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Atmospheric Measurement Techniques Discussions

Intercomparison of polar ozone profiles by IASI/MetOp sounder with 2010 Concordiasi ozonesonde observations

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Abstract

Validation of ozone profiles measured from a nadir looking satellite instrument over Antarctica is a challenging task due to differences in their height sensitivity with ozonesonde measurements. In this paper we compare the ozone observations provided by the Infrared Atmospheric Sounding Interferometer (IASI) instrument onboard the polar-orbiting satellite MetOp with ozone profiles collected between August and October 2010 at McMurdo Station, Antarctica, during the Concordiasi campaign. This campaign was aimed at satellite data validation and up to 20 zero-pressure sounding balloons carrying ozonesondes were launched during this period when the MetOp satellite was passing above McMurdo. This makes the dataset relevant for comparison, especially because those balloons covered the entire altitude range of IASI profiles. The validation methodology and the collocation criteria differ according to the availability of Global Positioning System auxiliary data with each Electro-Chemical Cell ozonesonde observation. We show that the relative mean difference depends on the altitude range investigated. The analysis shows a good agreement in the troposphere (below 10 km) and middle stratosphere (25–40 km), where the differences are lower than 10 %. However a significant positive bias of about 10–26 % is estimated in the lower stratosphere at 10–25 km, depending on altitude. The positive bias in the 10–25 km range is consistent with previously reported studies comparing in-situ data with thermal infrared satellite measurements. This study allows a better characterization of the IASI products over the polar region when ozone depletion/recovery is occurring.

1 Introduction

Surveying of ozone distribution over Antarctica is an important task to quantify ozone depletion over the poles (Newman et al., 2009), and to assess the efficiency of the international protocols controlling the emission of chlorine containing compounds. Stratospheric ozone is essential for ultra-violet radiation protection which allows life to remain

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on Earth and is closely linked to climate change and stratospheric circulation over the poles (WMO, 2011). For decades satellites have provided valuable measurements of the composition of the atmosphere, in particular to follow the ozone chemistry in the polar stratosphere in Spring.

In 2010 the Concordiasi campaign was organized at McMurdo Station (Lon: 166.67°, Lat: −77.85°), Antarctica (see Fig. 1), by teams from France and the United States, to improve knowledge and understanding of the interactions between ozone depletion, stratospheric clouds and atmospheric dynamics (Rabier et al., 2012). This campaign also aimed to provide additional information to better exploit the temperature, water vapour and ozone observations provided by the Infrared Atmospheric Sounding Interferometer (IASI) instrument onboard the European polar-orbiting satellite MetOp. Such information is required by atmospheric models yet soundings above the ice sheet are known to be difficult, as the radiance data provided by thermal infrared instruments are noisy due the low temperatures encountered there (e.g. Vincensini et al., 2012; Pommier et al., 2012; Mercer et al., 2007).

Two types of balloons were launched during the campaign (see Rabier et al., 2012): (i) Driftsondes carrying dropsondes released on demand inside the polar vortex and (ii) stratospheric zero-pressure balloons launched from McMurdo and following a given air mass to document stratospheric dynamics and ozone depletion. These balloons were equipped with radiosondes and Electro-Chemical Cell (ECC) ozonesondes to measure ozone during their ascent. Only the latter will be used in this study and will be called ozonesondes hereafter.

Ozone is one of the key species measured by the IASI mission and will be the focus of this paper. Previous studies (e.g. Dufour et al., 2012) have shown that the ozone products retrieved from IASI spectra are reliable, although there is still room for improvements, both for accuracy and the characterization of profile data. In this study we present comparisons between ozone profiles retrieved by IASI and measured by ozonesondes onboard zero-pressure plastic balloons during the campaign.The article is organized as follows. Section 2 gives a description of IASI and ozonesonde data.

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Section 3 explains the validation methodology to compare IASI and ozonesondes profiles. Section 4 discusses the results and Sect. 5 summarizes the findings of this study.

