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Climatology and comparison of ozone from ENVISAT/GOMOS and SHADOZ/balloon-sonde observations in the southern tropics

N. Mze[1], **A. Hauchecorne**[2], **H. Bencherif**[1], **F. Dalaudier**[2], **and J.-L. Bertaux**[2]

[1]Laboratoire de l'Atmosphère et des Cyclones, Université de la Réunion, CNRS-INSU, UMR 8105, St.-Denis, Reunion Island, France
[2]Laboratoire Atmosphères, Milieux, Observations Spatiales, Université Versailles St.-Quentin, CNRS-INSU, Verrières-le-Buisson, France

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Abstract. In this paper, the stellar occultation instrument GOMOS is compared with ozonesondes from the SHADOZ network. We only used nighttime O_3 profiles and selected 8 Southern Hemisphere stations. 7 years of GOMOS datasets (GOPR 6.0cf and IPF 5.0) and 11 years of balloon-sondes are used in this study. A monthly distribution of GOMOS O_3 mixing ratios was performed in the upper-troposphere and in the stratosphere (15–50 km). A comparison with SHADOZ was made in the altitude range between 15 km and 30 km.

In the 21–30 km altitude range, a satisfactory agreement was observed between GOMOS and SHADOZ, although some differences were observed depending on the station. The range for monthly differences generally decreases with increasing height and is within ±15%. It was found that the agreement between GOMOS and SHADOZ declines below ∼20 km. The median differences are almost within ±5%, particularly above 23 km. But a large positive bias was found below 21 km, in comparison to SHADOZ.

1 Introduction

The long-term evolution of stratospheric ozone concentrations depends not only on changes in a large number of stratospheric constituents (including ozone-depleting substances (ODSs), greenhouse gases (GHGs), water vapour and aerosols), but also on changes in the troposphere and in the stratosphere caused by natural variability and anthropogenic forcing (WMO, 2006). Moreover, the decrease of ODSs and the associated context of ozone recovery have resulted in stratospheric ozone becoming a topic of importance for ongoing research. Air enters into the stratosphere from the troposphere primarily in the ozone photochemical source region: the tropics (Shepherd et al., 2000). It is indeed important to follow and investigate the evolution of stratospheric ozone in the tropics. Ozonesonde networks such as SHADOZ (Southern Hemisphere Additional Ozonesondes) provide continuous and accurate measurements at various selected locations. On the other hand, satellites provide global coverage. But these measurements have to be compared with ground-based observations like balloon-sondes, in order to validate the results. Furthermore, the role of satellites for comparing ground-based instruments is also essential in detecting possible station to station biases.

Global Ozone Monitoring by Occultation of Stars (GOMOS), on board the European satellite ENVISAT (ENVIronmental SATellite), is the first instrument dedicated to the study of atmosphere using the technique of stellar occultation (Bertaux et al., 2004). The instrument has the advantage of a method of self-calibrating and good vertical resolution, with global coverage (Kyrölä et al., 2004). The key objective of GOMOS is long-term ozone monitoring with high vertical resolution, high accuracy at global coverage and assessment of ozone trends in the stratosphere (Bertaux et al., 2000).

The purpose of this paper is to give an overview of GOMOS ozone climatology in the southern tropics and a comparison with ground-based ozonesondes at different stations operating in the framework of the SHADOZ network.

Correspondence to: N. Mze
(nahoudha.mze@univ-reunion.fr)

Contrary to the Northern Hemisphere, there are very few ground-based stations in the Southern Hemisphere. Moreover, the tropical stratosphere is a zone where ozone is created by sunlight and where significant changes are expected to occur. The tropical stratosphere is, however, a zone where it is difficult to measure ozone by satellite experiments, due to increased Rayleigh atmospheric attenuation, high altitude clouds, low temperature, high humidity and dense aerosols (Borchi et al., 2007). It is, therefore, essential to compare the few stations operating in the SHADOZ project with the performances of the stellar occultation instrument GOMOS. The study focuses on the validation of GOMOS level 2 data processing, version GOPR 6.0cf (and IPF 5.0).

In this respect, we used GOMOS data from August 2002 to December 2008 and focused on the Southern Hemisphere sites based on SHADOZ ozonesonde network (Thompson et al., 2003). SHADOZ datasets are well known and increasingly used for climatological studies (Lamsal et al., 2004; McPeters et al., 2007), variability studies (Logan et al., 2003; Witte et al., 2008) or comparison studies (Liu et al., 2006; Sivakumar et al., 2007), for case studies such as ozone isentropic transport in the lower stratosphere (Semane et al., 2006; Bencherif et al., 2007), and for trend analyses (Clain et al., 2009).

The first results for multi-year GOMOS ozone climatology were obtained by Kyrölä et al. (2007). They concluded that, even if GOMOS data contained gaps due to instrument failure or nighttime conditions, the available time series allowed ozone variations in the stratosphere and in the mesosphere to be investigated. Meijer et al. (2004) validated the ozone data GOPR 5.4b derived from GOMOS observations under dark limb conditions with correlative data based on balloon-sondes and ground based instruments. They reported an insignificant negative bias from 2.5% to 7.5% between 14 km and 64 km, with standard deviations of 11–16% between 19 km and 64 km. Furthermore, this result was demonstrated to be independent of the star temperature, magnitude and the latitude, except in polar regions in the altitude range between 35 km and 45 km, where a slightly larger bias was observed.

