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

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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 a requirement selection at 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 is performed in the upper-troposphere and in the stratosphere (15–50 km). A comparison with SHADOZ is done in the altitude range from 15 km to 30 km.

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

1 Introduction

The long-term evolution of stratospheric ozone concentrations depends not only on changes of many stratospheric constituents (including ozone-depleting substances (ODSs), greenhouse gases (GHGs), water vapor, and aerosols), but also on changes in the troposphere and in the stratosphere caused by natural variability and anthropogenic forcing (WMO, 2006). Besides, the decrease of ODSs and the associated context of ozone recovery make that stratospheric ozone is a thematic of importance for ongoing researches. 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 different selected locations. On the other hand, satellites provide a global coverage. But these measurements have to be validated through comparisons with ground-based observations like balloon-sondes in order to give confidence to the results. Furthermore, the role of satellites for intercomparing ground-based instruments between them is also essential to detect 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 by the technique of stellar occultation (Bertaux et al., 2004). The instrument has the advantage of self calibrating method and a good vertical resolution with a global coverage (Kyrölä et al., 2004). The key objective of GOMOS is the long-term ozone monitoring with a high vertical resolution, a high accuracy at global coverage and consequently 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. The study focuses on the validation of the GOMOS level 2 data processing version GOPR 6.0cf (and IPF 5.0). In that regard, we use GOMOS data from August 2002 to December 2008 and focus 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 performed by Kyrölä et al. (2007). They concluded that, even if GOMOS data includes gaps due to instrumental difficulties or nighttime requirement, the available time series allow one to investigate ozone variations in the stratosphere and in the mesosphere. Meijer et al. (2004)

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validated the ozone data GOPR 5.4b derived from GOMOS observations under dark limb condition 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 latitudinal region, except in polar regions in the altitude range from 35 km to 45 km where a slightly larger bias was observed.

Kyrölä et al. (2006) provided a 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 the diurnal variation of ozone above 45 km. They added that GOMOS finds a few percent less ozone than Fortuin-Kelder in the middle and lower stratosphere. On the opposite, 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-latitudes 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 somewhat worse 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-latitudes stations was reported by Renard et al. (2006). Liu et al. (2008) perfomed 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 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%. 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 versus 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. They agree 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 have shown an agreement for ozone within 15% in the 21–40 km height range between the instruments. Dupuy et al. (2009) observed a good agreement in the stratosphere between GOMOS and ACE-FTS (Atmospheric Chemistry Experiment-Fourier Transform Spectrometer). The median relative differences were within ±10%.

This work investigates 7 years of GOMOS measurements in order to evaluate its potential for establishing a climatology of stratospheric ozone in comparison with 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. 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 O_3 and other species, i.e., NO_2, NO_3, neutral density, aerosols, H_2O and O_2 from the upper troposphere up 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 the transmission spectra and divided into two processes: a spectral inversion allows retrieving the line densities and a vertical inversion permits 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 the same 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 from 15 km to 100 km. For more details about the instrument parameters, measurements characteristics and data processing the reader can refer to Bertaux et al. (2000, 2004) and Kyrölä et al. (2004, 2006) papers.

Ground based datasets used for the present study are obtained from balloon-soundes launched at 8 Southern Hemisphere stations. An overview is presented in Table 1 which summarizes, site by site, geographical and size-data characteristics. Figure 1 displays their geographical localisation on the map. Ozonesondes are used for measuring height 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 about quality or sonde parameters are described 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 are available from August 2002 to June 2006. And data from July 2006 to December 2008 are processed by the operational version IPF 5.00. Level 2 data products were analyzed with the Basic Envisat Atmospheric Toolbox software (BEAT). It provides tools for ingesting, processing, and analyzing atmospheric remote sensing data (http://www.stcorp.nl/beat/).

Moreover, it should be noted that only nighttime ozone profiles are 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 the stray light from the Sun (Meijer et al., 2004; Kyrölä et al., 2006). In addition, we considered 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 version 6.0cf of the algorithm, error is overestimated in the 25–40 km altitude range (Johanna 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 are taken into account.