2 Data

2.1 Satellite observations

IASI is a long term mission dedicated to atmospheric sounding using the thermal infrared absorption of the Earth-atmosphere system. The nadir radiances are collected and distributed in near real time to operational weather forecasting centers (Hilton et al., 2012; Collard and McNally, 2009) as well as for the monitoring of atmospheric composition changes (Clerbaux et al., 2009). IASI is a Fourier transform spectrometer on board the MetOp-A polar orbiting satellite which provides data on each location at least twice a day since June 2007. Due to polar orbits of MetOp, and its scan across the orbit, IASI provides data with high spatial and temporal resolutions. As it uses the thermal infrared spectral range, it provides day and night measurements all over the year (see Clerbaux et al., 2009 for additional information).

Ozone profiles are retrieved using an optimal estimation approach, implemented in the Fast Optimal Retrievals on Layers for IASI (FORLI) software (Hurtmans et al., 2012). FORLI-O3 inputs are spectral radiances extracted from IASI L1C data, and cloud cover, temperature and humidity profiles extracted from IASI L2 data retrieved by the European Organisation for the Exploitation of Meteorological Satellites (Eumetsat) (e.g. August et al., 2012). The algorithm uses the IASI 10 µm spectral region and 2 to 4 independent pieces of information are retrieved, depending on the location and on the season. The FORLI-O3 products have been validated with different ground-based, aircraft, and satellite data (Scannell et al., 2012; Anton et al., 2011; Pommier et al., 2012). The profiles are retrieved in 39 layers of 1 km thickness from the surface to 39 km, with an extra layer from 39 km to the top of the atmosphere. Along with the retrieved profiles, error covariance and Averaging Kernel (AK) matrices are also provided.

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The latter are essential to quantify the vertical sensitivity of the retrieved profiles (see Fig. 2). They are variable, dependent on surface properties and temperature profiles. Applications range from the study and the monitoring of the stratospheric ozone hole to tropospheric chemistry and air quality (e.g. Scannell et al., 2012; Parrington et al., 2012; Wespes et al., 2012).

2.2 Sounding balloons/Concordiasi campaign in 2010

Three field experiments were conducted, in Antarctica, as part of the Concordiasi campaign, two of them were during the Austral Spring 2008 and 2009 and a third one, which is the focus of this paper, was in Austral Spring 2010. These measurements were aimed at documenting the depletion of the stratospheric ozone layer, the ozone layer seasonal evolution, and stratospheric dynamics; three highly interrelated topics. In this study, we use profiles measured by ozonesondes during the field campaign. These are carried by 20 zero-pressure balloons performing a single ascent.

In Fig. 3, trajectories of eight balloons equipped with GPS receivers are presented along with the ozone concentrations measured during the flights. In Fig. 1, the black box east to McMurdo identifies the region including all the balloon trajectories shown in Fig. 3. The balloons carried ENSCI (Environmental Science Corporation) ozonesondes interfaced to either Vaisala or Imet radiosondes to measure ozone concentration along their paths. The ECCs used 0.5 % KI buffered solutions to sense ozone. For more technical details, the readers are requested to refer to Mercer et al. (2007). Some of the ozonesondes were equipped with GPS receivers, which allowed to obtain a better collocation and thus to make comparison more accurate. Ozone mixing ratio is measured every 5 s during balloon flight which lasts between 1 and 3 h. The shortest sample contained around 850 measurements while the longest contained around 2000 measurements (the difference is due to differences in balloon ascent rate). Table 1 lists all the observations that were used in the framework of this study. It also provides supplementary information such as altitude and the collocation criteria used. The number of profiles corresponds to the number of IASI profiles which are close enough to the

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balloon path for comparison with the ozonesonde profiles. The underlying assumption of this selection is that the closer to the trajectory the more likely ozonesondes and IASI profiles sound the same air parcel. If the balloon was equipped with a GPS receiver, all IASI profiles which were along the GPS path were used. If there was no GPS receiver, the collocation criteria was a radius around McMurdo where the IASI profiles were selected. Last column of the table gives the time interval between the middle of the balloon flight and the time when the satellite passed above the site.

