VALIDATION OF TROPOSPHERIC OZONE FROM IASI WITH OZONE SONDES

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ABSTRACT

We present the validation of tropospheric ozone products derived from the IASI satellite instrument measurements. IASI is a nadir-viewing Fourier transform spectrometer operating in the thermal infrared aboard the MetOp platform. The retrieved products that we produce are ozone partial columns (especially 0-6 km columns) and ozone profiles. A first validation exercise using balloon sonde measurements that has been performed during the first year of IASI operation for the northern midlatitudes observations showed that tropospheric partial columns do not present any significant bias (< 5%) and that the retrieval errors are consistent with the standard deviation of the difference between the sonde and IASI measurements (see ref [1]). We present here an extended validation exercise that covers the period from January 2008 to December 2008 and focuses on both the mid-latitudes and the tropics. In order to evaluate the quality and the performance of the products, comparisons of the vertical ozone concentration profiles and the derived partial tropospheric columns retrieved from IASI spectra and measured by balloon sondes are performed. This leads to estimates of the systematic and random errors in the IASI ozone products. The first results obtained for the midlatitudes are consistent with the first validation exercise.

1. INTRODUCTION

Ozone is a key species of tropospheric chemistry affecting the troposphere’s oxidative capacity and is a well-known pollutant with significant impact on health and vegetation [2]. Ozone is also an important greenhouse gas with large radiative forcing in the upper troposphere [3]. Monitoring of tropospheric ozone is essential to quantify its sources, transport, chemical transformation [4] and to evaluate and improve models used for climate and pollution modelling.

Tropospheric ozone concentrations are mainly measured at surface level using national operational networks and vertical information is for the most part provided at selected sites by meteorological balloon sondes or during dedicated aircraft campaigns. In addition to these in situ measurements, satellite observations in the nadir geometry are very promising because of their large spatial coverage. However, tropospheric ozone retrieval from satellite observations is a challenging task because most of the ozone is contained in the stratospheric ozone layer. The first satellite measurements of tropospheric ozone have been obtained using ultraviolet-visible sounders [e.g. 5, 6] but they have some limitations in the mid- and high latitudes. The recent development of infrared nadir sounders allows accurate measurements of tropospheric ozone, with the advantage that measurements are also possible during the night. The first demonstration of tropospheric ozone column retrieval has been done using the IMG (Interferometric Monitor for Greenhouse gases) instrument [7, 8]. More recently, the TES (Tropospheric Emission Spectrometer) instrument has provided measurements of tropospheric ozone [9] with applications to air quality modelling [10] and climate [11]. Finally more recently, using measurements from the IASI (Infrared Atmospheric Sounding Interferometer) instrument aboard the European Metop-A satellite (launched in October 2006), tropospheric ozone during the heat wave over Europe in summer 2007 has been observed and compared with balloon sondes and predictions from a photochemical tropospheric model [12], demonstrating the potential of IASI measurements for air quality applications. Here we present validation results obtained for a one-year period (January 2008 to December 2008) using balloon sonde measurements.

2. THE IASI INSTRUMENT

The IASI (Infrared Atmospheric Sounding Interferometer) [13] is a nadir viewing spectrometer onboard the MetOp-A satellite and was designed for operational meteorology. The MetOp-A satellite launched in October 2006 flies in a polar synchronous orbit (about 800 km altitude) and crosses the equator at two fixed local solar times 9:30 am (descending mode) and 9:30 pm (ascending mode). The IASI instrument is a Fourier-transform spectrometer with a 2 cm optical path difference covering the 645-2760 cm⁻¹ spectral range. The apodized spectral resolution is 0.5 cm⁻¹ (Full-Width at Half-Maximum). The radiometric accuracy in noise-equivalent radiance temperature at 280 K is 0.20 K at 650 cm⁻¹ and 0.47 K at 2400 cm⁻¹. IASI measures the thermal infrared radiation (TIR) emitted by the Earth’s surface and the atmosphere. The instrument scans the surface perpendicular to the satellite’s flight track with 15 individual views on each side of the track. The distance between two successive overpasses is 25° in longitude (i.e. 2800 km at the equator). For latitudes higher than
45° in latitude, the footprints of two successive overpasses overlap. At the nadir point, the view size is 50 × 50 km². The view is composed of 4 individual ground pixels with 12 km diameter each. The maximum scan angle of 48.3° from the nadir corresponds to coverage for one swath of about 2200 km in the direction perpendicular to the satellite’s track. In addition to meteorological products (surface temperature, temperature and humidity profiles, cloud information), the IASI instrument provides distributions of several trace gases (e.g. O₃, CO) [12, 14].