Kyrölä et al. (2006) provided nighttime stratospheric ozone climatology and a comparison of GOMOS 2003 data (GOPR 6.0a). In fact, they compared GOMOS stratospheric ozone with the Fortuin-Kelder ozone climatology (Fortuin and Kelder, 1998) and found large differences in polar areas correlated with large increases of NO_2. They also observed that GOMOS values are systematically larger in the upper stratosphere, due to diurnal variation of ozone above 45 km. They added that GOMOS finds a slightly lower percentage of ozone than Fortuin-Kelder in the middle and lower stratosphere. However, they reported that in the equatorial areas, GOMOS values are much lower than Fortuin-Kelder climatological values in the upper troposphere-lower stratosphere.

Moreover, GOMOS dark occultations were compared with ozone soundings at high-latitude stations: Marambio (64.3° S, 56.7° W) and Sodankylä (67.4° N, 23.6° E) by Tamminen et al. (2006). They found a good agreement in the 15–30 km altitude range. The differences between the averages were within ±5% for Marambio and more marked for Sodankylä (up to −10%). In addition, a good agreement in the middle stratosphere between GOMOS and various balloon-borne instruments at mid- and high-latitude stations was reported by Renard et al. (2008). Liu et al. (2008) performed a comparison of GOMOS and MIPAS (Michelson Interferometer for Passive Atmospheric Sounding) with ozonesonde profiles at Beijing (39.48° N, 116.28° E). They observed a good agreement above 15 km. The differences between GOMOS and balloon-sonde were found to be positive and significant within ±10% above 15 km, particularly between 19 km and 30 km, where biases were found below 5%. A cross validation was also performed with the ground-based microwave radiometer SOMORA (Stratospheric Ozone Monitoring Radiometer) by Hocke et al. (2007). The relative differences were within 10% at altitudes below 45 km.

Comparisons were also performed between satellite data. Verronen et al. (2005) compared nighttime ozone profiles from MIPAS and GOMOS (version 5.4b and 6.0a). They reported a good agreement between the two instruments. The results of these agreed within 10–15% in the middle atmosphere. Bracher et al. (2005) compared three ENVISAT instruments: MIPAS, SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) and GOMOS (dark observations, version 6.0a). Cross comparisons showed an agreement for ozone within 15% in the 21–40 km altitude range between the instruments. Dupuy et al. (2009) observed a close agreement in the stratosphere between GOMOS and ACE-FTS (Atmospheric Chemistry Experiment-Fourier Transform Spectrometer). The median relative differences were within ±10%.

This study investigates 7 years of GOMOS measurements in order to evaluate its potential for establishing a climatology of stratospheric ozone, in comparison to ground-based observations at different tropical/subtropical locations in the Southern Hemisphere, operated in the framework of the SHADOZ program. Section 2 describes data measurements and methods of analysis. Results are reported and discussed in Sect. 3. A summary is presented in Sect. 4.

2 Datasets and analysis

The Global Ozone Monitoring by Occultation of Stars (GOMOS) on board the European Space Agency's ENVISAT satellite was launched on 1 March 2002. GOMOS is a medium resolution spectrometer covering the wavelength range from 250 nm to 950 nm. The four spectrometers of the instrument cover the spectral ranges: 248–387 nm, 387–693 nm, 750–776 nm and 915–956 nm. This coverage allows monitoring of O_3 and other species, i.e., NO_2, NO_3, neutral density, aerosols, H_2O and O_2 from the upper troposphere up

Table 1. Overview of SHADOZ stations used in this study.

Location	Latitude	Longitude	Period	Profiles	Elevation	Sonde Info*
Equatorial stations						
Nairobi	1.27° S	36.8° E	1998–2008	459	1795 m	EnSci 2Z
Natal	5.42° S	35.38° W	1998–2008	394	42 m	EnSci Z, Science Pump 6A
Java, Watukosek	7.57° S	112.65° E	1998–2008	282	50 m	MEISEI RSII-KC79D, EnSci 2Z
Ascension	7.98° S	14.42° W	1998–2008	492	91 m	Science Pump 6A
Tropical stations						
Samoa	14.23° S	170.56° W	1998–2008	383	77 m	Science Pump 6A
Fiji	18.13° S	178.40° E	1998–2008	275	6 m	Science Pump ECC6A
Reunion	21.06° S	55.48° E	1998–2008	319	24 m	EnSci Z & SPC 6A
Irene	25.90° S	28.22° E	1998–2008	232	1524 m	Science Pump ECC6A

* See more details for instruments and solution strengths in Thompson et al. (2003, 2007).

to the mesosphere. The altitude sampling resolution is better than 1.7 km (Bertaux et al., 2000, 2004; Kyrölä et al., 2004).

The retrieval method from GOMOS occultations is based on transmission spectra and divided into two processes: a spectral inversion makes it possible to retrieve line densities and a vertical inversion makes it possible to retrieve the vertical distribution of the local densities using the onion-peeling method (Bertaux et al., 2004; Kyrölä et al., 2004). The vertical resolution of the retrieved ozone profiles is 2 km below 30 km and then it increases linearly to 3 km up to 40 km and remains constant above, due to the inversion algorithm, which is based on Tikhonov regularization (Sofieva et al., 2004; Kyrölä et al., 2006). The height range covered by GOMOS is typically between 15 km and 100 km. For more details about the instrument parameters, measurement characteristics and data processing, the reader can refer to Bertaux et al. (2000, 2004) and Kyrölä et al. (2004, 2006).