According to Kuttippurath et al. (2010), the edge of the vortex varies between −30 and −45 Potential Vorticity Unit (PVUs) during the August–November period at 475 K. Figure 4 shows the −30\−45 PVU boundaries of the vortex at 475 K, using the ECMWF operational analysed Potential Vorticity (PV) field for several example comparisons. In fact all of the ozonesondes were flown within the polar vortex since that was a criteria for the measurements. This guarantees that the comparisons are made under conditions with a low ozone spatial gradient, reducing the risk of a poor comparison. The fact that McMurdo is inside the vortex guarantees stability to ozone profiles and makes the comparisons more useful.

3 Validation methodology

The IASI retrieved quantity is not a real concentration profile, but a reflection of the ability of the instrument to discriminate different atmospheric layers. Therefore one cannot compare directly satellite retrieved profiles with high-resolution in-situ observations (aircraft, sondes, etc.) and model results. To compare the high-resolution profile measured by the sonde with IASI profiles, the high-resolution profiles are convolved by the IASI AK matrix with the a-priori profile, following Eq. (1):

$$\boldsymbol{X}_{\text{smoothed}} = \mathbf{A}_{\text{low}}\boldsymbol{X}_{\text{high}} + (\mathbf{I} - \mathbf{A}_{\text{low}})\boldsymbol{X}_{\text{a,low}}, \quad (1)$$

where $\boldsymbol{X}_{\text{smoothed}}$ is the smoothed profile which uses low resolution measurement characteristics. $\mathbf{A}_{\text{low}}$ is the low resolution AK. $\boldsymbol{X}_{\text{high}}$ is the high resolution profile given by

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the sonde and $\boldsymbol{X}_{\mathrm{a,low}}$ is the low resolution a-priori profile. The a-priori covariance matrix is constructed from the McPeters/Labow/Logan climatology of ozone profiles, which combines long term satellite limb measurements and measurements from ozonesondes (see McPeters et al., 2007; Hurtmans et al., 2012). If the retrieval was ideal $\mathbf{A}_{\mathrm{low}}$ would tend to $\mathbf{I}$ and the influence of a-priori on the retrieved quantity would be zero (see Rodgers and Connor, 2003 for more details).

This smoothing process reduces ozonesonde profiles sample from around one measurement every 40 m to one measurement every kilometer according to altitude dependence given by IASI AK. The resulting smoothed profile is then compared to the IASI profile. Equation (1) can be seen as a linear combination between an a-priori profile and the observation, the weight of which is given by the AK. Simultaneously it allows to project high resolution observation profiles on IASI lower resolution space. A single a-priori profile representative of the standard ozone concentration in Antarctica is used for these retrievals.

The mean relative error between IASI and ozonesondes profiles and its confidence interval are calculated from the individual comparisons estimated via Eq. (2). The relative error is given by:

$$\Delta \boldsymbol{X} = (\boldsymbol{X}_{\mathrm{iasi}} - \boldsymbol{X}_{\mathrm{smoothed}})/\boldsymbol{X}_{\mathrm{smoothed}}, \quad (2)$$

where $\boldsymbol{X}_{\mathrm{iasi}}$ is the IASI profile and $\boldsymbol{X}_{\mathrm{smoothed}}$ is the smoothed ozonesonde profile calculated through Eq. (1). We estimated this difference for each ozonesonde observation and each collocated IASI profile. The 95 % confidence interval for this comparison is calculated through the sample mean, $\mathbf{E}$ and is given by:

$$\left[\mathbf{E}[\Delta \boldsymbol{X}] - 1.96\frac{\sigma}{\sqrt{n}};\ \mathbf{E}[\Delta \boldsymbol{X}] + 1.96\frac{\sigma}{\sqrt{n}}\right], \quad (3)$$

where n is the total number of comparisons and σ is the variance of the differences. This mean relative error ($E[\Delta \boldsymbol{X}]$) gives the error made by IASI at each altitude range. The 95 % confidence interval given by Eq. (3) indicates the reliability of the mean and

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represents the interval which would include the error with a 0.95-probability if the comparison is repeated (See Frontier et al., 2007 for additional details on confidence intervals).