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

Additionnaly, 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 issue, can be performed within a limited altitude range, i.e., in the 15–30 km altitude range. In that regard, ozone profiles from GOMOS and balloon-sonde have been interpolated into a 1 km vertical grid. In addiditon, all GOMOS and SHADOZ data have been monthly averaged. As mentioned above, balloon-sonde profiles are 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 on the pointing system that occurred on January 2005 (Kyrölä et al., 2006). Figure 2 shows the monthly numbers of 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 less GOMOS dark limb occultations by 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 height range between 15 km and 50 km. The altitude range for the maximum of mixing ratio is between 29 km and 37 km. The maximum mixing ratios 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 austral winter (June–July). A lack of data is generally observed in August between 15 km and 20 km. The mean altitude of the maximum mixing ratios for equatorial and tropical stations is ~31.3 km and ~32.2 km, respectively. The mean of maximum mixing ratios for equatorial and tropical stations is 9.8 ppmv and 8.9 ppmv, respectively. The range for maximum mixing ratios 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 are in agreement with 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, in percent:

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

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

For all stations, the variability is larger during austral winter (5 to 10%) than during austral 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%), partially 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 from 15 km to 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 second 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:

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

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

It can be noted however that for all sites, GOMOS finds much larger values than SHADOZ for heights between 15 km and ~20 km. Indeed, GOMOS seems to overestimate ozone mixing ratios in this altitude range over all the studied sites whatever the season (>50%). Above 20 km, a better agreement is found for each site. The range in percent for the differences between ~20 km and 30 km is generally decreasing with increasing height and is within ±15% for almost all the stations. However it is found that over Nairobi and Irene ozone climatological values derived from GOMOS observations are less than the values obtained from balloon-sondes above 25 km and 22 km, respectively. At Nairobi SHADOZ is 2–10% larger than GOMOS and at Irene SHADOZ is 2–15% larger than GOMOS. On the opposite, GOMOS values obtained over Natal, Java and Ascension are 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 is the poorest at Ascension (within 20–45%) between ∼20 km and 27 km for the period from April to June. GOMOS is larger than SHADOZ at Samoa, except in May, July and between September and November in the 26–30 km heights range. At Fiji, GOMOS is larger than SHADOZ except during the period from May to September above 27 km. And GOMOS values are larger than SHADOZ values at Reunion except in August in the 20–25 km heights range and 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 observed differences. On the average, GOMOS is ∼5–10% larger than SHADOZ between 20 km and 30 km and we will come back later to these point. Despite the observed differences, the agreement between GOMOS and SHADOZ in this altitude range can be considered as for almost all the months and the stations.

The global median and mean differences between GOMOS and SHADOZ ozone mixing ratios are presented in Fig. 6 for each station. We note that the mean values nearly 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 due to 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. 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, sensing solutions changes) at higher altitudes, i.e., at lower ambient pressure.

On average, the percentage of differences between GOMOS and SHADOZ is nearly within ±10% in the height range from 21 km to 23 km and decrease 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 comes that GOMOS systematically and increasingly overestimates ozone mixing ratios with decreasing height. This is in agreement with 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. And 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 during the Southern Hemisphere summer in 2003 and 2004. And they reported a degradation of GOMOS performances in the stratosphere below 22 km. Above 21 km, we observe a good agreement between ozone measurements derived from GOMOS occultations and ground-based balloon-sonde, similar to results reported in previous studies at tropical station (Meijer et al., 2004). And these results in the tropics complete the good agreement observed at mid- and high-latitude stations between GOMOS and ozonesondes (Tamminen et al., 2006; Renard et al., 2006; Liu et al., 2008).

4 Summary

In this work we provided ozone climatology based on 7 years of GOMOS data at Southern Hemisphere stations from 15 km to 50 km. We required a quality selection in order to have good data measurements. The range for maximum mixing ratios at the equatorial stations 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. In the altitude range from 20 km to 50 km, ozone variability varies between 3% and 10% over all the months and it is larger during austral winter in the 27–35 km altitude range.