3. RETRIEVAL METHOD

The ozone products from IASI (mainly partial tropospheric columns) presented in this paper are based on profile retrieval of ozone. The retrievals are performed using the radiative transfer model KOPRA (Karlsruhe Optimised and Precise Radiative transfer Algorithm, [15]) and its inversion module KOPRAFIT, both adapted to the nadir-viewing geometry. A constrained least squares fit method using an analytical altitude-dependent regularization is used. The regularization method applied as well as the error calculations are detailed in [12]. To summarize, the regularization matrix is a combination of zero, first and second order Thikonov [16] constraints with altitude-dependent coefficients. The coefficients are optimized to both maximize the degrees of freedom (DOF) of the retrieval and to minimize the total error on the retrieved profile.

The analysis of IASI data is performed in three steps. First, the effective surface temperature is retrieved from selected windows between 800 and 950 cm⁻¹ considering a blackbody with an emissivity equal to unity. In the second step, the atmospheric temperature profile is retrieved from CO₂ lines in the 15 μm spectral region and using the ECMWF profiles as a priori. In the third step, the ozone profiles are retrieved from seven spectral windows in the 975-1100 cm⁻¹ region that avoid strong water vapor lines. The spectroscopic parameters of ozone are from the MIPAS database [17] and from HITRAN 2004 for the other species. The a priori profile used during the retrieval is compiled from the climatology of [18] and is the same independently of the time and the location of the observations (in the midlatitudes).

Note that before the retrieval, the IASI spectra are filtered for cloud contamination. Only spectra for clear sky conditions are considered. A quality flag is also applied to the retrieved products to discard unphysical results. The error on the profile ranges between 20 and 40% and the error on the 0-6km columns ranges between 15 and 30% depending on the thermal contrast.

4. VALIDATION WITH OZONE SONDE MEASUREMENTS

In this section, we present validation of the ozone products produced by our team with ozone sonde measurements. The validation time period used ranges between January 2008 and December 2008. The spatial and temporal coincidence criteria retained for the comparison with the sonde measurements are ± 110km (square) and 12 hours. The list of the stations used for the comparisons is given in Table 1. For the validation, the ozone profiles measured by the balloon sondes are assumed to be a good estimate of the real state of the atmosphere. Note that the vertical resolution of the sonde measurements is much better than the vertical resolution of IASI products (a maximum of about 1.5 degrees of freedom in the troposphere [1]). The sonde profiles are then smoothed (Eq. 1) by the averaging kernel (A) of the IASI retrievals in order to compare the IASI retrieved profiles with the expected retrieved profiles according to the true state given by the sonde [24].

\[ x_{\text{smoothed}} = x_{\text{a priori}} + A(x_{\text{sonde}} - x_{\text{a priori}}) \]