4 Results and discussion

Figure 5 shows the overall comparisons that have been carried out between IASI satellite data and 20 ozonesonde measurements during the Concordiasi campaign. The blue lines represent the raw observed profiles measured by the ozonesondes ($\boldsymbol{X}_{\text{high}}$ in Eq. 1). IASI profiles ($\boldsymbol{X}_{\text{iasi}}$ in Eq. 2) are presented in subplots by green lines. Black lines are the constant IASI a-priori profiles ($\boldsymbol{X}_{\text{a,low}}$ in Eq. 1). Finally, red lines represent the smoothed profiles calculated from, $\boldsymbol{X}_{\text{smoothed}}$ of Eq. (1).

Each IASI profile has its own AK, so Eq. (1) is calculated for each IASI profile. The relevant comparison in Fig. 5 is to be done between red (smoothed ozonesonde profile) and green lines (IASI profile). The smaller the collocation criteria, the better the match between the IASI profiles and the smoothed ozonesonde profile. For example, in Fig. 5, the balloon launched on 14 September (2nd row, 3rd column) was equipped with a GPS receiver and there were four IASI profiles in a perimeter of 30 km along its path. The agreement between IASI profiles (green lines) and the smoothed sonde profiles (red lines) is much closer than, for example, for 22-August balloon, which was not equipped with GPS receiver and for which the closest IASI profiles were around 100 km far from McMurdo.

In Fig. 6a, all observations are considered. The black lines represent the mean relative error ($\boldsymbol{E}[\Delta\boldsymbol{X}]$) and the 95 % confidence interval (Eq. 3) considering all comparisons between ozonesondes and IASI profiles. The red lines show similar results but only considering comparisons with the GPS equipped ozonesondes. This average difference is calculated as the mean of the relative error between IASI profiles and the smoothed ozonesonde profiles (Eq. 2). Note that the width of the confidence interval is constant with altitude and equal to $\approx 1.5\,\%$ for both errors.

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The average relative difference remains between −10 % and +26 %, dependent on altitude. In the troposphere, between 0 km and 10 km, IASI data show a particularly good agreement (i.e. relative difference remains between −7 % and 0 %). We show that comparisons based on ozonesondes equipped with GPS tend to significantly improve the agreement, with an error less than 5 % in the troposphere. The improvement near the surface comes from a better selection of IASI profiles, where collocations were improved by the available GPS data. Moreover, the collocation of profiles is carried out based on the matching of the two soundings at the surface altitude, which also favours a better comparison at the lower part of the profiles.

However, between 10 km and 25 km (corresponding to the lower stratosphere), IASI tends to overestimate the observations by up to 26 %. This bias, in the lower stratosphere, confirms the bias estimated by previous works (e.g. Scannell et al., 2012) and in other regions such as Iberian Peninsula (Anton et al., 2011) or at midlatitudes and in the tropics (Dufour et al., 2012). Dufour et al. (2012) showed that three independent IASI ozone retrieval codes tend to overestimate ozone in the upper troposphere/lower stratosphere region in the midlatitudes and the tropics.

A large gradient due to ozone loss can be detected on each ozonesonde profile (blue lines) in Fig. 5 from 19 September. To verify whether the overestimation is induced by this gradient or not, Fig. 6b compares the profiles observed before and after 19 September, which corresponds to the time when ozone depletion was clearly observed in the ozone mixing ratio profiles, although it was observed earlier in profiles of ozone partial pressure or number density, typically in the first week of September at McMurdo (see Fig. 5). The figure illustrates that the overestimation of IASI between 10 km and 25 km is not due to ozone depletion as it is observed both before and during the depletion process. Then, at this altitude range, the overestimation of IASI ozone does not depend on the distribution of ozone, but should be concidered as systemic to IASI retrieval process. At this altitude range, the use of GPS receivers does not reduce the error. Between 15 km and 20 km, the error seems to increase when only the GPS sondes are used, but the difference with the overall comparisons is not significantly

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high (i.e. the GPS-only error is included in the confidence interval of the overall comparisons and vice-versa).