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We compared GOMOS dark limb occultations with 8 southern ozonesondes stations based on SHADOZ network. GOMOS is in satisfactory agreement with SHADOZ in the altitude range from ∼20 km to 30 km. On most of the stations, in that altitude range, GOMOS is larger than SHADOZ by ∼5–10%. A possible explanation is a bias in the altitude registration of ozonesondes due to their time constant. 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 observed differences. In the altitude range from 21 km to 30 km the monthly differences are generally within ±15%. And the median of the relative percentage of differences between GOMOS and SHADOZ ozone mixing ratios in the 21–23 km height range is nearly within ±10% for almost all the stations and decrease to nearly ±5% above 23 km. Below 21 km, GOMOS data show an increasing variability with decreasing altitude and an increasing positive bias compared to SHADOZ in the tropics. We recommend using with caution GOMOS measurements below 21 km in the tropics.

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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)

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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

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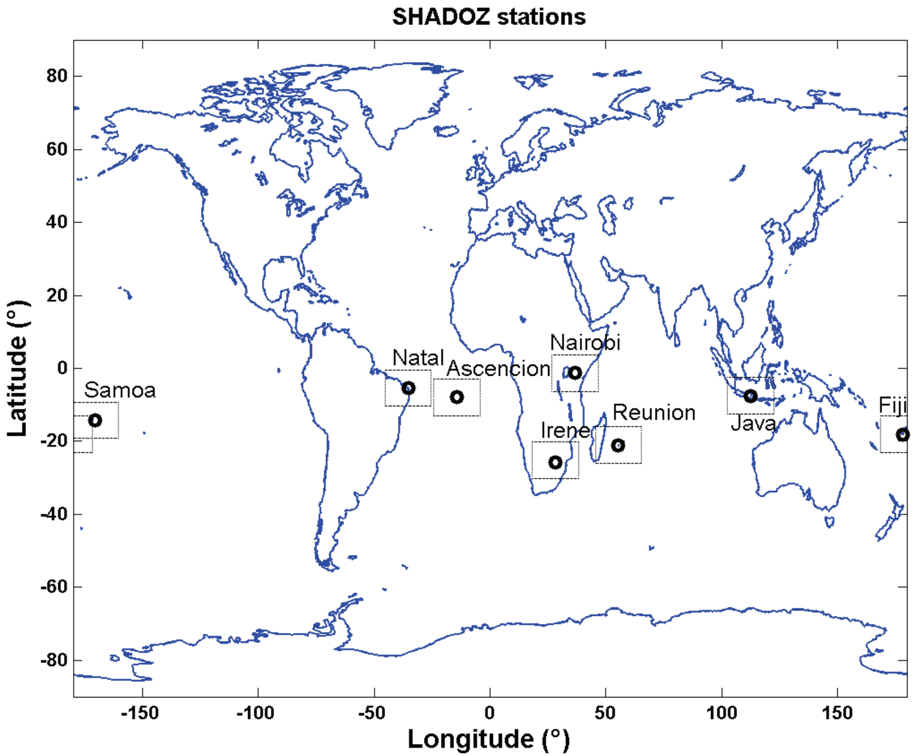

Fig. 1. Map of SHADOZ stations in the Southern Hemisphere. Ozone profiles obtained by radiosonde experiments at 8 stations (black circles) are used for the purpose at the present issue, from west to east: Samoa, Natal, Ascension Island, Irene, Nairobi, Reunion, Java and Fiji. The regions where GOMOS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

