, the SBUV v8.6 and GTO-ECV data records show very good agreement both in the monthly zonal mean total ozone and the monthly zonal mean anomalies between 60°S and 60°N. The GB zonal means showed larger scatter in the monthly mean data compared to satellite-based records, but the scattering was significantly reduced when seasonal zonal averages were analysed. The differences between SBUV and GB total ozone data presented in Chiou et al. (2014) are well in agreement with Labow et al. (2013), who systematically compared SBUV (v8.6) total ozone data with that measured by Brewer and Dobson instruments at various stations as a function of time, satellite solar zenith angle, and latitude. The comparisons showed good agreement (within ±1%) over the past 40 years with very small bias approaching zero over the last decade. Comparisons with ozone sonde data showed good agreement in the integrated column up to 25 hPa with differences not exceeding 5% (Labow et al., 2013).

The observed small biases (at the percentage level) between satellite and GB observations of total ozone, as have been documented in the above studies, ensure the provision of accurate satellite ozone measurements. The high accuracy and stability of the satellite instruments is essential for monitoring the expected recovery of the ozone layer resulting from measures adopted by the 1987 Montreal protocol and its amendments (e.g., Zerefos et al., 2009; Loyola et al., 2011). It is known that total ozone varies strongly with latitude and longitude as a result of chemical and transport processes in the atmosphere. Total ozone also varies with season. Seasonal variations are larger over middle and high latitudes and smaller in the tropics (e.g. WMO, 2014). On longer time scales total ozone variability is related to large scale natural oscillations such as the Quasi-Biennial Oscillation (QBO) (e.g. Zerefos et al., 1983; Baldwin et al., 2001), the El Nino Southern Oscillation (ENSO) (e.g. Zerefos et al., 1992; Oman et al., 2013; Coldewey-Egbers et al., 2014), the North Atlantic Oscillation (NAO) (e.g. Ossó et al., 2011; Chehade et al., 2014) and the 11-year solar cycle (e.g. Zerefos et al., 2001; Tourpali et al., 2007; Brönniman et al., 2013). Moreover, volcanic eruptions may also alter the thickness of the ozone layer (Zerefos et al., 1994; Frossard et al., 2013; Rieder et al., 2013; WMO, 2014). These natural perturbations affect the background atmosphere and consequently the distribution of the ozone layer. In this context, the study of the effect of known natural fluctuations in total ozone could serve as additional tool for evaluating the long-term variability of satellite total ozone data records.

The objective of the present work is to examine the ability of the GOME-2A total ozone data to capture the variability related to dynamical proxies of global and regional importance such as the QBO, ENSO and NAO, in comparison to GB measurements, other satellite data and model calculations. The variability of total ozone from GOME-2A is compared with the variability of total ozone from the other examined data sets during these naturally-occurring fluctuations. The analysis is performed in the frame of the validation strategy of GOME-2A data on longer time scales within the project of EUMETSAT, AC SAF. The validation includes the study of monthly means of total ozone, the annual cycle of total ozone, the amplitude of the annual cycle [i.e., (max-min)/2], the relation with the QBO (zonal winds at the equator at 30 hPa), the relation with ENSO (correlation with SOI) and the relation with the NAO (correlations with the NAO index in winter (DJF mean)).

The annual cycle describes regular oscillations in total ozone that occur from month to month within a year. In general, month-to-month variations of total ozone are larger in middle and high latitudes than in the tropics. The QBO dominates the variability of the equatorial stratosphere (~16-50 km) and is easily seen as downward propagating easterly and westerly wind regimes, with a variable period averaging approximately 28 months. Circulation changes induced by the QBO affect temperature and chemistry (Baldwin et al., 2001). ENSO and NAO are naturally-occurring patterns or modes of atmospheric and oceanic variability, which orchestrate large variations in climate over large regions with profound impacts on ecosystems (Hurrell and Deser, 2009). We present the level of agreement between satellite-derived GOME-2A and GB total ozone in depicting natural oscillations like QBO, ENSO and NAO, highlighting the importance of these climatological proxies to be used as additional tool for monitoring the long-term stability of satellite-ground truth biases.

2 Data sources

The analysis uses GOME-2 satellite total ozone columns for the period 2007-2016. This data forms part of the operational EUMETSAT AC SAF GOME-2/MetopA GDP4.8 data product provided by the German Aerospace Center (DLR). The GOME-2 total ozone data have been monthly averaged on a $1^{o}x1^{o}$ latitude longitude grid. The overview of the GOME-2A satellite instrument and of the GOME-2 atmospheric data provided by AC SAF can be found in Hassinen et al. (2016).

To examine the natural variability of ozone on longer time scales, we have additionally analysed the GOME/ERS-2, SCIAMACHY/Envisat, GOME-2A, and OMI/Aura merged prototype level 3 harmonized data record (GTO-ECV, $1^{o}x1^{o}$) for the period 1995-2016 (Coldewey-Egbers et al., 2015; Garane et al., 2018). This GTO-ECV ozone data product was generated and provided by DLR as part of the European Space Agency Ozone Climate Change Initiative (ESA O3 CCI) project. The ESA O3 CCI merged level-3 record, which is based on GOME/SCIAMACHY/GOME-2A/OMI level-2 data, was obtained using the GODFIT v3.0 retrieval algorithm. More on ESA O3 CCI datasets can be found in the studies by Van Roozendael et al. (2012), Lerot et al. (2014), Koukouli et al. (2015) and Garane et al. (2018).

Both datasets are compared with a combined TOMS/OMI/OMPS satellite total ozone data set constructed using data from the Total Ozone Mapping Spectrometer (TOMS) on Nimbus 7 (1979-1993), TOMS on Meteor 3 (1991-1994), TOMS on Earth Probe (1996-2005), the Ozone Monitoring Instrument (OMI) onboard the NASA Earth Observing System (EOS) Aura satellite (2005-present) and data from the next generation Ozone Mapping Profiler Suite (OMPS) nadir profiler instrument, launched in October 2011 on the Suomi National Polar-orbiting Partnership (NPP) satellite (McPeters et al., 2015). The total ozone data are available at 1^{o} x 1.25^{o} (TOMS) or 1^{o} x 1^{o} (OMI/OMPS) resolution from https://acd-ext.gsfc.nasa.gov/anonftp/toms/ (last access: 15 June 2018). From these data we constructed monthly mean total ozone data on a 5^{o} x 5^{o} grid. To account for known biases between the instruments (e.g., Labow et al., 2013) we use the Solar Backscatter Ultraviolet (SBUV) version 8.6 Merged Ozone Data Set (MOD) monthly zonal mean total ozone (https://acd-ext.gsfc.nasa.gov/Data_services/merged/index.html, also see next paragraph; last access: 15 June 2018) as a reference. We adjust each instrument such that the zonal mean in each 5o band averaged over the instrument lifetime matches the corresponding SBUV MOD zonal mean average. Thus the inherent longitudinal variability is retained from the TOMS/OMI/OMPS measurements but any latitude-dependent bias between the instruments is removed. With the exception of Meteor 3 TOMS in the northern hemisphere, all offsets where within 2% at low and mid-latitudes. Such a data set should not be used for long-term trends but is sufficient for analyzing periodic variability such as QBO, ENSO and NAO. We used data for the period 1995-2016.

In addition, we compare with satellite SBUV station overpass data from 1995 to 2016. The satellite data are based on measurements from three SBUV-type instruments from April 1970 to the present (continuous data coverage from November 1978). Even though the time series includes different versions of the SBUV instrument, the basic measurement technique remains the same over the advancement of the instrument from the Backscatter Ultraviolet (BUV) to SBUV/2 (Bhartia et al., 2013). Satellite overpass data over various ground-based stations are provided per day from https://acd-ext.gsfc.nasa.gov/anonftp/toms/sbuv/MERGED/ (last access: 15 June 2018). These overpass data are analogous to the SBUV MOD monthly zonal mean data previously mentioned. Both are constructed by first filtering lesser quality measurements and then averaging data from individual satellites when more than one instrument is operating. Monthly averages have been calculated by averaging the daily merged ozone overpass data for stations listed in Supplement Table S1. Details about the data are provided by McPeters et al. (2013) and Frith et al. (2014).

We also compare with GB observations of total ozone from a number of stations contributing to the World Ozone and Ultraviolet Radiation Data Centre (WOUDC). The WOUDC data centre is one of six World Data Centres which are part of the Global Atmosphere Watch programme of the World Meteorological Organization (WMO). The WOUDC data centre is operated by the Meteorological Service of Canada, a branch of Environment Canada. In total, we analysed total ozone daily summaries from 193 ground-based stations operating either Brewer, Dobson, filter, SAOZ or microtops instruments. The GB total ozone measurements are available from the website https://woudc.org/archive/Summaries/TotalOzone/Daily_Summary/ (last access: 15 June 2018). The various stations used in this study are listed in Table S1.

We have also analysed simulations of total ozone from the global 3-D chemical transport model (CTM) Oslo CTM3 (Søvde et al., 2012). The Oslo CTM3 has traditionally been driven by 3-hourly meteorological forecast data from the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS) model, whereas in this study we apply the OpenIFS model (https://software.ecmwf.int/wiki/display/OIFS/) (last access: 15 June 2018), cycle 38r1, which is an improvement from Søvde et al. (2012). Details on the model are given in Søvde et al. (2012). The Oslo CTM3 comprises both detailed tropospheric and stratospheric chemistry. Photochemistry is calculated using fast-JX version 6.7c (Prather, 2012), and chemical kinetics from JPL 2010 (Sander et al., 2011). Total ozone columns compare well with measurements and other model studies (Søvde et al., 2012 and references therein). The horizontal resolution of the model is 2.25^{o} x 2.25^{o}. We made use of the global monthly mean total ozone columns for the period 1995-2016.

To examine the QBO component on total ozone we made use of the monthly mean zonal winds at Singapore at 30 hPa. The zonal wind data at 30 hPa were provided by the Freie Universität Berlin (FU-Berlin) at http://www.geo.fu-berlin.de/met/ag/strat/produkte/qbo/qbo.dat (last access: 15 June 2018) (Naujokat, 1986). The impact of ENSO in the tropics was investigated by using the Southern Oscillation Index (SOI) from the Bureau of Meteorology of the Australian Government (http://www.bom.gov.au/climate/current/soi2.shtml) (last access: 15 June 2018). The correlation between total ozone and the NAO index was computed for the winter-mean (DJF) when the NAO amplitude is large (e.g. Hurrell and Deser, 2009), over Canada, Europe and the North Atlantic Ocean. Use was made of the principal component (PC)-based NAO index (DJF) which was provided by the Climate Analysis Section, NCAR, Boulder, USA (available at: https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based) (last access: 15 June 2018). Total ozone variability is also related to dynamical variability for example variability in tropopause height (e.g. Dameris et al., 1995; Hoinka et al., 1996; Steinbrecht et al., 1998). The impact of tropopause variability on total ozone variability was examined by analyzing the tropopause pressure from the independently produced NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) reanalysis 1 data set computed on a 2.5^{o} grid. The NCEP/NCAR reanalysis data were provided from the web site at https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.tropopause.html (last access: 15 June 2018) (Kalnay et al., 1996).