In the upper part of the profile, which roughly corresponds to the middle stratosphere (i.e. between 25 km and 40 km) the discrepancies decrease again (between −10 and −5 %). This bias at the top of profiles is mainly due to the decreasing sensitivity of IASI (see Fig. 2). Boxe et al. (2010) performed a similar study with Tropospheric Emission Spectrometer satellite, also a thermal infrared nadir instrument, during the Arctic Research on the Composition of the Troposphere from Aircraft and Satellites field mission between April and July 2008 in Northern latitudes (between 44° and 71°). They show similar biases in the distribution of ozone in the troposphere, UT/LS and middle stratosphere region. At this altitude range, GPS equipped radiosondes do not show a significant improvement.

5 Conclusions

Accurate measurements of ozone profiles using satellite instruments remain difficult over the poles, in particular when the decrease of ozone is observed in Spring. For thermal infrared remote sensors such as IASI, the difficulty is amplified by the cold surface temperature. In this work we use 20 ozonesonde profiles observed during the Concordiasi balloon campaign which took place at McMurdo station, Antarctica, in 2010 to compare with FORLI-O3 IASI data. Some of them were carrying GPS receivers which makes the comparisons more accurate as we can select the closest IASI profiles. Ozonesonde profiles were first smoothed with AKs to be compared with IASI observations. We found a good agreement between the two datasets. In the troposphere (between surface and 10 km) and also between 25 km and 40 km, a relative difference between −10 and 0 % was found, provided the data are well collocated (sondes equipped with GPS).

The overestimation of ozone in the 10–25 km range has already been highlighted in previous studies and with other instruments (e.g. TES as described in Boxe et al.,

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2010). We show that this overestimation can not be explained by the difficulty of IASI to measure the high gradient due to ozone depletion process. Consequently, this means that IASI is able to measure ozone depletion events as well as it measures ozone distribution during regular events. Previous studies showed similar biases at different latitudes (e.g. Boxe et al., 2010; Anton et al., 2011) and in this study we show that their finding remains valid at southern latitudes. This work should trigger a detailed study of why a systematic bias is observed in the lower stratosphere, at midlatitudes and in the tropics, but also over Antarctica. It might be due to spectroscopic issues (a UV-TIR bias was pointed in previous studies), to inadequacy of a priori covariance matrix, or to any other reason still to be identified.

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Table 1. Balloon data used in this study. First column presents the month and day ("mm-dd") the balloon was launched, second column indicates whether the balloon was equipped with a GPS ("0") or not ("X"). Third column gives the bursting altitude of the balloon above sea level. Then the number of IASI profiles considered for each comparison and the collocation criteria are respectively given in fourth and fifth column. Sixth column gives an approximation of the time interval between the middle of the balloon flight and time when the satellite passed above the site.

Day of launch	GPS	Altitude (km)	Number of prof.	Colloc. crit. (km)	Time interval
20 August	X	30.23	3	10	02 h 00 min
22 August	X	30.46	6	100	07 h 00 min
26 August	O	29.82	18	5	02 h 30 min
3 September	X	30.32	7	10	02 h 00 min
8 September	X	31.54	7	10	07 h 00 min
10 September	X	31.43	4	10	02 h 30 min
14 September	O	31.54	3	30	00 h 30 min
16 September	X	32.66	4	30	02 h 30 min
19 September	X	26.84	1	10	08 h 00 min
25 September	X	32.09	4	20	03 h 00 min
27 September	X	29.41	2	20	06 h 00 min
30 September	X	33.29	5	30	02 h 00 min
4 October	X	32.22	3	30	04 h 30 min
8 October	X	34.03	3	30	04 h 30 min
12 October	O	28.04	4	5	04 h 30 min
15 October	O	31.01	15	5	03 h 30 min
18 October	O	31.34	5	10	03 h 30 min
21 October	O	31.68	7	5	01 h 00 min
25 October	O	30.26	15	10	02 h 30 min
28 October	O	29.59	12	5	00 h 30 min