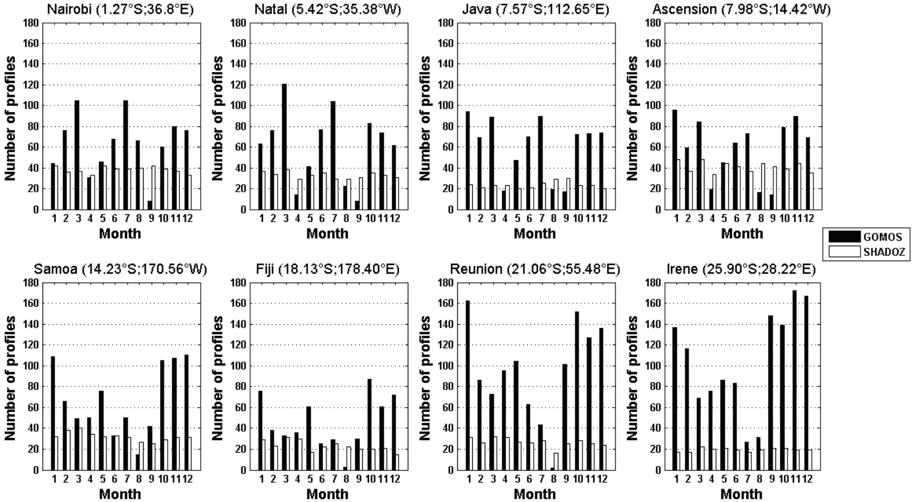

Fig. 2. Monthly distributions of the number of the GOMOS dark occultations (black bars) and SHADOZ profiles (white bars). GOMOS dataset has a global coverage for the time period from 2002 to 2008, while SHADOZ dataset is from 1998 to 2008 and includes 8 southern tropical/subtropical sites.

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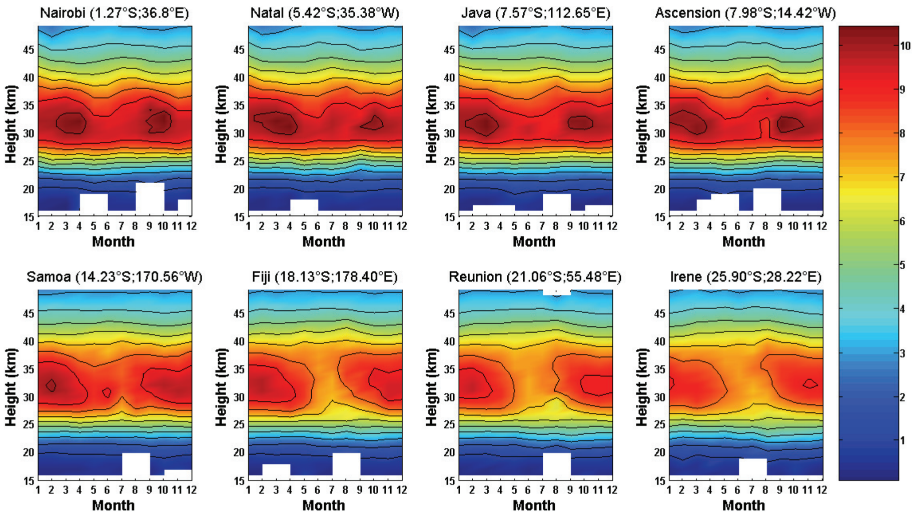

Fig. 3. Monthly median distributions of ozone mixing ratio (in ppmv) as derived from GOMOS observations per station. The contours are separated by 1 ppm.

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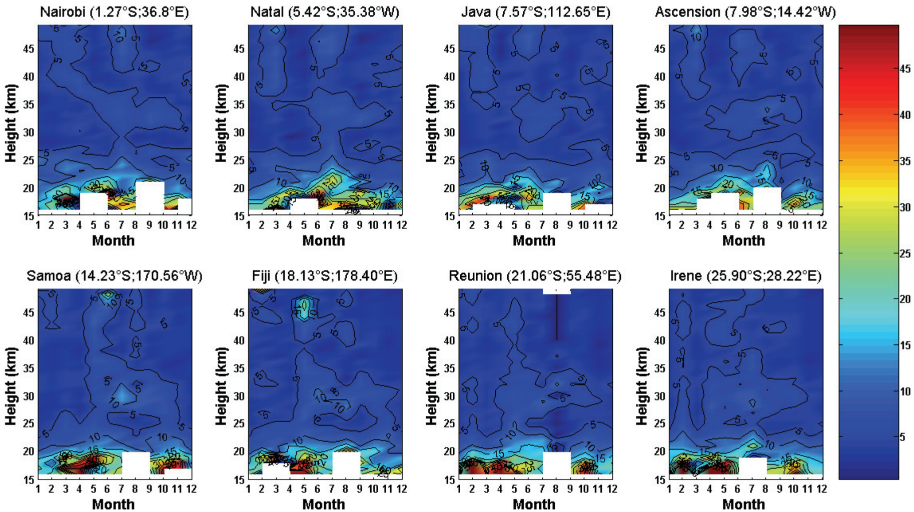

Fig. 4. Contour plots of ozone variability (in %) from GOMOS observations. Variability is defined as the ratio between the interquartile range (iqr) and the median. Contours are separated by 5%.