Ground based datasets used for the present study are obtained from balloon-sondes launched at 8 Southern Hemisphere stations. An overview is presented in Table 1, summarising, site by site, geographical and size-data characteristics. Figure 1 displays their geographical localisation on the map. Ozonesondes are used for measuring altitude profiles of ozone from ground to about 30 km (balloon burst) with a precision of about 5% (Thompson et al., 2003). The present study uses 11 years of ozone-radiosonde datasets from 1998 to 2008. All balloon-sonde profiles are available on the SHADOZ website: http://croc.gsfc.nasa.gov/shadoz/. Details of quality or sonde parameters are given by Johnson et al. (2002) and by Thompson et al. (2003, 2007).

With regard to ozone profiles derived from GOMOS occultations, level 2 data processing version 6.0cf is used. Reprocessed data is available from August 2002 to June 2006. Data from July 2006 to December 2008 is processed by the operational version IPF 5.00. Level 2 data produced was analysed using Basic Envisat Atmospheric Toolbox software (BEAT). This provides tools for ingesting, processing and analysing atmospheric remote-sensing data (http://www.stcorp.nl/beat/).

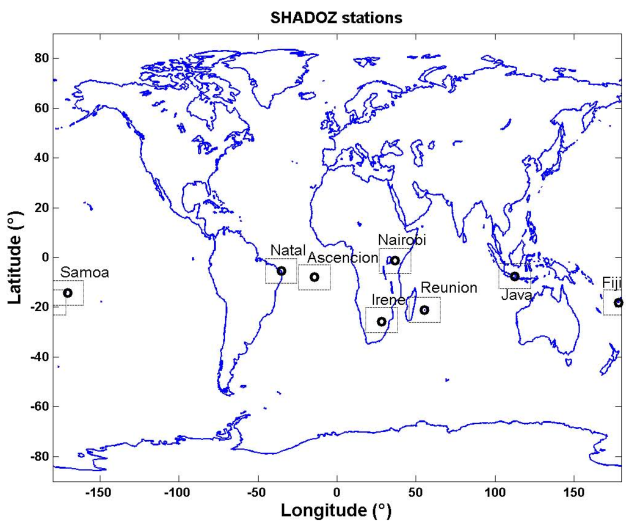

Fig. 1. Map of SHADOZ stations in the Southern Hemisphere. Ozone profiles obtained by radiosonde experiments at 8 stations (black circles) are used for the purpose of the present study, from west to east: Samoa, Natal, Ascension Island, Irene, Nairobi, Reunion, Java and Fiji. The regions where GOMOS profiles are selected within ±5° latitude and ±10° longitude differences over each station are also represented (dotted boxes).

Moreover, it should be noted that only nighttime ozone profiles were used in the altitude range between 15 km and 50 km. Only occultations with solar zenith angle (SZA) larger than 108° dark limb limit at the geolocation of the tangent point are usable. Daytime retrieval suffers from additional noise caused by stray light from the sun (Meijer et al., 2004; Kyrölä et al., 2006). In addition, we considered

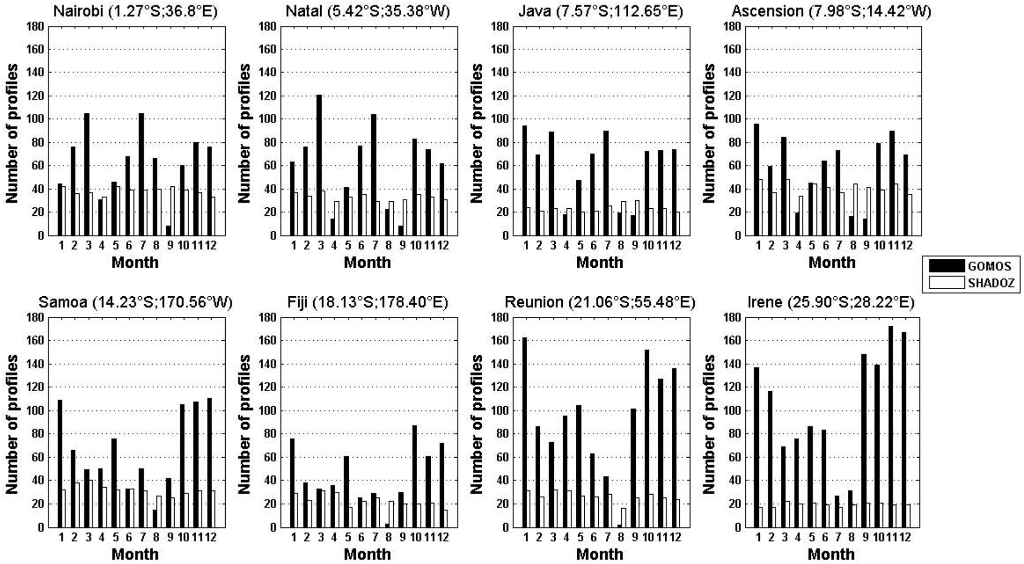

Fig. 2. Monthly distributions of the number of the GOMOS dark occultations (black bars) and SHADOZ profiles (white bars). The GOMOS dataset has a global coverage for the period 2002 to 2008, while the SHADOZ dataset covers the period between 1998 and 2008 and includes 8 southern tropical/subtropical sites.

dark limb occultations with latitudinal and longitudinal differences of ±5° and ±10° over each station. With data product GOPR 5.4b and GOPR 6.0a, Meijer et al. (2004) and Bracher et al. (2005) used a quality filter and took into account only measurements with a reported error below 20%. But in the 6.0cf version of the algorithm, error is overestimated in the 25–40 km altitude range (J. Tamminen, personal communication, 2009). We, therefore, included GOMOS measurements recorded with a reported error below 30% and only O_3 concentrations between 0 and 10^{19} mol/m^3 were taken into account.