<table>
<thead>
<tr>
<th>Station</th>
<th>location</th>
<th>coincidences</th>
<th>Station</th>
<th>location</th>
<th>coincidences</th>
<th>Station</th>
<th>location</th>
<th>coincidences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Midlatitudes</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Churchill</td>
<td>(58.7, -94.1)</td>
<td>54</td>
<td>Sapporo</td>
<td>(43.1, 141.3)</td>
<td>34</td>
<td>Hilo</td>
<td>(19.4, -155.0)</td>
<td>9</td>
</tr>
<tr>
<td>Edmonton</td>
<td>(53.5, -114.1)</td>
<td>63</td>
<td>Trinidad</td>
<td>(40.8, -124.2)</td>
<td>62</td>
<td>Alajuela</td>
<td>(10.0, -84.2)</td>
<td>10</td>
</tr>
<tr>
<td>Goose Bay</td>
<td>(53.3, -60.4)</td>
<td>36</td>
<td>Madrid</td>
<td>(40.5, -3.6)</td>
<td>35</td>
<td>Paramaribo</td>
<td>(5.8, -55.2)</td>
<td>9</td>
</tr>
<tr>
<td>Legionowo</td>
<td>(52.4, 21.0)</td>
<td>26</td>
<td>Ankara</td>
<td>(40.0, 32.9)</td>
<td>14</td>
<td>San Cristobal</td>
<td>(4.9, -39.6)</td>
<td>14</td>
</tr>
<tr>
<td>Lindenberg</td>
<td>(52.2, 14.1)</td>
<td>39</td>
<td>Boulder</td>
<td>(40.0, -105.5)</td>
<td>24</td>
<td>Nairobi</td>
<td>(-1.3, 36.8)</td>
<td>16</td>
</tr>
<tr>
<td>Valentina</td>
<td>(51.9, 10.3)</td>
<td>44</td>
<td>Wallops</td>
<td>(37.9, -75.5)</td>
<td>25</td>
<td>Maxaranguane</td>
<td>(-5.5, -35.2)</td>
<td>22</td>
</tr>
<tr>
<td>Brittany Lake</td>
<td>(50.2, -104.7)</td>
<td>50</td>
<td>Lauder</td>
<td>(-45.0, 169.7)</td>
<td>6</td>
<td>Watukosek</td>
<td>(-7.5, 112.6)</td>
<td>4</td>
</tr>
<tr>
<td>Praha</td>
<td>(50.0, 14.4)</td>
<td>39</td>
<td>Macquarie</td>
<td>(-54.5, 158.9)</td>
<td>19</td>
<td>Ascension</td>
<td>(-8.0, -14.4)</td>
<td>6</td>
</tr>
<tr>
<td>Kelowna</td>
<td>(49.9, -119.4)</td>
<td>47</td>
<td>Ushuaia</td>
<td>(-54.9, -68.3)</td>
<td>22</td>
<td>Samoa</td>
<td>(-14.2, -170.6)</td>
<td>4</td>
</tr>
<tr>
<td>Hohenpeiss.</td>
<td>(47.8, 11.0)</td>
<td>87</td>
<td>Tropics</td>
<td>La réunion</td>
<td>(-21.1, 55.5)</td>
<td>9</td>
<td></td>
<td></td>
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<tr>
<td>Payerne</td>
<td>(46.5, 6.6)</td>
<td>119</td>
<td>Naha</td>
<td>(26.2, 127.7)</td>
<td>14</td>
<td>Irene</td>
<td>(-25.9, 28.2)</td>
<td>16</td>
</tr>
</tbody>
</table>
The main differences arise in the upper troposphere/lower stratosphere: IASI retrieval overestimates ozone values measured by the sonde. However, the difference (<15%) remains smaller than the retrieval errors that are estimated to be about 30% at these altitudes. To investigate the quality of the individual products, we compared the retrieved individual tropospheric partial columns (0-6km, 6-14km, 0-11km, and 0-14km) to the corresponding ozone sonde measurements. The corresponding scatter plots are reported in Fig. 2 for the midlatitudes. The correlation is relatively high for the different partial columns considered in Fig. 2. It ranges between 0.78 and 0.83. The bias is small (<2%) for the 0-6km partial column and reaches 9.4% for the 6-14km partial column. This is consistent with the overestimation of IASI observed in the profiles (Fig. 1). Note that the rms of the difference between the IASI retrieved columns and the sonde columns is in agreement with the error budget of the retrieval.