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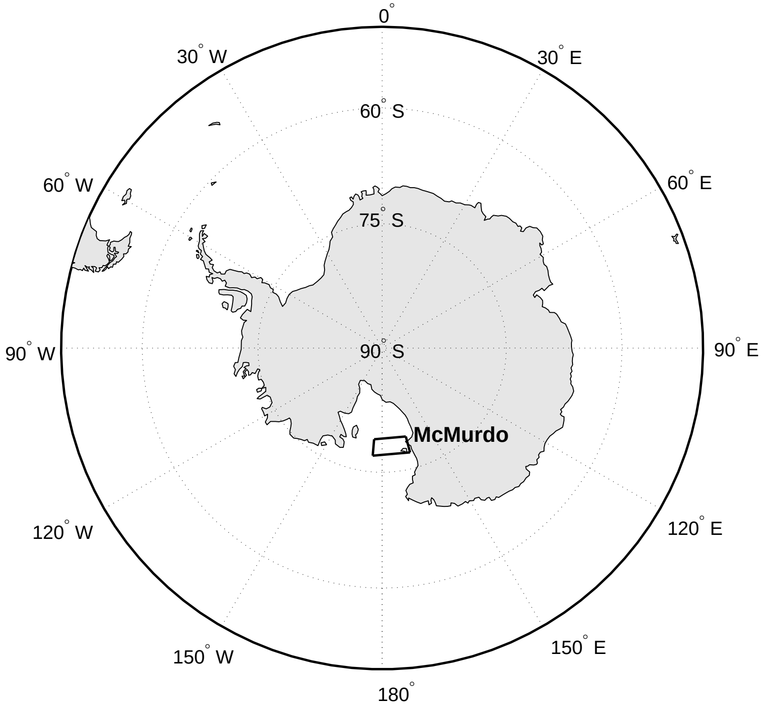

Fig. 1. The McMurdo station, Antartica, is located on the southern tip of Ross Island. The black box gives a hint on the longitudes/latitudes in which the sondes profiles plotted in Fig. 3 were launched.

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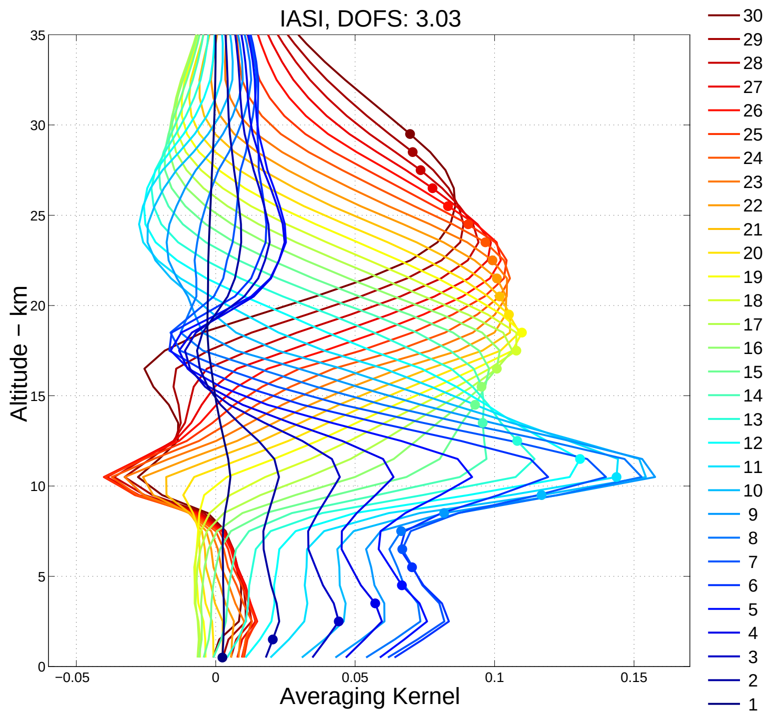

Fig. 2. Typical averaging kernel matrice and DOFS of ozone profile provided by IASI. The figure shows an example observed on 16 September 2010 over McMurdo. Each coloured line corresponds to the altitude indicated by the coloured dot.