Furthermore, ozone mixing ratios were obtained by dividing the GOMOS ozone number density by the atmospheric neutral density included in the data produced and calculated from ECMWF fields (Kyrölä et al., 2006).

Additionally, following the method of analysis used by Kyrölä et al. (2006), we used the median and the interquartile range (iqr) as a robust estimator and statistic tools on GOMOS profiles. The interquartile range is defined as: $q_3 - q_1$ where q_3 and q_1 are the 75th and 25th percentiles, respectively (or third and first quartile, respectively). In this way, the study of GOMOS ozone climatology and variability is less affected by outliers.

Due to height limitation in balloon-sonde data, comparison between ground-based and satellite observations, as studied in this paper, can be carried out within a limited altitude range, i.e., in the 15–30 km altitude range. In this respect, ozone profiles from GOMOS and balloon-sonde have been interpolated into a 1 km vertical grid. In addition, all GOMOS and SHADOZ data have been calculated as a monthly average. As mentioned above, balloon-sonde profiles were recorded from 1998 to 2008, while GOMOS observations cover the period from August 2002 to December 2008. It should be noted that there is no GOMOS data in February, April and May 2005, due to technical problems with the pointing system that occurred in January 2005 (Kyrölä et al., 2006). Figure 2 shows the monthly numbers for dark limb occultations and of balloon-sonde profiles for each station. For the most part, the number of GOMOS occultations is larger than the number of ground-based profiles. In fact, the number of observations used in this work is 2836 profiles from SHADOZ sites and 6708 profiles from GOMOS occultations. It can be seen from the figure that there are fewer GOMOS dark limb occultations for August, in comparison with the other months of the year.

3 Results

The monthly distributions of ozone mixing ratio derived from GOMOS observations are illustrated in Fig. 3 for each station in the altitude range between 15 km and 50 km. The altitude range for the maximum mixing ratio is between 29 km and 37 km. The maximum mixing ratio is in the range from 7.5 ppmv to 10.5 ppmv. Furthermore, Fig. 3 illustrates the semi-annual variation of ozone for equatorial stations (Nairobi, Natal, Java and Ascension) with maxima in February–March and September–October and the annual variation in tropical stations (Samoa, Fiji, Reunion and Irene), with a minimum during southern winter (June–July). A lack of data is generally observed in August between 15 km and 20 km. The mean altitude of maximum mixing ratios for equatorial and tropical stations is ∼31.3 km and

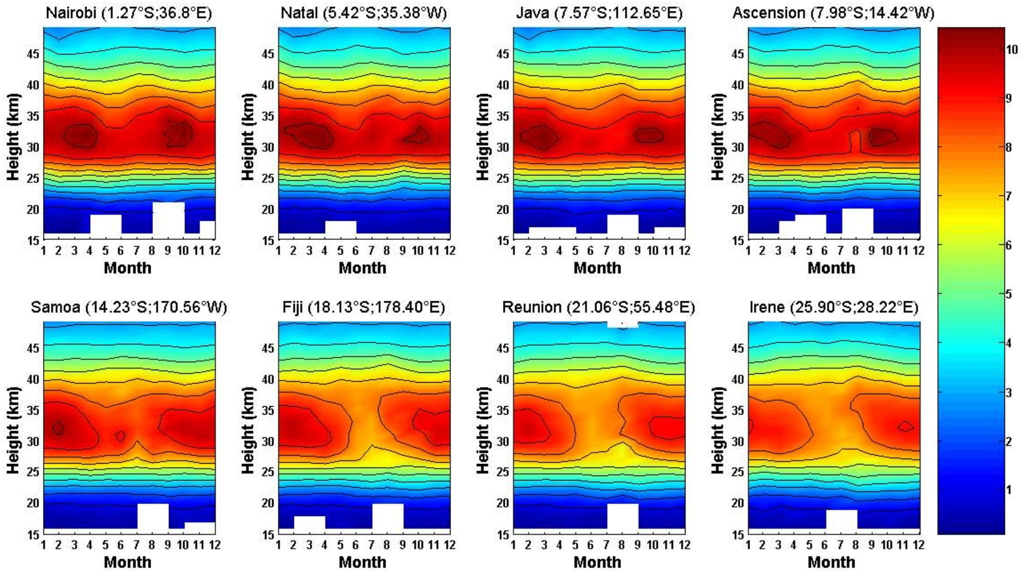

Fig. 3. Monthly median distributions of ozone mixing ratio (in ppmv) as derived from GOMOS observations per station. The contours are separated by 1 ppm.