3 Results and discussion

3.1 Monthly zonal means and annual cycle

Figure 1 compares monthly mean total ozone from GOME-2A and SBUV (v8.6) satellite overpass data for stations shown in Table S1 (Supplement). The GOME-2A data were taken at a spatial resolution of 1^{o}x1^{o} around each of the ground-based monitoring stations listed in Table S1 and then averaged over the tropics, middle and high latitudes of both Hemispheres in 30^{o} latitudinal zones to provide the large scale monthly zonal means for the GOME-2A data. Accordingly, SBUV satellite overpass data were averaged over each geographical zone to provide the large scale zonal means for the SBUV observations. Mean differences and standard deviations between GOME-2A and SBUV total ozone were found to be +0.1 ± 0.7% in the tropics (0-30 deg.), about +0.8 ± 1.6% in mid-latitudes (30-60 deg.), about +1.3 ± 2.2% over the northern high latitudes (60-80 deg. N) and about -0.5 ± 2.9% over the southern high latitudes (60-80 deg. S). The differences were estimated as [GOME-2A – SBUV] / SBUV (%) from January 2007 to December 2016. Small differences were also found between GOME-2A and GB measurements (Figure 2 and Table 1), where here GB stations data have been averaged over each geographical zone to provide the large scale zonal means for the GB measurements. Mean differences and standard deviations between GOME-2A and GB total ozone were found to be -0.7 ± 1.4% in the tropics (0-30 deg.), +0.1 ± 2.1% in mid-latitudes (30-60 deg.), +2.5 ± 3.2% over the northern high latitudes (60-80 deg. N) and 0.0 ± 4.3% over the southern high latitudes (60-80 deg. S). We remind all estimates refer to the period between January 2007 and December 2016.

In summary, the largest differences between GOME-2A, SBUV (v8.6) and GB measurements are found over the southern high latitudes. In the tropics and mid-latitudes the respective differences are within ±1% or less, and the results are in line with Chiou et al. (2014). Validation results were also presented by Loyola et al. (2011), Koukouli et al. (2012), Coldewey-Egbers et al. (2015), Koukouli et al. (2015), updates of which are included in Hassinen et al. (2016). Our results based on updated to 2017 data largely confirm those studies, pointing to the good performance of GOME-2A when extending the period of record.

Next, we have studied the correlation between total ozone from GOME-2A and SBUV satellite data using linear regression analysis for the period 2007–2016. The regression model showed statistically significant correlations between the different datasets as follows: $R = +0.99$ in the tropics, mid-latitudes and the northern high latitudes and $R = +0.94$ in the southern high latitudes. All correlation coefficients are highly statically significant (99.9% confidence level). In the long-term, statistically significant correlation coefficients ($R \geq +0.94$) are also found between GOME-2A satellite and GB measurements (Figure 2) despite the different type of instruments used to measure total ozone from the ground.

A large part of the strong correlations shown in Figures 1 and 2 is attributable to the seasonal variability of total ozone which is presented in Figure 3 for GOME-2A, SBUV and GB data. More specifically, Figure 3 shows the seasonal variations of total ozone from stations mean data averaged per 10 degree latitude zones north and south. At high latitudes our analysis stops at 80 degrees. There is a very good agreement between the annual cycles of total ozone from the three datasets denoting the consistency of the satellite retrievals with GB observations. Similar annual cycles are also found with the GTO-ECV ozone data (not shown). Similar consistency is also revealed for the amplitudes of the annual cycles, computed as [(maximum value – minimum value)/2] in Dobson Units (DU). Figure 4 shows global maps of the amplitude of annual cycle of total ozone for the period 2007-2016 from GOME-2A (upper left panel), GTO-ECV (upper right) and the TOMS/OMI/OMPS (lower left) satellite data. All maps are plotted against the sine of latitude north and south in order to show areas according to their actual size. As can be seen from Figure 4, the amplitude of annual cycle is less than 20 DU in the tropics, increasing as we move towards middle and high latitudes up to 75 DU. Interestingly, there is pattern with small amplitude of annual cycle in the southern mid-latitudes with values of about 10-15 DU, seen in Figure 4 as a blue curved line crossing the longitudes around 60 degrees south, the origin of which is attributed to the small annual variation of total ozone in these parts. These features are consistent between all examined satellite data sets and are reproduced to a large extend by the Oslo CTM3 model as well, except in the southern mid-latitudes where the model seems to underestimate the observed annual cycle (Figure 4 lower right).

In summary, we find similar annual cycle and amplitude of annual cycle between total ozone from GOME-2A and the other examined total ozone data sets. The mean differences in the annual cycles of GOME-2A and SBUV satellite data are small in the tropics (0-30 deg.: 0.3 ± 2.4 DU), and increase as we move to mid-latitudes (30-60 deg.: 2.4 ± 4.4 DU) and higher latitudes (60-80 deg.: 1.7 ± 4.8 DU). These numbers are consistent with the ones found between GOME-2A and GB measurements (tropics: 1.1 ± 2.3 DU; mid-latitudes: 1.2 ± 5.1 DU; high latitudes: 5.1 ± 7.1 DU). In all latitude zones the correlation coefficients between the annual cycles of GOME-2A – SBUV and GOME-2A – GB data pairs were found to be greater than 0.9.

Before examining correlations with the large scale natural fluctuations QBO, ENSO and NAO, the mean annual cycle has been removed from the ozone data sets as described in the next section.

3.2 Correlation with QBO

We then studied how changes in dynamics affect the ozone columns in the atmosphere. The time series obtained have been deseasonalised by subtracting the long-term monthly mean from each individual monthly mean value. Ozone column variations for different latitude zones in the Northern and Southern Hemispheres have been compared. Figure 5 compares total ozone deseasonalised anomalies (in % of the mean) from GOME-2A and SBUV satellite retrievals in the tropics (10^o N–10^o S), sub-tropics (10^o–30^o) and mid-latitudes (30^o–60^o). The right panel of Figure 5 shows the respective anomalies from GTO-ECV data. Mean differences between GOME-2A and SBUV deseasonalised total ozone data between 60^o N and 60^o S are less than ±0.5% (Table 2). As can be seen from Table 2 and Figure 5, there is a very good agreement between the GOME-2A, GTO-ECV and SBUV total ozone anomalies over the entire period of observations. The correlation coefficients between GOME-2A and SBUV are highly significant everywhere (30^o–60^o N: +0.94; 10^o–30^o N: +0.95; 10^o N–10^o S: +0.98; 10^o–30^o S: +0.93; 30^o–60^o S: +0.87). The same stands when correlating the GTO-ECV with SBUV deseasonalised data (30^o–60^o N: +0.96; 10^o–30^o N: +0.97; 10^o N–10^o S: +0.98; 10^o–30^o S: +0.96; 30^o–60^o S: +0.93).

The line with dots in the middle panel of Figure 5 shows the equatorial zonal winds at 30 hPa which were used as a proxy index to study the impact of QBO on total ozone. The general features include a QBO signal in total ozone at latitudes between 10^o N and 10^o S which almost matches with the phase of QBO in the zonal winds. At higher northern and southern latitudes there is a clear phase shift in the QBO impact on total ozone. The impact of QBO is most pronounced in the tropics with amplitudes of +4% to −4% and it is less pronounced in the sub-tropics and mid-latitudes. As such, strong positive correlations with the QBO are found in the tropics (correlation between GOME-2A and QBO of about +0.77, t-test = 12.91) and weaker (usually of opposite sign) less significant correlations are found at higher latitudes (about −0.15 in the northern and about −0.45 in the southern extra tropics). Similar strong correlations in the tropics and weaker correlations in the extra tropics with the QBO are found for the GTO-ECV, SBUV and GB data.

These features are also evident in Figure 6 which compares GOME-2A (and GTO-ECV) satellite total ozone with GB observations with respect to the QBO. Mean differences and standard deviations between GOME-2A and GB and between GTO-ECV and GB deseasonalised total ozone data do not exceed one percent (Table 2). Again, correlation coefficients between deseasonalised GOME-2A and deseasonalised GB data are highly significant in all latitude zones (30^o–60^o N: +0.91; 10^o–30^o N: +0.91; 10^o N–10^o S: +0.94; 10^o–30^o S: +0.87; 30^o–60^o S: +0.88). The same stands for the GTO-ECV and GB data pairs (30^o–60^o N: +0.94; 10^o–30^o N: +0.89; 10^o N–10^o S: +0.94; 10^o–30^o S: +0.87; 30^o–60^o S: +0.85). Our results are in line with Eleftheratos et al. (2013) and Isaksen et al. (2014) who compared QBO-related ozone column variations from the chemical transport model Oslo CTM2 with SBUV satellite data for shorter time periods. In summary, it has been shown that GOME-2A depicts the significant effects of QBO on stratospheric ozone in concurrence with SBUV and GB measurements. The instrument captures correctly the variability of ozone in the tropics and the mid-latitudes, which is nearly in phase with the QBO in the tropics and out of phase in the northern and the southern mid-latitudes as have been shown by earlier studies (e.g. Zerefos, 1983; Baldwin et al., 2001).

3.3 Correlation with ENSO

Apart from the QBO, which affects the variability of total ozone in the tropics, an important mode of natural climate variability in the tropics is ENSO. To examine the impact of ENSO on total ozone in the tropics we first removed correlations with the QBO and then performed the correlation analysis with the SOI. The effect of the QBO was removed from the time series by using a linear regression model for the total ozone variations at each grid box, of the form:

$$D(t) = a0 + a1 * QBO(t) + residuals(t); 0 < t \leq T \qquad (1)$$

where D(t) is the monthly deseasonalised total ozone and t is the time in months with t=0 corresponding to the initial month and t=T corresponding to the last month. The term $a0$ is the intercept of the statistical model. To model QBO we made use of the equatorial zonal winds at 30 hPa. The term $a1$ is the regression coefficient of QBO. The QBO component was removed from the time series by using a phase lag with maximum correlation of 28 months (month lag -14 to month lag 13). Then, the remainders from Eq. (1) have been analysed to study the correlations between total ozone and SOI at each individual grid box.