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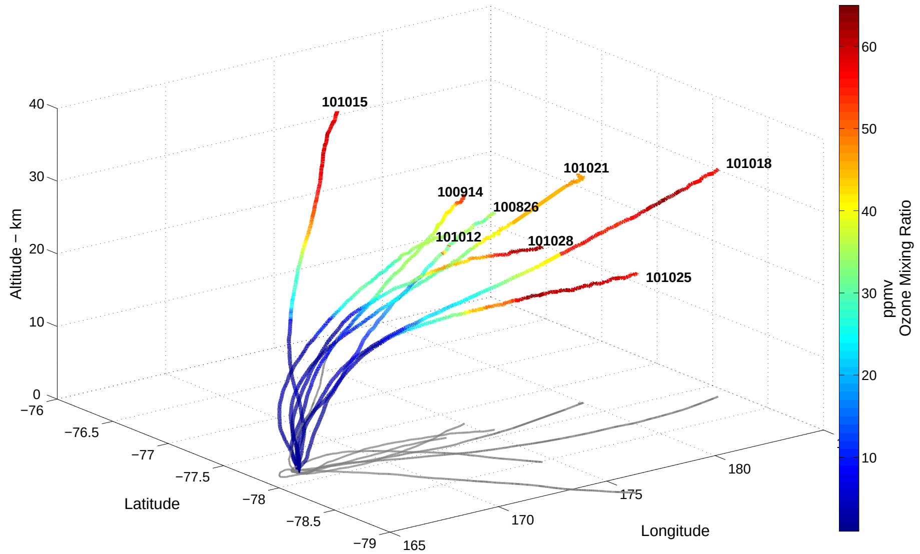

Fig. 3. Ozone profiles measured by zero-pressure balloons at McMurdo during the 2010 Concordia campaign. The figure presents the flight paths of the 8 balloons equipped with GPS receivers. Grey lines display the shadows of the trajectories. Each profile is named by its date ("yymmdd") at the top of the profile and ozone units are given in ppmv. The black square in Fig. 1 identifies the entire latitude/longitude region covered by the sondes.

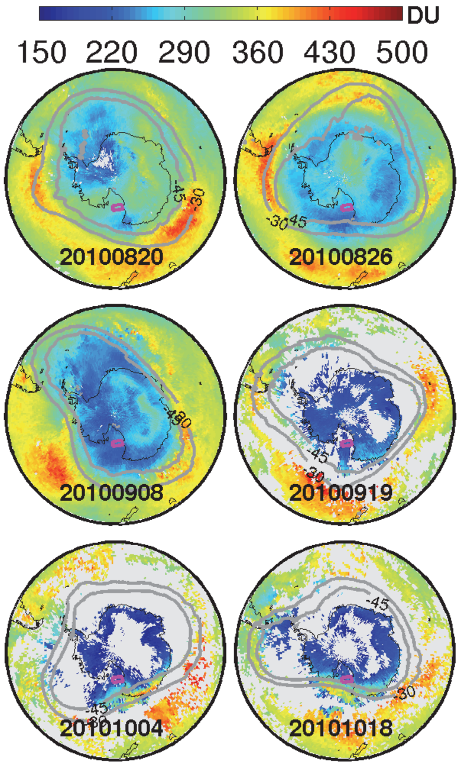

Fig. 4. The status of the vortex and position of McMurdo station during selected days of the Concordiasi campaign. Ozone total column retrived from IASI measurements are on the background. The overlaid grey lines represent −30 and −45 PVU, the approximate boundaries of the vortex. The station remained inside the vortex during the campaign period. Starting from 15 September, the number of IASI data around McMurdo has strongly decreased due to a major change in the Eumetsat temperature retrieval processing. This explains the missing value in Fig. 4. A dedicated processing was undertaken in the framework of this study to allow for more data in the McMurdo area.