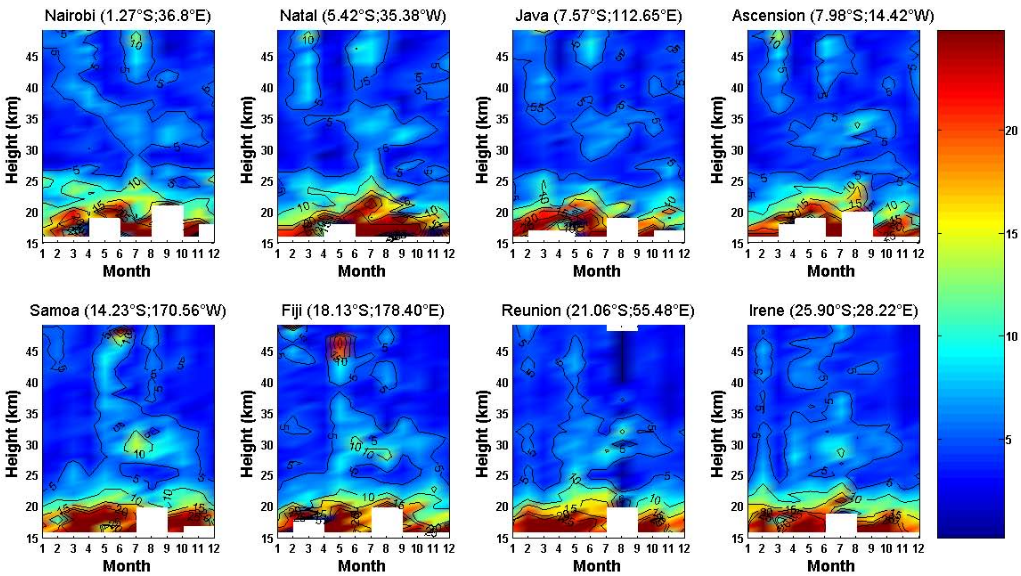

Fig. 4. Contour plots of ozone variability (in %) from GOMOS observations. Variability is defined as the ratio between the interquartile range (iqr) and the median. Contours are separated by 5%.

~32.2 km, respectively. The mean maximum mixing ratio for equatorial and tropical stations is 9.8 ppmv and 8.9 ppmv, respectively. The range for maximum mixing ratio at the equatorial sites is from 9.1 ppmv to 10.5 ppmv, while the range at the tropical stations is from 7.5 ppmv to 10.1 ppmv. These results correspond to those of Kyrölä et al. (2006) who provided a nighttime stratospheric ozone climatology measured by GOMOS in 2003.

Figure 4 displays the monthly distributions of ozone variability in the 15–50 km altitude range, as computed from GOMOS occultations above SHADOZ stations. Variability is defined as the ratio between the quartile deviation (interquartile range divided by 2) and the median, expressed as a percentage:

$$V = \frac{\text{iqr}}{2 \cdot \text{median}} \cdot 100 \qquad (1)$$

In the height range from 20 km to 50 km, the variability values fluctuate between 3% and 10% over all the months and all the sites.

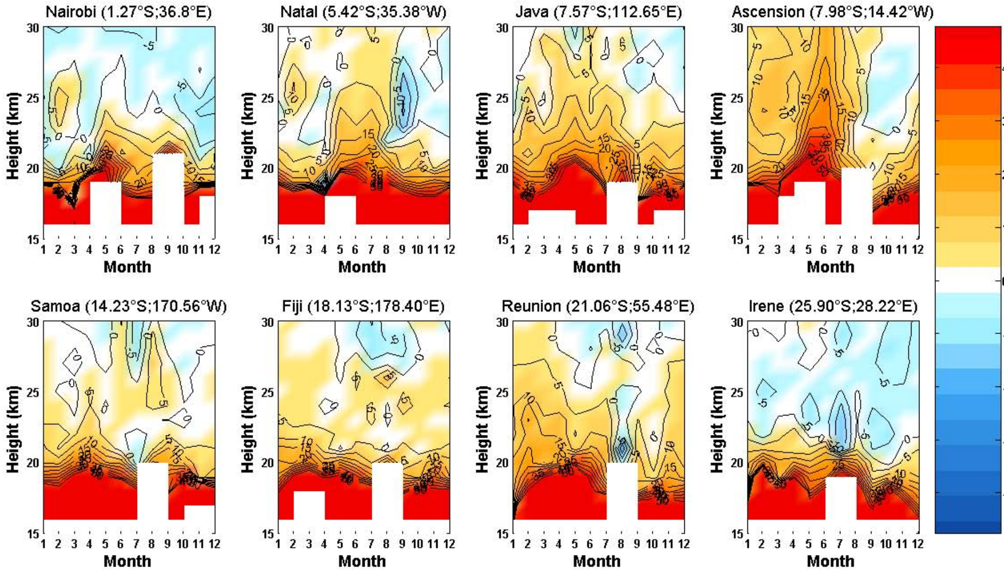

Fig. 5. Monthly distributions of the relative percentage of differences between GOMOS and SHADOZ observations (these differences are based on comparisons of monthly means). It is calculated with respect to ground based measurements in the altitude range between 15 km and 30 km. The contours are separated by 5%.

For all stations, the variability is larger during southern winter (5 to 10%) than during southern summer (less than 5%) in the 27–35 km altitude range. Furthermore, Fig. 4 shows much larger variability in the altitude range between 15 km and 20 km heights, regardless of seasons or sites. It displays strong deviations (>20%), partly due to larger error bars in the lower part of the profiles.

Taking into account the altitude range of overlapping between GOMOS and balloon-sonde ozone observations, their monthly climatological profiles are compared in the height range between 15 km and 30 km. This comparison can be used for two purposes: first to evaluate the quality of GOMOS data with SHADOZ profiles at different locations and secondly to inter-compare SHADOZ stations using the same space instrument, assuming that if a bias is present in GOMOS profiles, it will not be location dependent. Figure 5 displays the relative percentage of differences with respect to monthly climatological values obtained from balloon-sonde observations. It is defined as:

$$\Delta O_3(z) = \frac{[O_3]_{GOMOS} - [O_3]_{SHADOZ}}{[O_3]_{SHADOZ}} \cdot 100 \quad (2)$$

where $[O_3]_{GOMOS}$ represents the median values for GOMOS and $[O_3]_{SHADOZ}$ represents the averaged values for SHADOZ. It can be observed from Fig. 5 that differences between median ozone mixing ratios from GOMOS dark occultations and mean SHADOZ profiles depend on station (vary from station to station) and altitude.