Figure 7 presents the correlations between SOI and total ozone from GOME-2A (upper left panel), GTO-ECV (upper right) and TOMS/OMI/OMPS satellite data (bottom left), as well as between SOI and the Oslo model simulations (bottom right). All four plots refer to the period 2007-2016. As can be seen from Figure 7 (upper left), correlations of >0.3 between GOME-2A total ozone and SOI are found in the tropical Pacific Ocean at latitudes between 25 deg. north and south. These correlations were tested as to their statistical significance in the period 2007-2016 and were found to be statistical significant. A similar picture of correlation coefficients is also observed by the GTO-ECV and TOMS/OMI/OMPS data. Both data sets show similar results as to the range of correlations (>0.3) in the tropical Pacific for the common period of observations. Nevertheless, the spatial resolution is higher in the GOME-2A and GTO-ECV (1x1 deg.) data than in the TOMS/OMI/OMPS (5x5 deg.) data, so the former data sets perform better when looking at smaller space scales. We have to note here that in both maps there are larger areas with correlation coefficients >0.3 in the southern part of the tropics than in the northern part. However, this was mostly observed during the period 2007-2016. By examining the longer-term data record of the TOMS/OMI/OMPS data which extend back to the 1979, we find symmetry in the pattern of correlations north and south of the equator in the tropical Pacific Ocean (Figure A1 of Appendix A), which indicates that both sides of the tropical Pacific are affected more or less in a similar way by El Niño/La Niña events. Finally, the Oslo CTM3 gives small correlations (<0.3) in the tropical Pacific Ocean around the equator, except over the northern and southern subtropics where the model compares better with the observations.

The small rectangle in Figure 7 corresponds to the South Pacific region (10^{o}-20^{o} S, 180^{o}-220^{o} E) and the blue cross to the station Samoa (American Samoa; 14.25^{o} S, 189.4^{o} E), in which total ozone has been studied as for the impact of ENSO after removing variability related to the annual cycle and the QBO. Figure 8 shows an example of the ENSO impact on total ozone in the South Pacific Ocean. The upper panel shows the time series of total ozone anomalies from GOME-2A, GTO-ECV and TOMS/OMI/OMPS satellite data together with the SOI (Figure 8a). Comparisons of GOME-2A data with GTO-ECV data, SBUV overpass data and GB measurements at the station Samoa are shown in Figure 8b. The dotted line shows the respective tropopause pressure anomalies from NCEP reanalysis. All data sets point to the strong influence of ENSO on total ozone. Most evident is the strong decrease of about 4% in 1997/98 which was caused by the strongest El Niño event in the examined period. A strong decrease is also observed in the tropopause pressures by NCEP. Notable also is the strong La Niña event in 2010 which caused total ozone to increase by about 4%. We calculate a strong correlation between total ozone from GTO-ECV and SOI of +0.62 (99% confidence level), which accounts for about 40% of the variability of total ozone over the tropical Pacific Ocean when the annual cycle and QBO signal are removed. From the regression with SOI we estimated an ENSO-related term from which we calculated the amplitude of ENSO in total ozone as [maximum ozone - minimum ozone]/2. The amplitude of ENSO in total ozone was estimated to be 8.7 DU or 3.4% of the annual mean. This is comparable to the amplitude of annual cycle (7.7 DU or 3.0% of the mean) and ~3 times larger than the amplitude of QBO in this region (2.2 DU or 0.8% of the mean). These results are based on the GTO-ECV total ozone data. Similar results were also found at the station Samoa from GB observations (i.e. correlation with SOI: +0.51, amplitude of ENSO: 7.6 DU or 3.0% of the mean, amplitude of annual cycle: 6.7 DU or 2.7% of the mean). Statistics of total ozone such as mean, amplitude of annual cycle, amplitude of QBO and amplitude of ENSO in total ozone over the selected areas are presented in Table 3. Both satellite, GB and model data show consistent results. It also appears that the station Samoa represents well the greater area in the Southern Pacific as to the impact of ENSO.

From Figure 8 it also appears that there are high correlations with the tropopause height. The correlation coefficient between the NCEP tropopause pressure and GOME-2A total ozone over the South Pacific Ocean is of the order of +0.55 (Student's t-test statistics results: t-value = 7.11591, p-value <0.0001, N = 119). Accordingly, the correlation with GTO-ECV ozone data is the order of +0.59 (t-value = 11.67077, p-value <0.0001, N = 259) and with TOMS/OMI/OMPS the order of +0.52 (t-value = 9.49874, p-value <0.0001, N = 241). The high correlation between the tropopause pressure and total ozone on interannual and longer time scales points to the very strong link between these parameters. These links were already documented in the past (e.g. Steinbrecht et al., 1998, 2001) and are verified with the GOME-2A data. At the same time a strong correlation is also evident between tropopause pressure and SOI, again on interannual and longer time scales (R= +0.66, t-value = 14.25036, p-value <0.0001, N = 264). The above results point to the strong impact of ENSO on the tropical ozone column through the tropical tropopause; warm (El Niño) and cold (La Niña) events affect the variability of the tropopause which in turn affects the distribution of stratospheric ozone. In the tropics, where total ozone is mainly stratospheric, as the tropopause moves to higher altitudes (lower pressure), the stratosphere is compressed, reducing the amount of stratospheric (total) ozone. This happens during warm (El Niño) episodes. The opposite phenomenon occurs during cold (La Niña) events when the tropopause height decreases (higher pressure) and total ozone is then increased. These events can affect the long-term ozone trends in the tropics when looking at time periods when strong El Niño and La Niña events occur at the beginning and the end of the trend period respectively (Coldewey-Egbers et al., 2014).

Furthermore, in Figure 8 we have marked 7 stations in the greater South Asia region (35^o-45^o N, 45^o-125^o E) where total ozone is anti-correlated with the SOI. Admittedly, these anti-correlations are weak (about -0.3) but we thought worthwhile presenting the time series in these areas as well. Figure 9 shows the variability of total ozone after removing seasonal and QBO related variations, over the South Asia region (upper panel) and over the 7 stations averaged within this region (lower panel). As can be seen from this figure, the explained variance by ENSO is small, not exceeding 9%. In summary, our findings indicate that GOME-2A captures well the disturbances in total ozone during ENSO events with respect to satellite SBUV and GB observations. Our findings on the ENSO-related total ozone variations (low ozone during ENSO warm events, high ozone during ENSO cold events, and magnitude of changes) are in line with recent studies (e.g. Randel and Thompson, 2011; Oman et al., 2013, Sioris et al., 2014) included in the recent Ozone Assessment report (Pawson et al., 2014; WMO, 2014).

3.4 Correlation with NAO

The residuals from Eq. (1), free from seasonal and QBO related variations, were also used to study the correlation between total ozone and NAO in winter (DJF mean). The results are presented in Figure 10 which shows the correlation coefficients between total ozone and NAO index in winter from the GOME-2A (upper left), GTO-ECV (upper right) and TOMS/OMI/OMPS satellite data (lower left), and the Oslo CTM3 model calculations (lower right). Negative correlations between total ozone and NAO are presented with blue colours while positive correlations with red colours. From Figure 10 (upper left) it appears that total ozone is strongly correlated with NAO in many regions. Strong negative correlation coefficients are observed in the majority of the northern mid-latitudes (R about −0.6) while positive correlations exist in the tropics and some negative correlations in the southern mid-latitudes. These characteristics are observed in both GTO-ECV and TOMS/OMI/OMPS datasets and are reproduced by the Oslo model as well, all for the common period 2008-2016.

We note here that the results of the correlation analysis for the period 2008-2016 were based on a small sample of data (9 winters as DJF means) and therefore many of these correlation coefficients may not be statistically significant. The statistical significance of the correlation coefficients in every grid box was tested only with the TOMS/OMI/OMPS data (Figure A2, Appendix A), which provided us the opportunity to calculate the respective correlations using more data (37 winter means). It appears that when extending the data back to the 1980's the negative correlations in the southern mid-latitudes disappear while the positive correlations in the tropics become weaker; yet the observed anti-correlation between total ozone and NAO index in the northern mid-latitude zone holds strong. The dotted line in the plot shows areas with statistically significant correlation coefficients (99% confidence level). Indeed, statistically significant correlations between total ozone and NAO index in the long-term are found only over the northern mid-latitudes and not elsewhere.

According to this finding we have restricted the analysis of NAO to the northern mid-latitudes. Rectangles (Figure 10, upper left) correspond to two regions in the North Atlantic, i.e., 35^o-50^o N, 20^o-50^o W and 15^o-27^o N, 30^o-60^o W respectively, which were studied for the impact of NAO on total ozone after removing variability related to the annual cycle and the QBO. In addition we have studied a number of stations in Canada, USA, and Europe contributing ozone data to WOUDC, which are marked by red and green crosses in Figure 10. The red crosses refer to the monitoring stations in Canada and the US, and the green crosses to the stations in Europe. In Figure 11 we present the times series of total ozone anomalies from GOME-2A, GTO-ECV and TOMS/OMI/OMPS satellite data along with the NAO index in winter over the North Atlantic. Model calculations are shown as well. The dotted line shows the respective tropopause pressure anomalies from NCEP reanalysis. Comparisons between GOME-2A, GTO-ECV, SBUV (v8.6) overpass data and GB measurements over the various stations in Canada, USA and Europe are shown in Figure 12.

The observed anomalies over the North Atlantic Ocean point to the strong influence of NAO on total ozone in winter. Most evident is the strong increase in total ozone in 2010 of more than 8% particularly over 35^{o}-50^{o} N and 20^{o}-50^{o} W. This increase was accompanied by a strong increase in tropopause pressures. Both changes (in total ozone and tropopause pressures) occurred under a strong negative phase of NAO, the strongest one in the past 20 years. We observe strong anti-correlations among total ozone and NAO index in winter (R= –0.72 over 35^{o}-50^{o} N, 20^{o}-50^{o} W), which is statistically significant at the 99% confidence level. This anti-correlation suggests that about 50% of the variability of total ozone in winter is explained by NAO when the annual cycle and QBO signal are removed. From the regression with the NAO index we derived a NAO-related term from which we calculated the amplitude of NAO in total ozone as [maximum ozone - minimum ozone]/2. The amplitude of NAO over the North Atlantic region (35^{o}-50^{o} N, 20^{o}-50^{o} W) was estimated to be about 18 DU or 5.8% of the annual mean. This is about half of the amplitude of the annual cycle (which is ~37 DU or 11.7% of the mean). Similar correlation and amplitude were also found with the combined TOMS/OMI/OMPS satellite data and the Oslo CTM3 model simulations.