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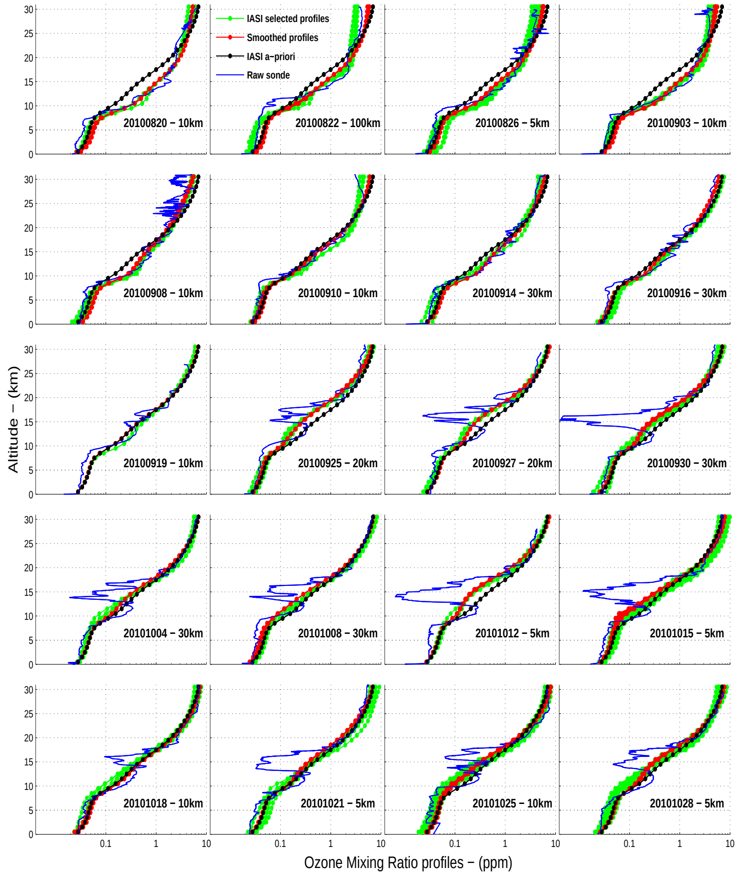

Fig. 5. Comparison between the high resolution raw ozonesonde profile (blue), the low resolution smoothed ozonesonde profiles (red) and the low resolution IASI/MetOp ozone profiles (green). Note that the graphs are using logarithmic x-scale. Collocation criteria is given on each plot next to the date.

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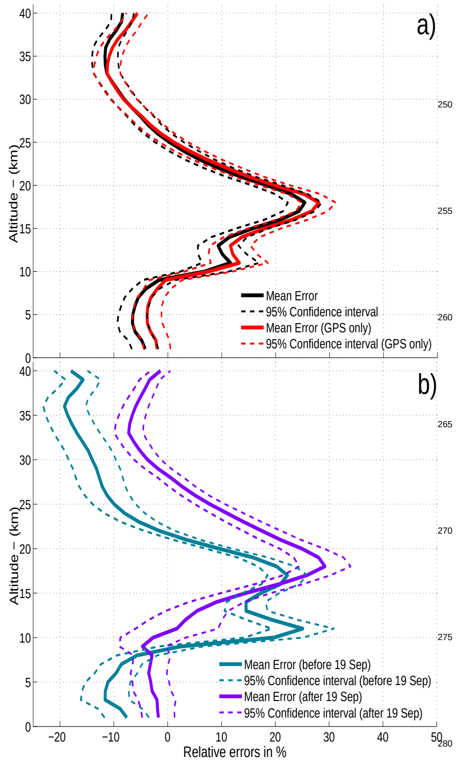

Fig. 6. Panel **(a)**: the average relative difference computed between IASI and radiosonde ozone profile measurements. It is the average of 20 comparisons, where the relative error is calculated as the difference between IASI profile and the smoothed balloon profile divided by the smoothed profile at each altitude. Black lines represent the mean and confidence interval of overall comparisons whereas red lines take into account only comparisons of GPS equipped ozonesondes. Panel **(b)**: blue lines represent the comparisons of profiles observed before 19 September, whereas violet lines represent profiles observed after 19 September (when ozone loss was clearly observed in the mixing ratio profiles).

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