It can be noted however that for all sites, GOMOS produced much larger values than SHADOZ for heights between 15 km and ∼20 km. Indeed, GOMOS seemed to overestimate ozone mixing ratios in this altitude range over all the sites studied, whatever the season (>50%). Above 20 km, a better agreement was found for each site. The range in percent for the differences between ∼20 km and 30 km generally decreased with altitude and was within ±15% for almost all the stations. However, it was found that over Nairobi and Irene, ozone climatological values derived from GOMOS observations were lower than the values obtained from balloon-sondes above 25 km and 22 km, respectively. At Nairobi, SHADOZ was 2–10% larger than GOMOS and at Irene, SHADOZ was 2–15% larger than GOMOS. However, GOMOS values obtained over Natal, Java and Ascension were larger than SHADOZ values, except during the period from September to December in the 22.5–30 km altitude range (25–30 km for Java). The agreement between GOMOS and SHADOZ was the poorest at Ascension (within 20–45%), between ∼20 km and 27 km for the period from April to June. GOMOS was larger than SHADOZ at Samoa, except in May and July and between September and November in the 26–30 km heights range. At Fiji, GOMOS was larger than SHADOZ, except during the period from May to September above 27 km. GOMOS values were larger than SHADOZ values at Reunion, except in August in the 20–25 km altitude range, between April to August above 27 km and in November and December above 29 km. Further studies are needed to understand the causes of the station-dependent differences observed. On average, GOMOS is ∼5–10% larger than SHADOZ between 20 km and 30 km. We will treat this point in more detail below. Despite the observed differences, there is a satisfactory agreement between GOMOS and SHADOZ in this altitude range.

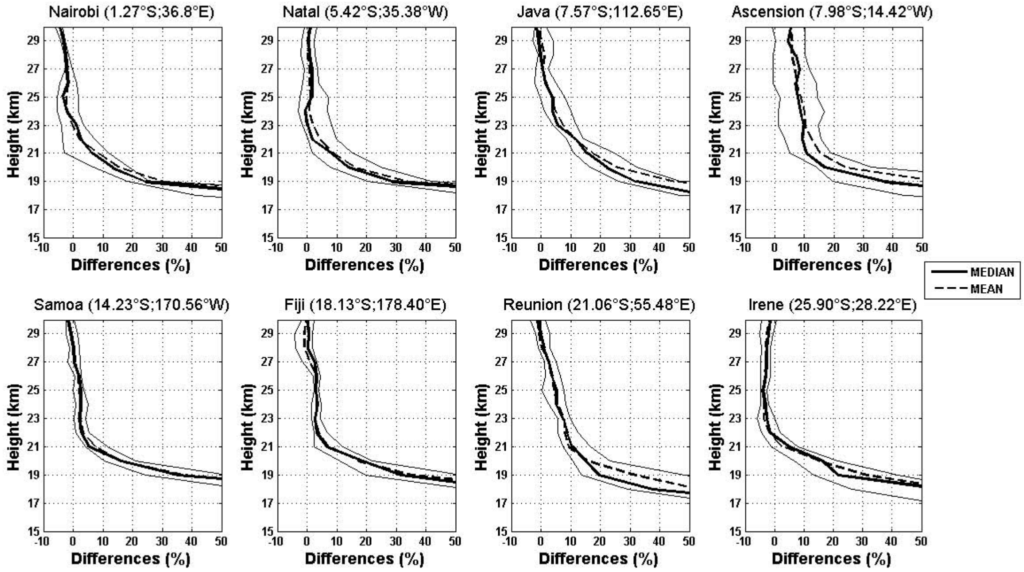

Fig. 6. Median (thick continuous lines) and mean (dashed lines) for all monthly comparisons between GOMOS and SHADOZ ozone mixing ratios, for altitudes between 15 km and 30 km. The thin continuous lines refer to the 25th and 75th percentiles for the median of the percentage differences.

The median and mean overall monthly comparisons between GOMOS and SHADOZ ozone mixing ratios are presented in Fig. 6 for each station. The purpose of analysing median and mean differences is to examine whether the statistical distribution of the differences is correctly represented by a standard Gaussian distribution (the mean and median values should be quite similar) or if this distribution is strongly influenced by outliers (mean and median values are very different). We can note that the mean values almost follow the median ones. In the 21–30 km altitude range, GOMOS is generally larger than SHADOZ at all sites, except at Nairobi and Irene, where we find that SHADOZ is larger than GOMOS above 23 km and 21.5 km, respectively, confirming the analysis on monthly mean differences. The observed differences between GOMOS and SHADOZ may be partly caused by an underestimation of ozone by sondes below the ozone maximum (around 26 km in the tropics), due to the 50–60 s time constant of electrochemical sondes, creating a shift up of 300 m in the altitude registration, as proposed by Borchi et al. (2005) who found a 5% negative bias in SHADOZ profiles compared to SAOZ (Système d'Analyse par Observation Zénithale). Johnson et al. (2002) and Thompson et al. (2003) also suggested that errors on sonde measurements could be introduced by instrumental uncertainties (pump efficiency corrections, modifications in sensing solutions) at higher altitudes, i.e., at lower ambient pressure. Moreover, GOMOS errors contribute to discrepancies. As reported by Tamminen et al. (2010), the main sources of GOMOS errors are random effects: measurement noise and scintillations (10% around 15 km and 0.5% to 4% in the stratosphere, values correspond to night-time measurements). Most of the systematic error is due to imperfect aerosol modelling, which mainly impacts the O_3 retrievals (other sources of systematic errors are uncertainties in cross-sections of the trace gases and in the atmospheric temperature). Scintillation caused by air density irregularities is a nuisance for retrieval of atmospheric composition. In GOMOS retrievals, the scintillation effect is corrected using scintillation measurements using the fast photometer (Sofieva et al., 2009). The remaining disturbances, due to the incomplete scintillation correction, are not negligible. This induces an error of 0.5–1.5% in ozone retrieval at altitudes 20–40 km; see recent studies by Sofieva et al. (2009) and Tamminen et al. (2010) for more details. The course spatial sampling using GOMOS could also be considered as a minor source of error. The displacement of the sondes from 0 to 30 km is most of the time lower than 120 km (assuming a wind speed $<20\,\mathrm{m\,s^{-1}}$ and an ascent time of 6000 s, $5\,\mathrm{m\,s^{-1}}$ ascent speed), which is small compared to the area of GOMOS observations around the station ($\pm 5°$, $\pm 10°$). Meteorology may partly explain the differences between GOMOS and SHADOZ, but it does not have a significant effect.