A similar but opposite correlation is found over the southern part of the North Atlantic (15^{o}-27^{o} N, 30^{o}-60^{o} W). Here, we estimate a significant correlation coefficient with NAO of +0.69, amplitude of NAO of about 9 DU (3.2% of the annual mean) and amplitude of annual cycle of about 16 DU (5.7% of the mean). Again, similar estimates are found with the TOMS/OMI/OMPS satellite data and reproduced by the model calculations as well. The annual mean total ozone and the amplitudes of annual cycle, QBO and NAO in total ozone over the studied regions in the North Atlantic are summarised in Table 4.

The time series of total ozone anomalies and of the NAO index for the examined stations in Canada, USA and Europe are presented in Figure 12. Table 5 presents the respective statistics. The correlation between total ozone and the NAO index in winter after removing from ozone variability related to the annual cycle and the QBO is –0.44 (95% confidence level). Again, a particular feature was the total ozone increase in 2010 by 6% of the mean associated with the negative NAO phase. Noteworthy on this increase is the consistency with the GB measurements and the satellite SBUV overpassing data, and in general the agreement found between the variability of the tropopause pressures and total ozone. Table 5 indicates that in Canada and USA, the amplitude of NAO in total ozone in winter is about 10 DU (or 3% of the mean), while it is higher over Europe estimated to be about 16 DU (or 5% of the mean).

In summary, our findings based on GOME-2A, GTO-ECV and SBUV overpass data are in line with those found by Ossó et al. (2011) and Steinbrecht et al. (2011) who analysed TOMS and OMI satellite data, and GB measurements at the station Hohenpeissenberg, respectively. During winter, total ozone variability associated with the NAO is particularly important over northern Europe, the U.S. East Coast, and Canada, explaining up to 30% in total ozone variance for this region (Ossó et al., 2011). Also, both studies found unusually high total ozone columns in 2010 over much of the Northern Hemisphere and related them to the negative phase of NAO or AO (the Arctic Oscillation).

4 Conclusions

We have studied the ability of GOME-2/MetopA (GOME-2A) satellite total ozone retrievals to capture known natural oscillations such as the QBO, ENSO and NAO. In general, GOME-2A depicts these natural oscillations in concurrence with GTO-ECV, TOMS/OMI/OMPS, SBUV (v8.6) satellite overpass data, ground-based measurements (Brewer, Dobson, filter and SAOZ) and chemical transport model calculations (Oslo CTM3).

Mean differences between GOME-2A and SBUV total ozone were found to be +0.1 ± 0.7% in the tropics (0-30 deg.), about +0.8 ± 1.6% in mid-latitudes (30-60 deg.), about +1.3 ± 2.2% over the northern high latitudes (60-80 deg. N) and about -0.5 ± 2.9% over the southern high latitudes (60-80 deg. S). These differences were estimated as [GOME-2A – SBUV] / SBUV (%) from January 2007 to December 2016. Small differences were also found between GOME-2A and GB measurements, with standard deviations of the differences being ± 1.4% in the tropics, ± 2.1% in mid-latitudes, and ± 3.2% and ± 4.3% over the northern and the southern high latitudes respectively.

The variability of total ozone from GOME-2A has been compared with the variability of total ozone from other examined data sets as to their agreement to depict natural atmospheric phenomena such as the QBO, ENSO and NAO. First, we studied correlations between total ozone and the QBO after removing from the ozone data sets variability related to the seasonal cycle. Then, we examined correlations between total ozone, ENSO and NAO, after removing variability related to the QBO. Our main results are as follows:

QBO: Total ozone from GOME-2A is well correlated with the Quasi-Biennial Oscillation (+0.8 in the tropics) in agreement with GTO-ECV, SBUV and GB data. The amplitude of QBO on total ozone maximizes around the equator and it is estimated to about 4% of the mean. Going from low to mid-latitudes there is a clear phase shift in the QBO impact on total ozone. Correlation coefficients between GOME-2A total ozone and the QBO over 30-60 deg. north and south are -0.1 and -0.5 respectively, in agreement with the correlations between GB total ozone and the QBO (-0.2 and -0.5, accordingly).

ENSO: Correlation coefficients among GOME-2A total ozone and SOI in the tropical Pacific Ocean are estimated to be about +0.6, consistent with GTO-ECV, SBUV and GB observations. It was found that the ENSO signal is evident and consistent in all examined datasets. The amplitude of the El Nino Southern Oscillation in total ozone is about 6–9 DU corresponding to about 2.5–3.5% of the annual mean. Differences between GOME-2A, GTO-ECV and GB measurements during warm (El Niño) and cold (La Niña) events are within ±1.5%.

NAO: The respective results as far as the impact of North Atlantic Oscillation over the northern mid-latitudes showed a clear NAO signal in winter in all data sets, with amplitudes of about 17–20 DU (about 5–6% of the annual mean). Comparison with GB observations over Canada and Europe showed very good agreement between GOME-2A, GTO-ECV and GB observations as to the influence by NAO, with differences within ±1%.

Additionally to the usual validation methods, which compare monthly mean and zonal mean total ozone data and analyse the differences between satellite and GB instruments, we showed here that quasi cyclical perturbations such as the QBO, ENSO and NAO can serve as independent proxies of spatiotemporal variation in validating GOME-2A satellite total ozone against ground-based and other satellite total ozone data sets. The agreement and small differences which were found between the variability of total ozone from GOME-2A and the variability of total ozone from other satellite retrievals and ground-based measurements during these naturally-occurring oscillations verify the good quality of GOME-2A satellite total ozone to be used in ozone-climate research studies.

Data availability

Satellite SBUV (v8.6) total ozone station overpass data were downloaded from https://acd-ext.gsfc.nasa.gov/Data_services/merged/index.html (last access: 15 June 2018) (McPeters et al., 2013; Bhartia et al., 2013). GTO-ECV total ozone data are available at http://www.esa-ozone-cci.org/?q=node/160 (last access: 15 June 2018) (Coldewey-Egbers et al., 2015; Garane et al., 2018). Ground-based total ozone daily summaries were obtained from the World Ozone and UV Data Centre (WOUDC) at https://woudc.org/archive/Summaries/TotalOzone/Daily_Summary/ (last access: 15 June 2018). The QBO component on total ozone was examined by using the monthly mean zonal winds at Singapore at 30 hPa. Zonal wind data at 30 hPa were provided by the Freie Universität Berlin (FU-Berlin) at http://www.geo.fu-berlin.de/met/ag/strat/produkte/qbo/qbo.dat (last access: 15 June 2018) (Naujokat, 1986). The Southern Oscillation Index (SOI) was provided by the Bureau of Meteorology of the Australian Government at http://www.bom.gov.au/climate/current/soi2.shtml (Australian Government – Bureau of Meteorology, 2018). The NAO index for December, January and February was provided by the Climate Analysis Section, NCAR, Boulder, USA at https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based (last access: 15 June 2018) (Hurrell and Deser, 2009). The tropopause pressures from the NCEP/NCAR reanalysis 1 data set were downloaded from https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.tropopause.html (last access: 15 June 2018) (Kalnay et al., 1996).

Competing interests

The authors declare that they have no conflict of interest.

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Appendix A

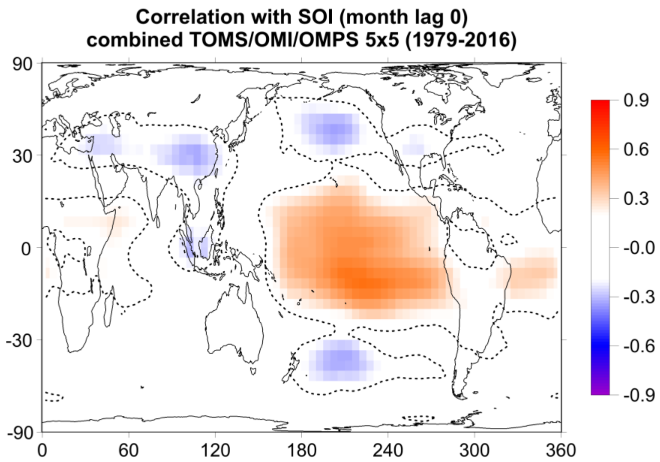

Figure A1. Map of correlation coefficients between total ozone from TOMS/OMI/OMPS satellite data and SOI for the whole period 1979-2016, after removing variability related to the seasonal cycle and the QBO. The dotted line bounds the regions where the correlation coefficients are statistically significant at the 99% confidence level (t-test).

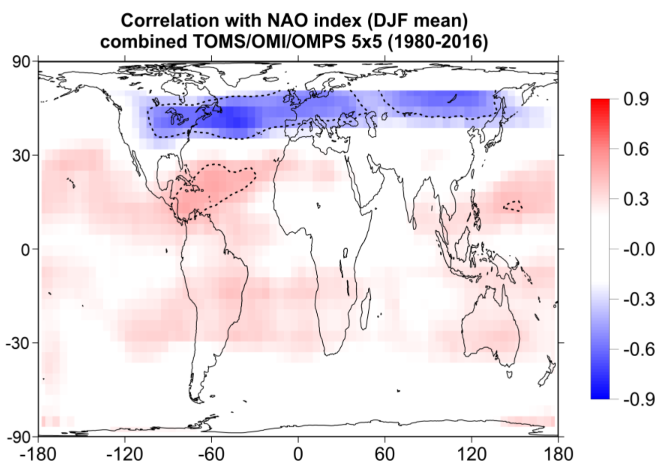

Figure A2. Map of correlation coefficients between total ozone from TOMS/OMI/OMPS satellite data and the NAO index in winter (DJF mean) for the whole period 1980-2016, after removing variability related to the seasonal cycle and the QBO. The dotted line bounds the regions where the correlation coefficients are statistically significant at the 99% confidence level (t-test).

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Table 1. Mean differences and their standard deviations in percent between total ozone from GOME-2A, SBUV (v8.6) satellite overpass data and ground-based observations over different latitude zones, as shown in Figures 1 and 2.