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Climatology and comparison of ozone

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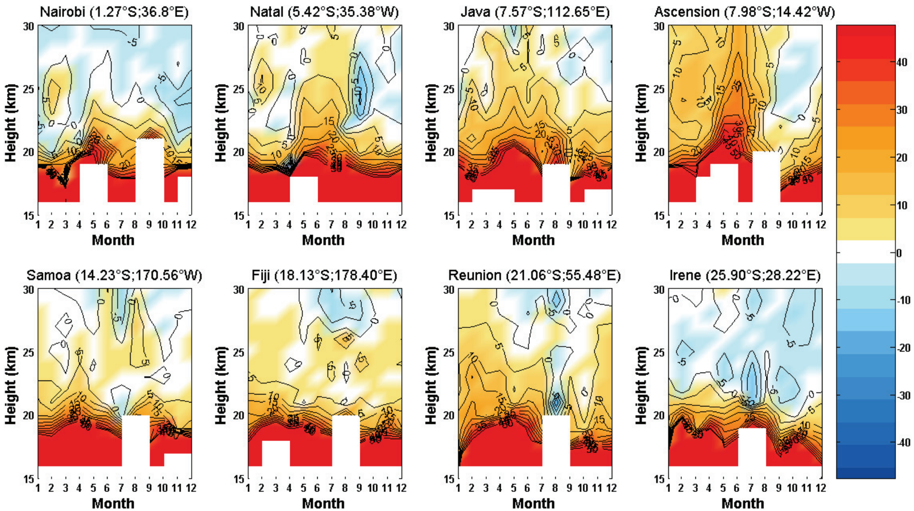

Fig. 5. Monthly distributions of the relative percentage of differences between GOMOS and SHADOZ observations. It is calculated with respect to ground based measurements in the altitude range from 15 km to 30 km. The contours are separated by 5%.

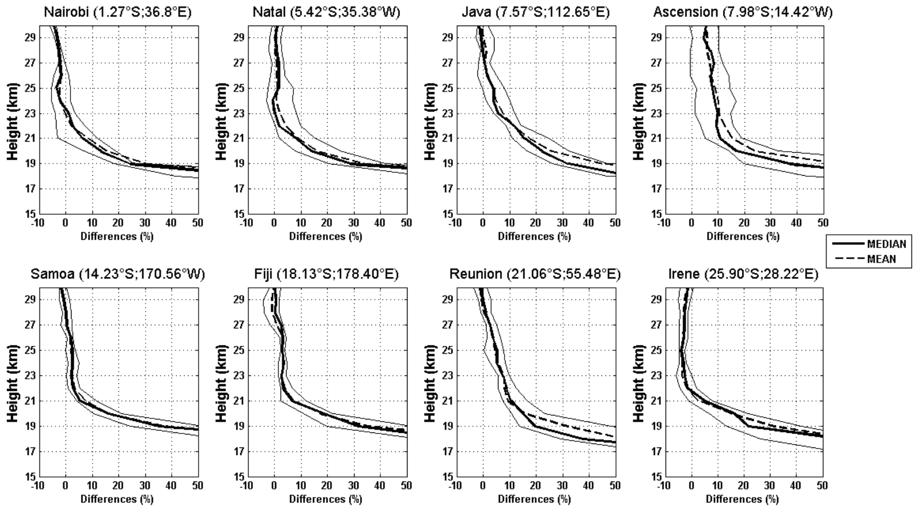

Fig. 6. Median (thick continuous lines) and mean (dashed lines) of the global differences between GOMOS and SHADOZ ozone mixing ratios, for heights between 15 km and 30 km. The thin continuous lines refer to the 25th and 75th percentiles for the median of the percentage of differences.

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