In order to provide evidence that the approach used in this study is free from artifacts due to imperfect co-location in time, coincident ozone profiles from both instruments are reconsidered at 3 stations at different latitudes in the Southern Hemisphere: Natal, Fiji and Irene. To study co-locating measurements between GOMOS dark occultations and ozone soundings, we added a time-collocation criterion, i.e., the time difference between GOMOS and SHADOZ observations is ± 12 h. The number of co-located profiles is 64 at Natal, 30 at Fiji and 47 at Irene. Figure 7 illustrates the

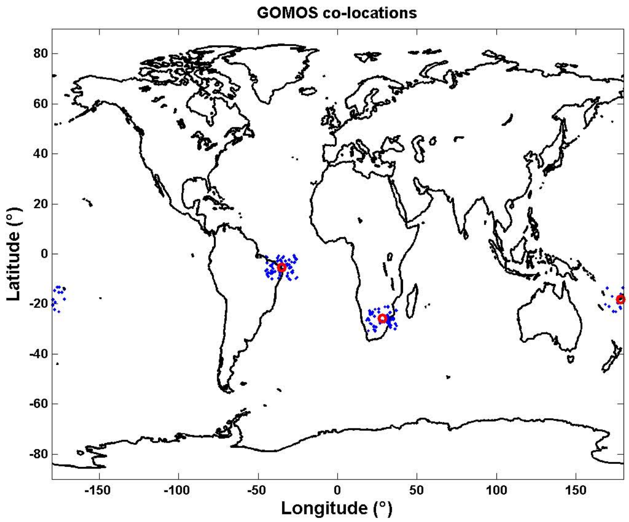

Fig. 7. Geographical locations of the GOMOS dark occultations (blue dots) compared with measurements from 3 stations: Natal, Fiji, Irene (red circles). Overpasses of GOMOS are measured within ±12 h time difference and spatial differences within ±5° latitude and ±10° longitude.

Table 2. Summary of results for the GOMOS comparison with SHADOZ. For each station: the vertical range used to calculate the median difference, mean value and minimum/maximum values in this range are indicated.

Location	Range (km)	Difference (%)	
		Mean	Range
Equatorial stations			
Nairobi	21–30	−0.89	−4.57 to +6.42
Natal	21–30	+1.75	−0.60 to +8.35
Java, Watukosek	21–30	+4.13	−1.48 to +15.66
Ascension	21–30	+8.00	+4.65 to +10.94
Tropical stations			
Samoa	21–30	+1.64	−1.58 to +5.53
Fiji	21–30	+2.68	+0.20 to +6.85
Reunion	21–30	+4.47	−0.74 to +10.71
Irene	21–30	−1.72	−3.85 to +5.05

geographical coordinates of GOMOS coincident ozone profiles. Figure 8 displays the mean differences between all the paired GOMOS and SHADOZ profiles. For comparison ozone mean differences obtained without time criterion (the mean overall monthly comparisons) are superimposed. It can be seen from Fig. 8 that the two methods (with and without time-collocation criterion) are in satisfactory agreement. In the 21–30 km GOMOS is generally larger than SHADOZ except at Irene where we find that SHADOZ is larger than GOMOS above 21.5 km. The obtained mean differences are within ±10% in the 21–23 km height range and within ±5% above 23 km. Below 21 km GOMOS overestimates increasingly ozone mixing ratios with decreasing height. These results show that the two methods are quite similar. This suggests indeed that one can use, with some confidence, GOMOS data in the tropical region without time-collocation criteria. In fact, that method allows reducing the uncertainty by increasing the number of profiles.