	[GOME-2A – SBUV] / SBUV (%) Stations mean data	[GOME-2A – GROUND] / GROUND (%) Stations mean data
60°-80° N	+1.3 ± 2.2	+2.5 ± 3.2
30°-60° N	+0.8 ± 1.6	+0.1 ± 1.9
0°-30° N	0.0 ± 0.7	–0.5 ± 1.2
0°-30° S	+0.1 ± 0.7	–0.9 ± 1.6
30°-60° S	+0.9 ± 1.6	0.0 ± 2.4
60°-80° S	–0.5 ± 2.9	0.0 ± 4.3

Table 2. Mean differences and their standard deviations in percent between deseasonalised total ozone data from GOME-2A, SBUV (v8.6) satellite overpass data and ground-based observations over different latitude zones, as shown in Figures 5 and 6.

	[GOME-2A – SBUV] (%) Stations mean deseasonalized data	[GOME-2A – GROUND] (%) Stations mean deseasonalized data
30°-60° N	–0.1 ± 0.7	–0.1 ± 0.9
10°-30° N	–0.3 ± 0.5	–0.8 ± 0.8
10° N-10° S	+0.1 ± 0.6	+0.1 ± 1.0
10°-30° S	0.0 ± 0.7	–0.1 ± 0.9
30°-60° S	–0.1 ± 1.0	–0.4 ± 1.0

Table 3. Annual mean total ozone, amplitude of annual cycle, amplitude of QBO and amplitude of ENSO in the period 1995-2016 from GTO-ECV, the combined TOMS/OMI/OMPS satellite data and Oslo CTM3 model calculations over the South Pacific region (10°-20° S, 180°-220° E) and at station Samoa (14.25° S, 189.4° E) located within this region.

	South Pacific Ocean			station Samoa		
	GTO-ECV	TOMS/OMI/OMPS	Oslo CTM3	GTO-ECV	GROUND	SBUV
Annual mean	254.7 DU	253.0 DU	259.5 DU	252.2 DU	249.2 DU	251.9 DU
Amplitude of annual cycle	7.7 DU (3.0%)	7.3 DU (2.9%)	5.2 DU (2.0%)	6.7 DU (2.7%)	6.7 DU (2.7%)	7.3 DU (2.9%)
Amplitude of QBO	2.2 DU (0.9%)	2.4 DU (0.9%)	2.3 DU (0.9%)	2.2 DU (0.9%)	2.7 DU (1.1%)	2.0 DU (0.8%)
Amplitude of ENSO	8.7 DU (3.4%)	6.0 DU (2.4%)	8.9 DU (3.4%)	7.6 DU (3.0%)	5.7 DU (2.3%)	7.6 DU (3.0%)

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Table 4. Annual mean total ozone, amplitude of annual cycle, amplitude of QBO and amplitude of NAO in the period 1995-2016 from GTO-ECV, the combined TOMS/OMI/OMPS satellite data and Oslo CTM3 model calculations over the North Atlantic Ocean: (a) region 35°-50° N, 20°-50° W, and (b) region 15°-27° N, 30°-60° W.

	North Atlantic Ocean					
	(a) 35°-50° N, 20°-50° W			(b) 15°-27° N, 30°-60° W		
	GTO-ECV	TOMS/OMI/OMPS	Oslo CTM3	GTO-ECV	TOMS/OMI/OMPS	Oslo CTM3
Annual mean	315.9 DU	317.3 DU	311.2 DU	276.4 DU	274.4 DU	282.6 DU
Amplitude of annual cycle	37.0 DU (11.7%)	36.9 DU (11.6%)	32.0 DU (10.3%)	15.8 DU (5.7%)	15.1 DU (5.5%)	15.5 DU (5.5%)
Amplitude of QBO	2.3 DU (0.7%)	2.6 DU (0.8%)	3.2 DU (1.0%)	2.8 DU (1.0%)	3.9 DU (1.4%)	4.3 DU (1.5%)
Amplitude of NAO (winter)	18.3 DU (5.8%)	17.5 DU (5.5%)	20.3 DU (6.5%)	8.8 DU (3.2%)	7.2 DU (2.6%)	8.0 DU (2.8%)

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Table 5. Annual mean total ozone, amplitude of annual cycle, amplitude of QBO and amplitude of NAO in the period 1995-2016 from GTO-ECV satellite data, ground-based observations and SBUV (v8.6) satellite overpass data over: (a) Canada and USA (11 stations mean), and (b) Europe (41 stations mean).

	(a) Canada and USA			(b) Europe		
	30^o-50^o N, 60^o-110^o W (11 stations mean)			35^o-55^o N, 10^o W-40^o E (41 stations mean)		
	GTO-ECV	GROUND	SBUV	GTO-ECV	GROUND	SBUV
Annual mean	320.6 DU	322.5 DU	320.9 DU	325.7 DU	326.9 DU	326.8 DU
Amplitude of annual cycle	34.1 DU (10.6%)	33.2 DU (10.3%)	34.0 DU (10.6%)	40.5 DU (12.4%)	39.2 DU (12.0%)	40.7 DU (12.4%)
Amplitude of QBO	2.5 DU (0.8%)	3.5 DU (1.1%)	2.6 DU (0.8%)	1.9 DU (0.6%)	2.8 DU (0.8%)	2.2 DU (0.7%)
Amplitude of NAO (winter)	9.5 DU (3.0%)	10.2 DU (3.2%)	11.1 DU (3.5%)	12.7 DU (3.9%)	16.5 DU (5.1%)	14.7 DU (4.5%)

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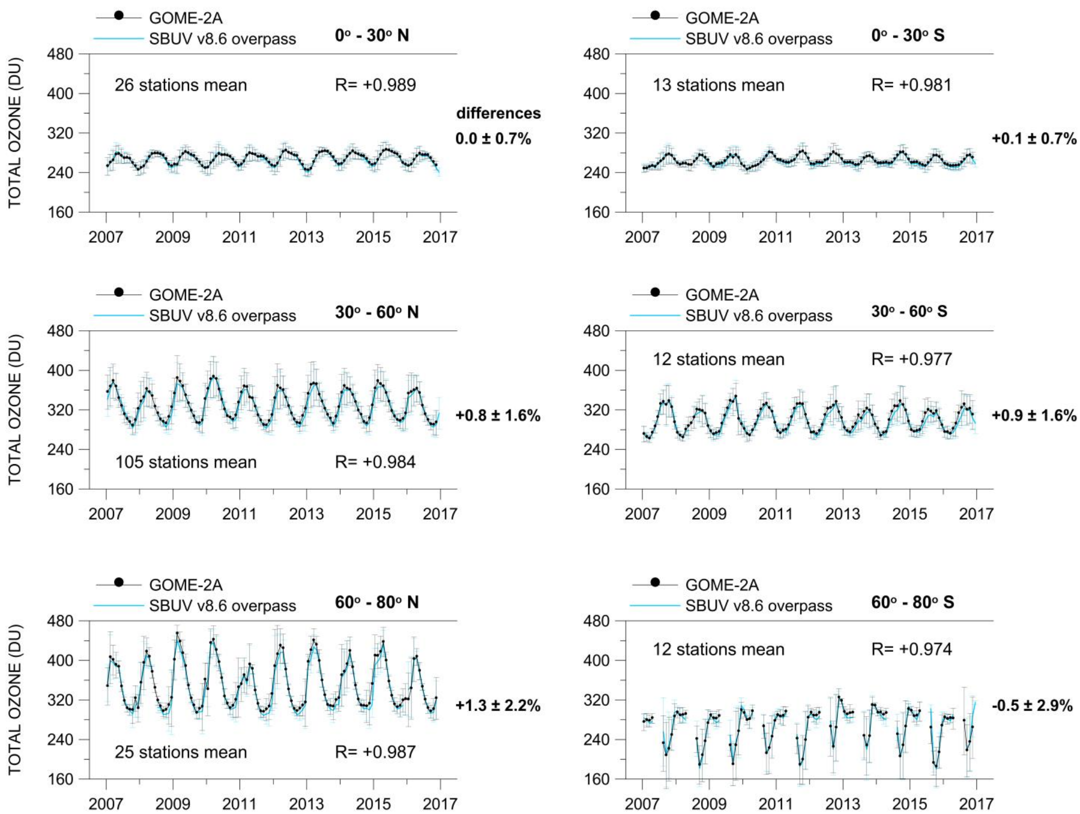

Figure 1. Monthly mean total ozone from GOME-2A as compared with monthly mean total ozone from SBUV (v8.6) satellite overpass data for the period 2007-2016 over the Northern and the Southern Hemisphere based on stations mean data. *R* is the correlation coefficient between the two lines. Error bars show the standard deviation of each monthly mean. Mean differences ± σ are given as [GOME-2A – SBUV] / SBUV (%).

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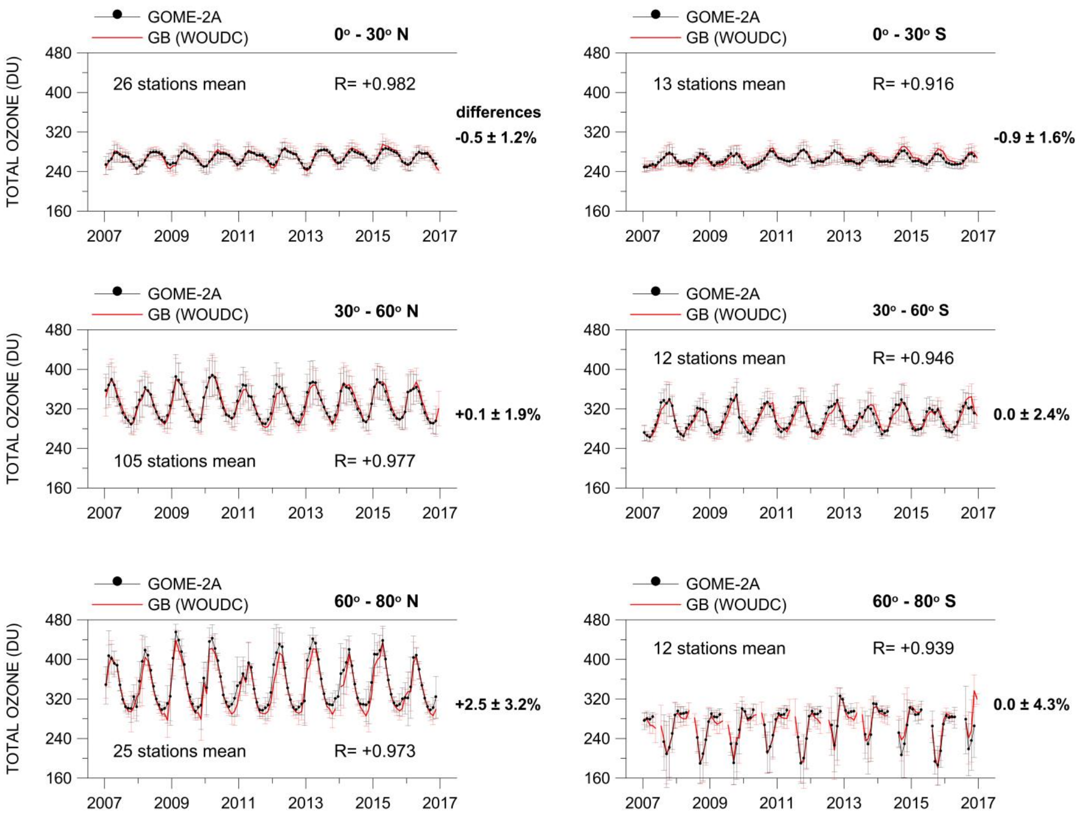

Figure 2. Same as in Figure 1 but for GOME-2A and GB observations. *R* is the correlation coefficient between the two lines. Error bars show the standard deviation of each monthly mean. Mean differences ± σ are given as [GOME-2A – GROUND] / GROUND (%).

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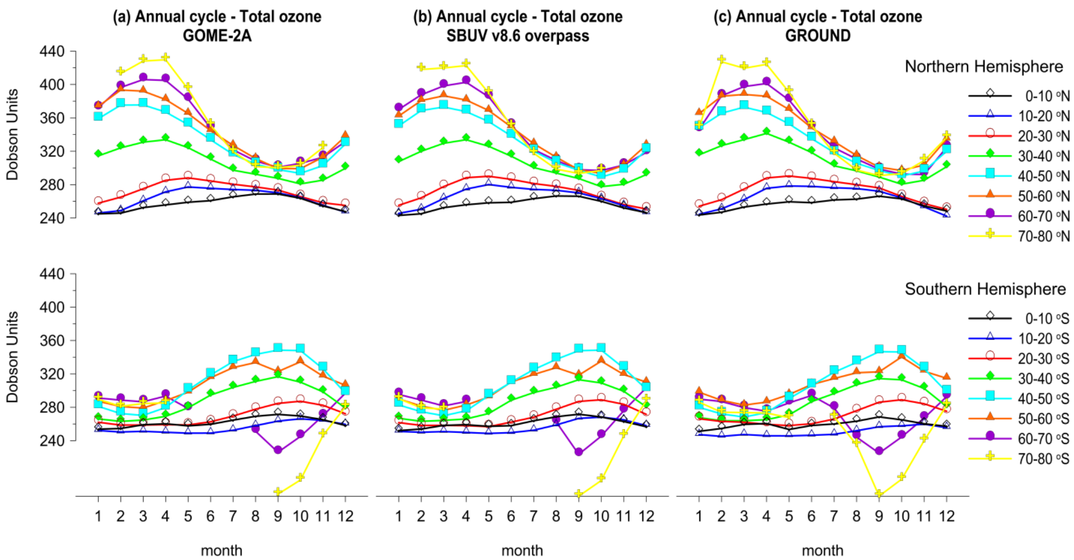

Figure 3. Comparison of the annual cycle of total ozone from GOME-2A with that from SBUV (v8.6) satellite overpass data and GB observations in the period 2007-2016 based on stations data averaged per 10 degree latitude zones. The annual cycle is distorted above 60 deg. S due to the Antarctic ozone hole.

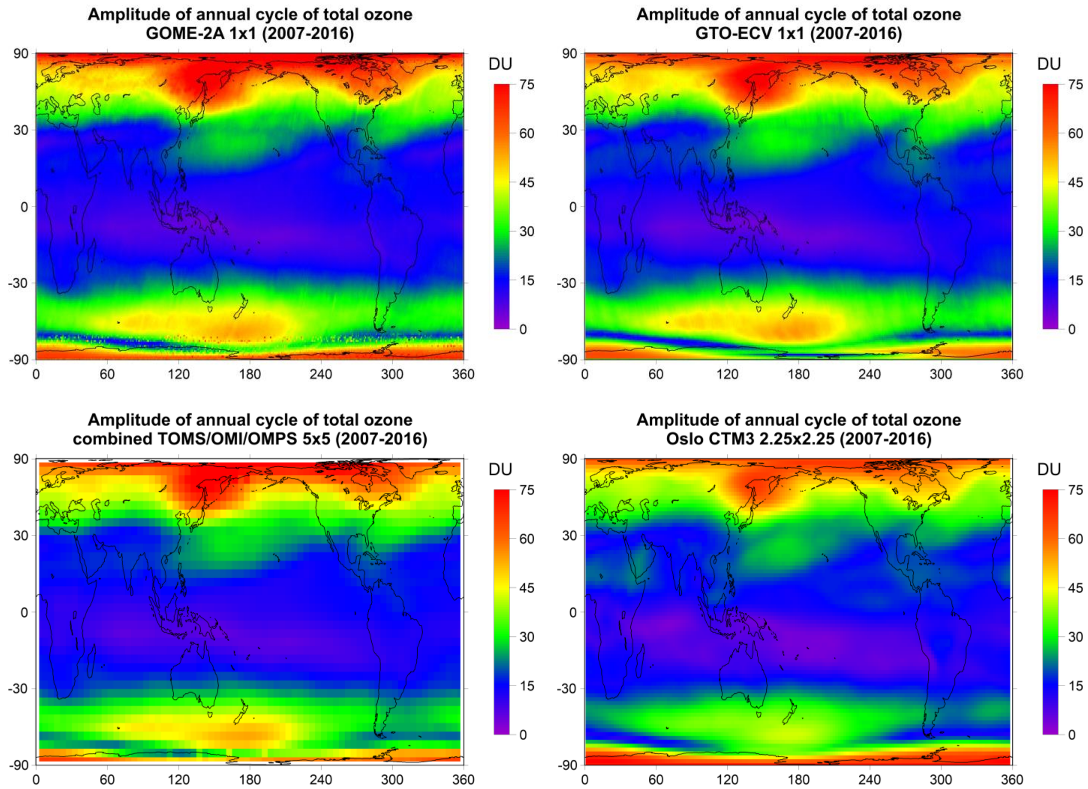

Figure 4. Comparison of the amplitude [i.e., (max-min)/2] of the annual cycle of total ozone from GOME-2A (upper left) with the amplitude of the annual cycle of total ozone from GTO-ECV (upper right), the combined TOMS/OMI/OMPS satellite data (lower left) and Oslo CTM3 model simulations (lower right).

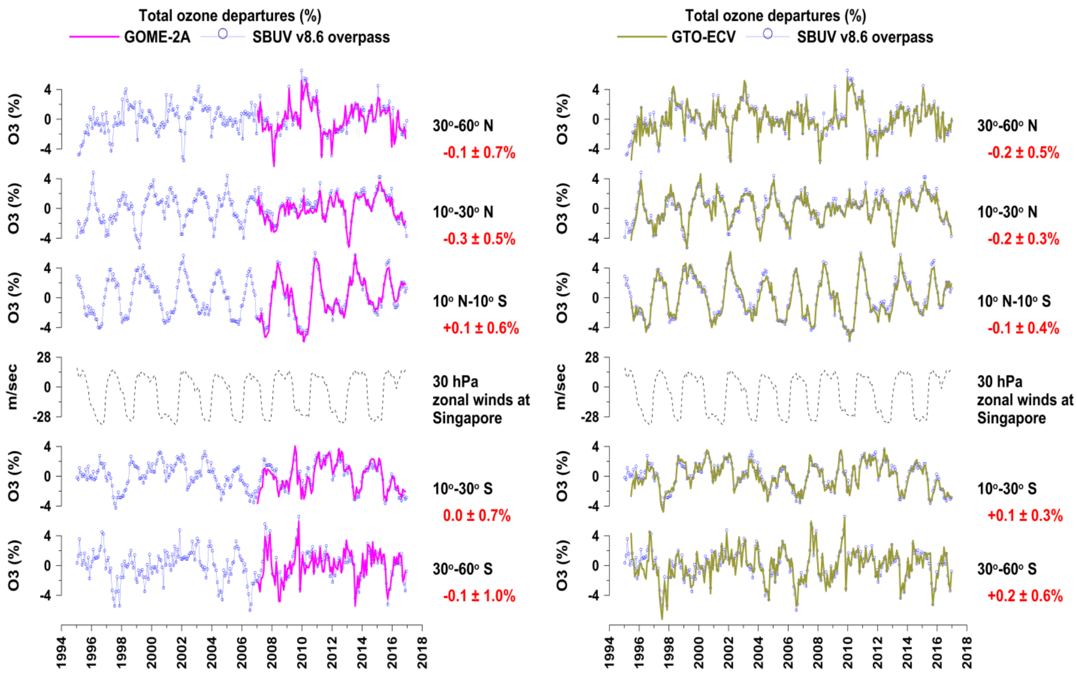

Figure 5. (Left panel) Time series of deseasonalised total ozone from GOME-2A and SBUV (v8.6) satellite overpasses over different latitude zones along with the equatorial zonal winds at 30 hPa as an index of the QBO; (Right panel) same as in left panel but for GTO-ECV and SBUV. Values with red colour refer to the mean differences ± σ (in %) between GOME-2A and SBUV deseasonalised data averaged over various WOUDC stations (150 stations in the northern mid-latitudes (30°-60° N), 21 stations in the northern subtropics (10°-30° N), 8 stations in the tropics (10° S-10° N), 10 stations in southern subtropics (10°-30° S) and 12 stations in the southern mid-latitudes (30°-60° S)).