On average, the percentage difference between GOMOS and SHADOZ is situated almost within ±10%, in the height range from 21 km to 23 km and decreases to nearly ±5% above 23 km, except for Ascension, where it reaches about 8%. The overall results of the comparison between 21 km and 30 km are summarized in Table 2. In the lower stratosphere (below 21 km), it can be observed that GOMOS systematically and increasingly overestimates ozone mixing ratios with decreasing height. This corresponds to the results of Meijer et al. (2004), who found an overestimation of GOMOS between 18 km and 21 km compared to ozonesondes in the tropical region, using GOPR v5.4b. This is consistent with Borchi et al. (2007), who found an altitude limitation of GOMOS measurements at 22 km in the tropics. They compared satellites and sondes with SAOZ on board long duration balloons during the Southern Hemisphere summer in 2003 and 2004. They observed a consistent agreement between GOMOS and SAOZ above 22 km in the stratosphere, showing no altitude shift and a slight low ozone bias for GOMOS of 1–2.5%. They reported a degradation of GOMOS performances in the stratosphere below 22 km. Above 21 km, we can observe a close agreement between ozone measurements derived from GOMOS occultations and ground-based balloon-sonde, similar to results reported in previous studies at tropical stations (Meijer et al., 2004). These results in the tropics complete the close agreement observed at mid- and high-latitude stations between GOMOS and ozonesondes (Tamminen et al., 2006; Renard et al., 2008; Liu et al., 2008). Indeed, previous validation studies with ozonesondes were performed in other regions. Tamminen et al. (2006) compared GOMOS dark occultations with ozone soundings during 2003 at high-latitudes stations: Marambio (64.3° S, 56.7° W) in Antarctica and Sodankylä (67.4° N, 23.6° E) in Finland (northern Europe). They found a good agreement in the 15–30 km altitude range. The differences between the averages were within ±5% for Marambio and more marked for Sodankylä (up to −10%). Moreover, a comparison was performed by Liu et al. (2008) between GOMOS night measurements and ozonesonde profiles at Beijing (39.48° N, 116.28° E) in China from September 2002 to July 2005. They observed a good agreement above 15 km. The differences between GOMOS and balloon-sonde are found to be positive and significant within ±10% above 15 km, particularly between 19 km and 30 km where biases are found below 5%. Therefore, results obtained here in the southern

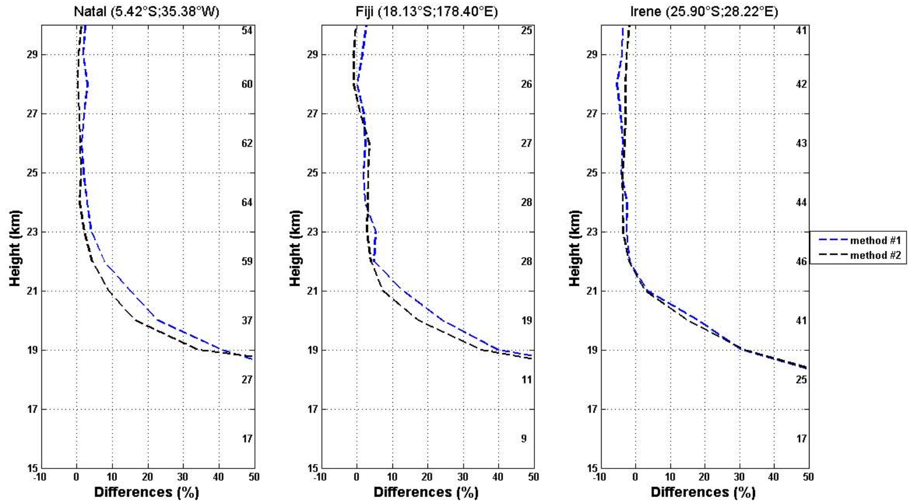

Fig. 8. Comparison results between the co-location method and the method applied without the time criterion. Method #1 (blue dashed lines) indicates the mean differences between all the paired GOMOS and SHADOZ profiles. And method #2 (black dashed lines) indicates the method applied without the time criterion. The numbers on the right vertical axis indicate the number of coincident pairs used at that altitude level for the method #1.

tropics (±10% in the 21–23 km height range and ±5% above 23 km) are consistent with those found in other regions, i.e., at mid- and high-latitude stations, except that the quality of GOMOS data seems poorer in the tropics below a threshold altitude, i.e., 21 km. In addition, application of the ozone climatology presented here corresponds to the primary objective of GOMOS, i.e., study and assessment of trends in the stratosphere. Furthermore, as reported by Bertaux et al. (2000), it could be essential for improving atmospheric models for prediction of future changes.

4 Summary

In this study, we provided ozone climatology based on 7 years of GOMOS data at Southern Hemisphere stations from 15 km to 50 km. We selected data to be used, in order to have reliable data measurements. The range for maximum mixing ratios at the equatorial stations is between 9.1 ppmv and 10.5 ppmv, while the range at the tropical stations is between 7.5 ppmv and 10.1 ppmv. In the altitude range between 20 km and 50 km, ozone variability varies between 3% and 10% over all the months and it is larger during southern winter in the 27–35 km altitude range.

We compared GOMOS dark limb occultations with 8 southern ozonesonde stations based on SHADOZ network. GOMOS findings correspond to those of SHADOZ in the altitude range between ∼20 km and 30 km. For most of the stations, in this altitude range, GOMOS values are higher than SHADOZ by ∼5–10%. A possible explanation is a bias in the altitude registration of ozonesondes due to the time constant and the impact of GOMOS errors (imperfect scintillation correction, inaccurate aerosol modelling and uncertainties in cross-sections of trace gases and in atmospheric temperature) on ozone data quality. On the contrary, at Nairobi and Irene, GOMOS values are generally lower than SHADOZ ones. Further studies are needed to understand the causes of the station-dependent differences observed. In the altitude range from 21 km to 30 km, the monthly differences are generally within ±15%. The median of the relative percentage differences between GOMOS and SHADOZ ozone mixing ratios in the 21–23 km height range is almost within ±10% for almost all the stations and decreases to almost ±5% above 23 km. Below 21 km, GOMOS data shows increasing variability with decreasing altitude and increasing positive bias compared to SHADOZ in the tropics. We recommend using GOMOS measurements with caution below 21 km in the tropics.

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