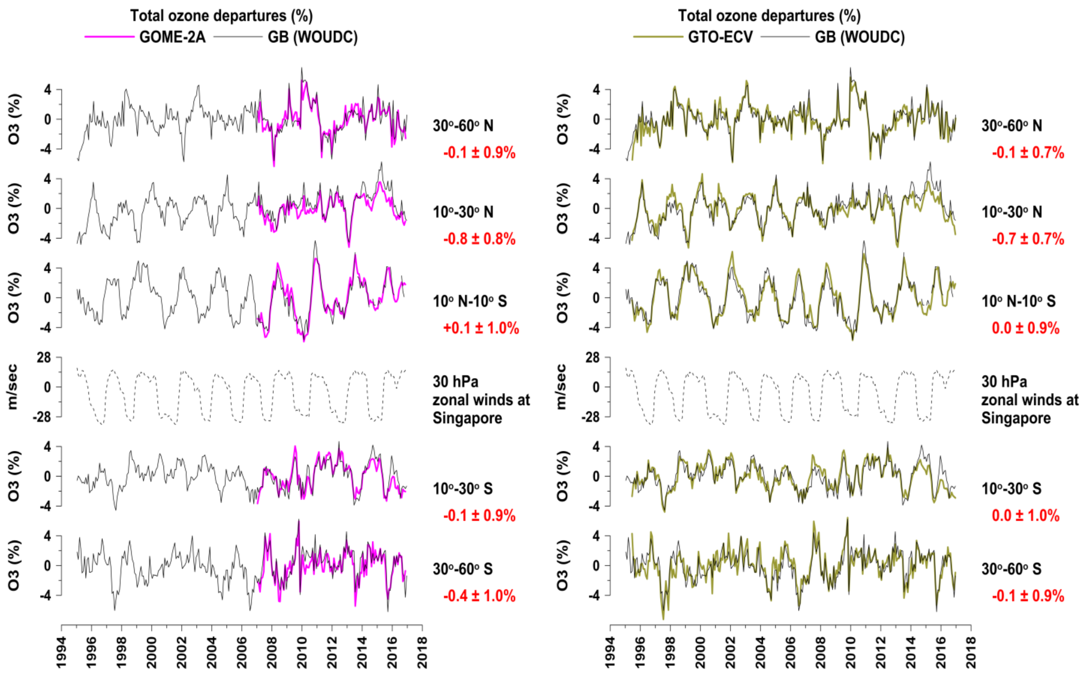

Figure 6. Same as in Figure 5 but for GOME-2A and GB observations (left panel), and for GTO-ECV and GB observations (right panel).

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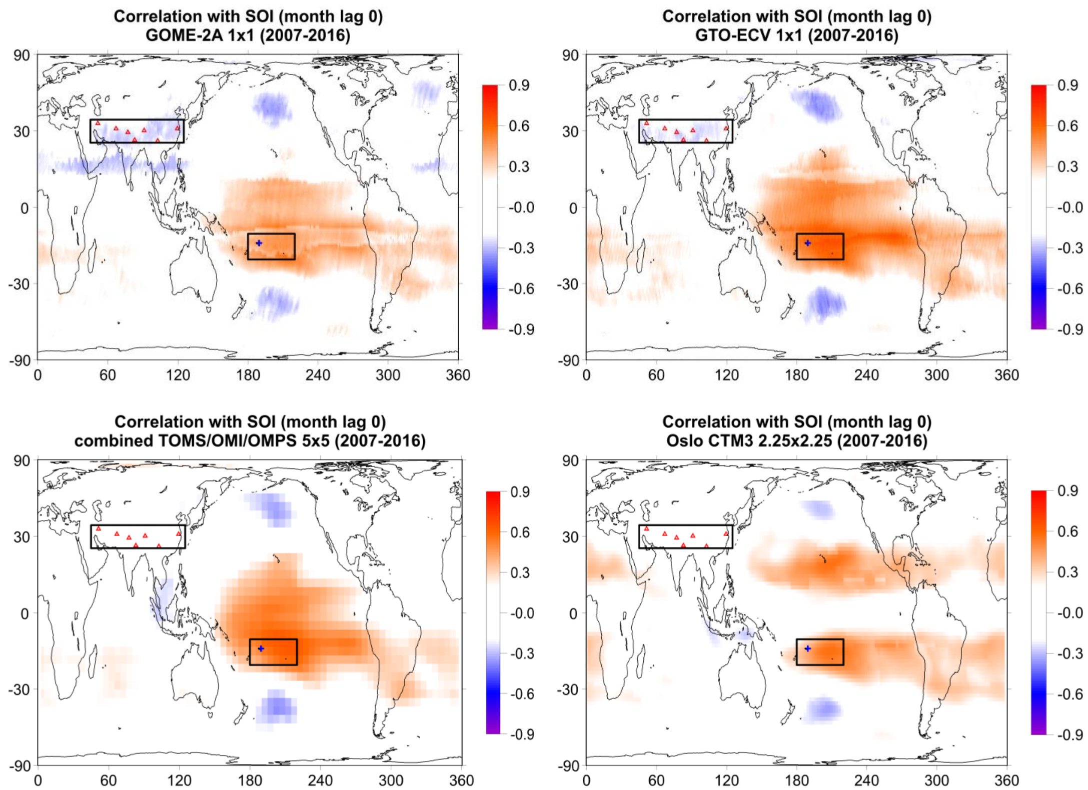

Figure 7. Map of correlation coefficients between total ozone and SOI for GOME-2A (upper left), GTO-ECV (upper right), TOMS/OMI/OMPS satellite data (lower left) and Oslo CTM3 model simulations (lower right). Rectangles correspond to the South Pacific region (10-20 °S, 180-220 °E) and South Asia region (35-45 °N, 45-125 °E), blue cross to the station Samoa (14.25 °S, 189.4 °E) and red triangles to stations in South Asia, in which total ozone has been studied as for the impact of ENSO after removing variability related to the annual cycle and the QBO. Positive correlations are shown by red colours while negative correlations by blue colours. Only correlation coefficients above/below ±0.2 are shown.

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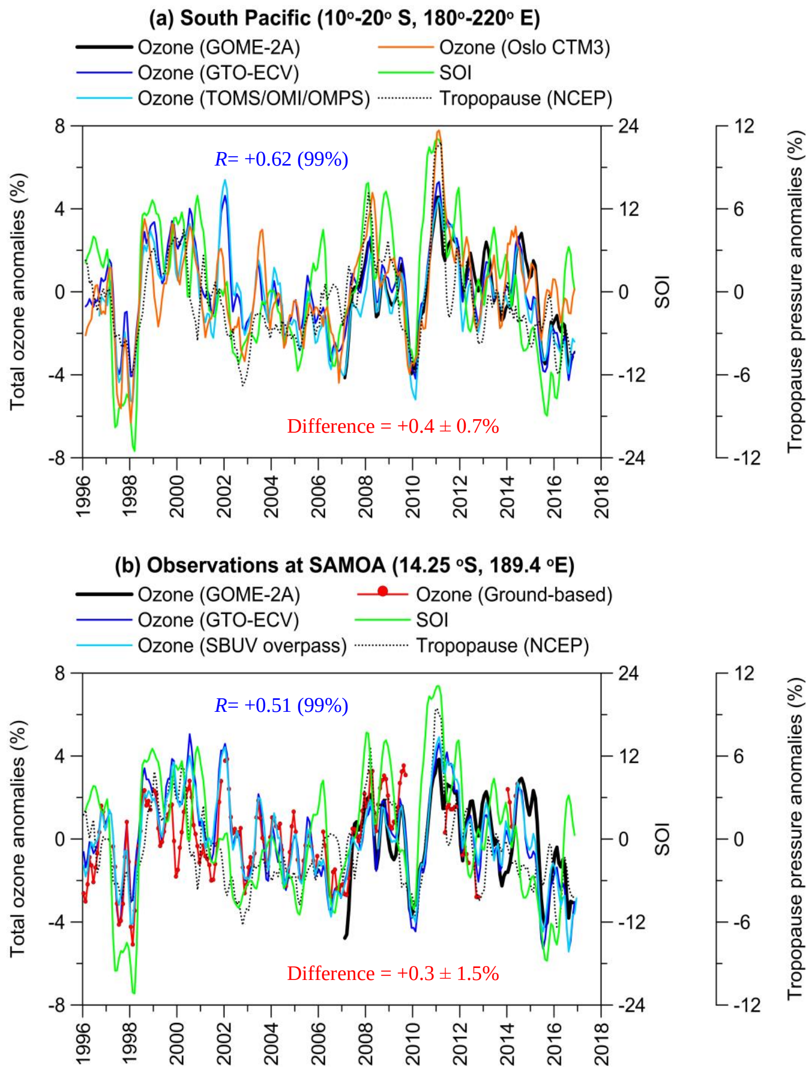

Figure 8. (a) Example of regional time series of total ozone (%) over the South Pacific region (10°-20° N, 180°-220° E) along with SOI. The dotted line shows the respective tropopause pressure variability from NCEP. *R* is the correlation coefficient between GTO-ECV total ozone and SOI (statistical significance of *R* is given in parentheses). The difference refers to the mean difference ± σ (in %) between GTO-ECV and the combined TOMS/OMI/OMPS satellite data. (b) Same as in (a) but for SBUV overpass and GB data at the station Samoa. The difference refers to the mean difference ± σ (in %) between GTO-ECV and GB data.

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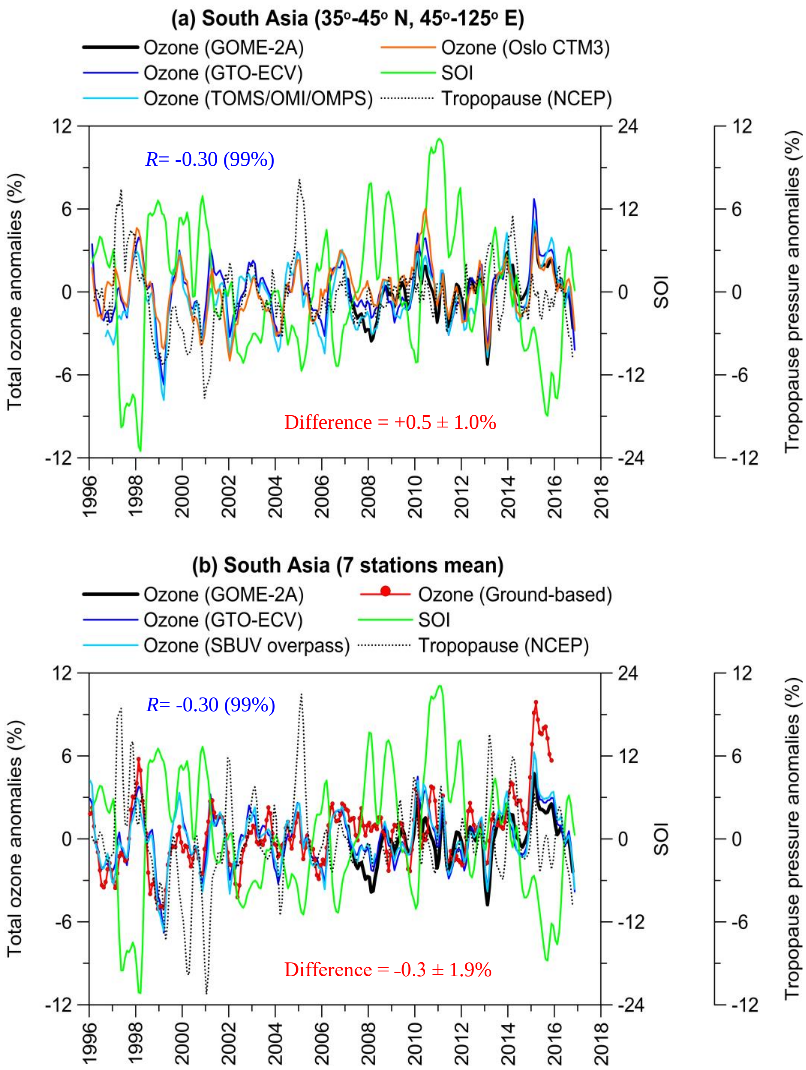

Figure 9. (a) Example of regional time series of total ozone (%) over South Asia (35°-45° N, 45°-125° E) along with SOI. The dotted line shows the respective tropopause pressure variability from NCEP. *R* is the correlation coefficient between GTO-ECV total ozone and SOI (statistical significance of *R* is given in parentheses). The difference refers to the mean difference ± σ (in %) between GTO-ECV and the combined TOMS/OMI/OMPS satellite data. (b) Same as in (a) but with SBUV overpass and GB data averaged at 7 stations in South Asia. The difference refers to the mean difference ± σ (in %) between GTO-ECV and GB data.

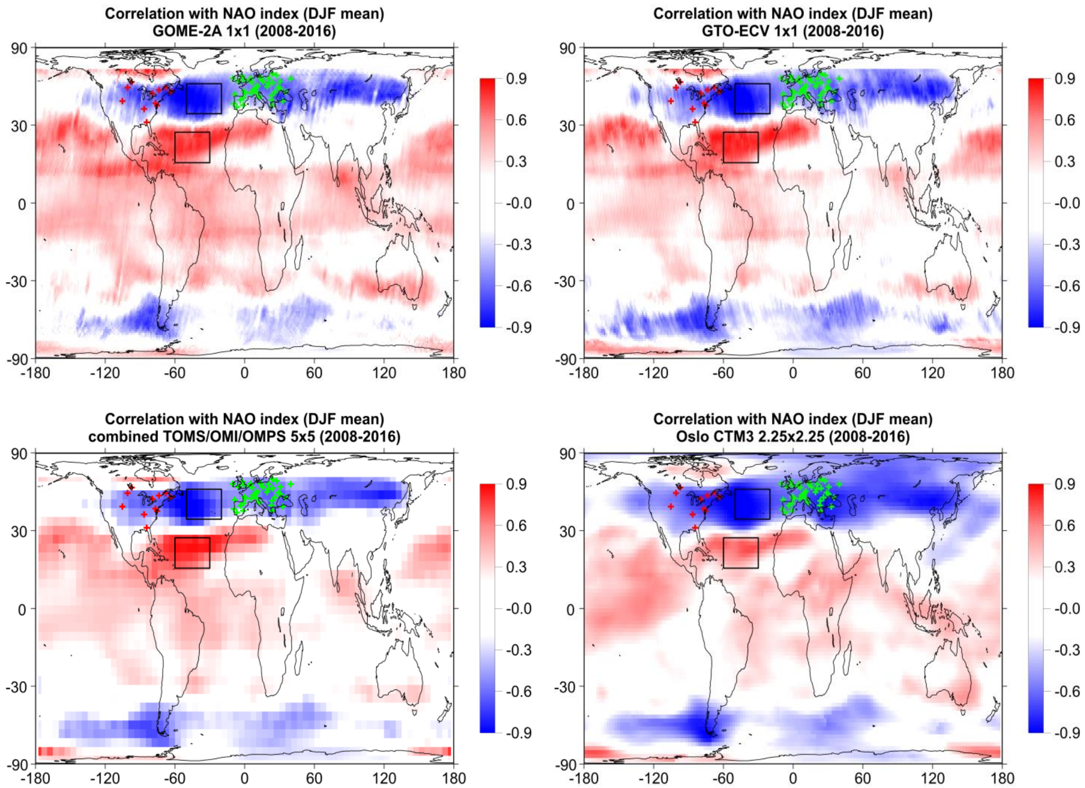

Figure 10. Map of correlation coefficients between total ozone and the NAO index in winter (DJF mean) for GOME-2A (upper left), GTO-ECV (upper right), TOMS/OMI/OMPS satellite data (lower left) and Oslo CTM3 model simulations (lower right). Rectangles correspond to regions in the North Atlantic (35°-50° N, 20°-50° W; 15°-27° N, 30°-60° W), and red and green crosses to stations in Canada/USA and Europe, in which total ozone has been studied as for the impact of NAO after removing variability related to the annual cycle and the QBO. Positive correlations are shown by red colours while negative correlations by blue colours. Only correlation coefficients above/below ±0.2 are shown.

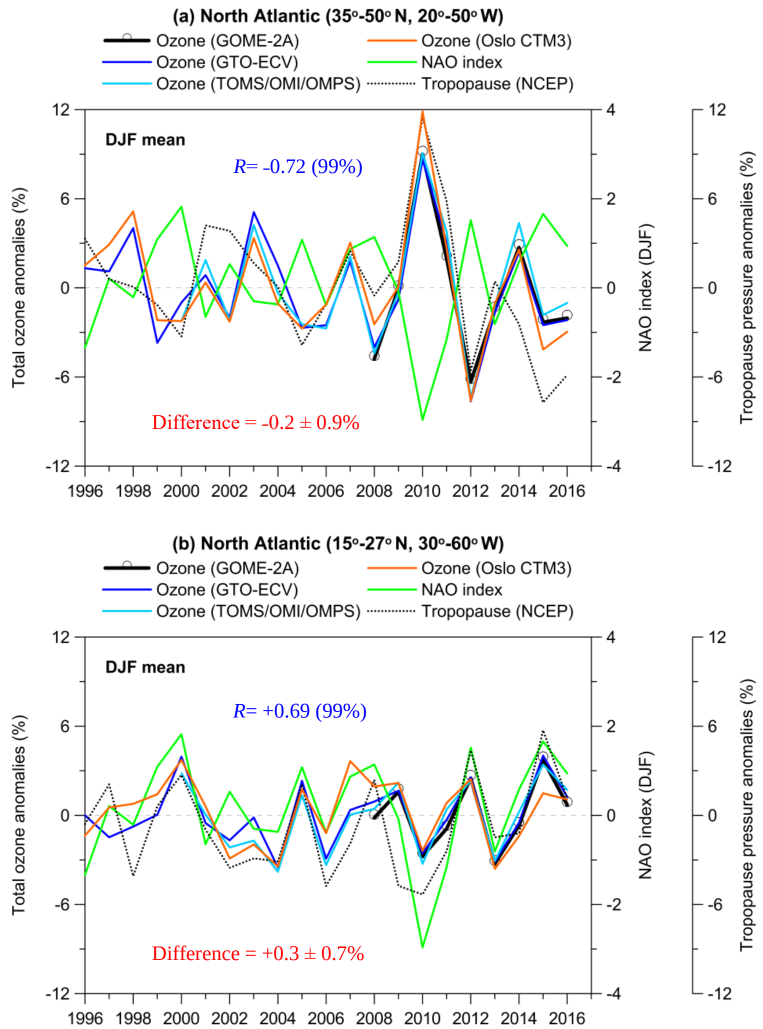

Figure 11. Example of regional time series of total ozone (%) over the North Atlantic regions (a) 35°-50° N, 20°-50° W and (b) 15°-27° N, 30°-60° W in winter (DJF mean) along with the NAO index. The dotted line shows the respective tropopause pressure variability from NCEP reanalysis. *R* is the correlation coefficient between GTO-ECV total ozone and the NAO index. The differences refer to the mean differences ± σ (in %) between GTO-ECV and the combined TOMS/OMI/OMPS satellite data.

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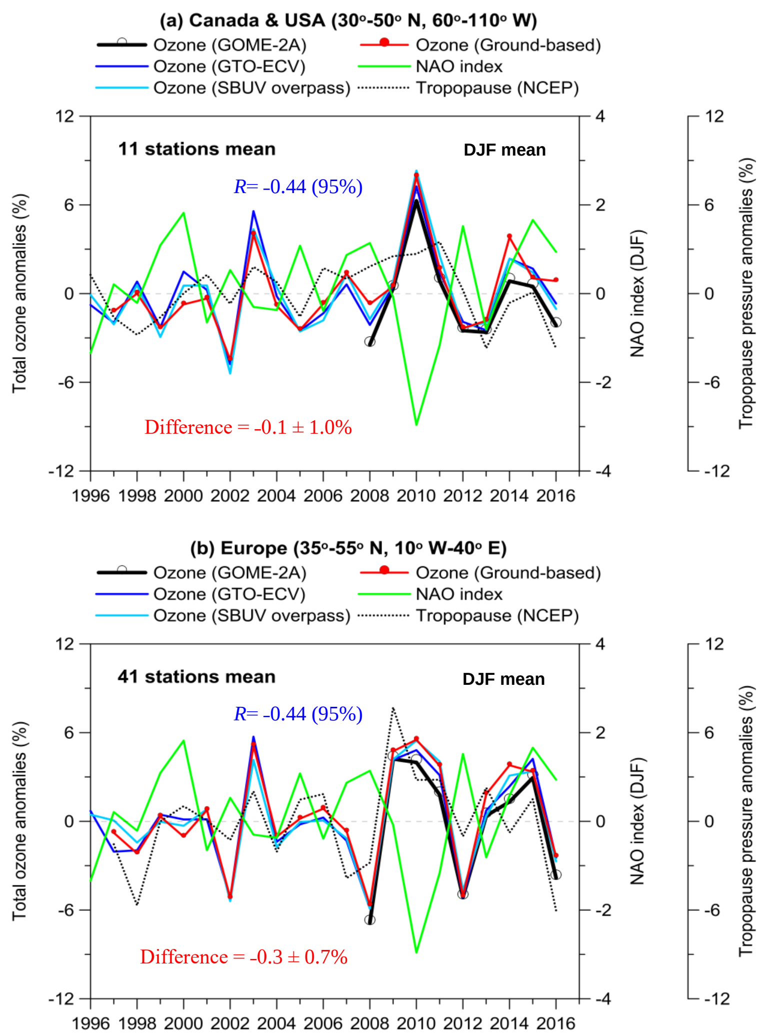

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806 **Figure 12. Comparison with GB observations over: (a) Canada and USA and (b) Europe in winter (DJF**
807 **mean). *R* is the correlation coefficient between GTO-ECV total ozone and the NAO index. The differences**
808 **refer to the mean differences ± σ (in %) between GTO-ECV and GB data.**

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