In addition for the midlatitudes, we investigated if the bias is dependent of the season, of the time of the measurement (morning or evening overpasses), and of the considered hemisphere. As expected the bias is larger during winter when the measurements are less sensitive to the lower troposphere due to the unfavourable thermal conditions (low surface temperature and thermal contrast). Moreover, the sign of the bias changes from winter to summer for the 0-6km partial column. The bias is positive with IASI larger than the sonde in winter, spring and fall but negative with IASI smaller than the sonde in summer. The separate comparison between the sonde and the retrieval of the morning pixels and between the sonde and between the evening pixels reveals some significant differences especially for the 0-6 km columns. Actually the bias (<1%) and the rms (18.4%) observed on the morning pixels is smaller than the bias (2.4%) and the rms (22.6%) observed on the evening pixels. This is related to a better sensitivity in the lower troposphere the morning when the surface temperature and the thermal contrast are usually larger than the evening. Note that we also observed differences in the performance of the retrieval of the northern and southern midlatitudes. The agreement is better with ozone sonde of the northern hemisphere than with ozone sonde of the southern hemisphere. Several factors can explain this difference: (1) the a priori profiles used in the retrieval is set-up for the northern midlatitudes. Ozone amounts in the northern hemisphere are larger and the use of this a priori can introduce a bias; (2) the number of stations measuring ozone in the southern hemisphere is small (only 3 stations available). The number of coincidence is then less statistically reliable.

### Table 1. Midlatitude and tropical ozone sonde stations used in the comparison of the LISA retrievals, including their latitude, longitude, and the number of days with coincidences between IASI and sonde data. The total number of coincidences is 896 in the midlatitudes and 153 in the tropics.

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Longitude</th>
<th>Days of Coincidence</th>
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<tbody>
<tr>
<td>10</td>
<td>10</td>
<td>120</td>
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<tr>
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<td>120</td>
<td>120</td>
<td>120</td>
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<tr>
<td>130</td>
<td>130</td>
<td>120</td>
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</tbody>
</table>

Fig. 1 shows the comparison between the retrieved profiles and the smoothed sonde profiles averaged over the year 2008 for all the midlatitude stations. The agreement between the mean IASI retrieved profile and the mean sonde profile is less than 13% from the surface up to 20 km. The main differences arise in the upper troposphere/lower stratosphere: IASI retrieval overestimates ozone values measured by the sonde. However, the difference (<15%) remains smaller than the retrieval errors that are estimated to be about 30% at these altitudes.

**Figure 1.** Left: Mean tropospheric profiles for all the stations (896 coincidence days) of the LISA retrieval (black) and the sonde profiles convolved with the AK (red) Right: the differences as solid line for absolute differences (black) and as dotted line for relative differences (red).

**Figure 2.** Correlation plot between the 0-6km, 6-14km, 0-11km, and 0-14km ozone columns retrieved from IASI and measured by the sonde (smoothed with the IASI averaging kernels) for the midlatitude stations.
similar comparisons of the profiles and partial columns have been done between IASI retrievals and ozone sonde measurements available in the tropics. The number of sonde stations operating in the tropics is less important than in the midlatitudes (Table 1): the total number of day with coincidences is 153. The retrieval set-up is slightly different from those in midlatitudes. We use a regularization matrix different but adapted to the tropics. Similarly the used a priori profile corresponds to the climatological ozone profile between 10°N and 30°N from the McPeters’ climatology [18]. Comparisons of the different partial columns (0-6km, 6-14km, 0-11km, and 0-14km) are presented in Fig. 3. A good correlation (between 0.7 and 0.8) is observed but larger biases for the 0-6km and 6-14km partial columns arise. IASI retrieval underestimates the ozone amounts between the surface and 6km by ~15%, whereas it overestimates the ozone amounts between 6 and 14 km by 24%. Due to compensation effect, the bias is small (~2%) for the 0-14km partial columns. Considering the rms, they seem underestimated compared to the error budget especially for the 0-6km column. Additional work is needed to improve the retrieval and decrease the bias in the retrieval.

![Figure 3. Correlation plot between the 0-6km, 6-14km, 0-11km, and 0-14km ozone columns retrieved from IASI and measured by the sonde (smoothed with the IASI averaging kernels) for the tropical stations.](image)

5. CONCLUSION

The validation results presented in this paper show that our IASI product presents a small bias (< 5%) in the troposphere for the midlatitudes. The main differences arise in the upper troposphere/lower stratosphere where IASI retrieval overestimates ozone amounts. The variability of the errors (rms) is consistent with the errors in the retrieved columns and the ozone measurements used as reference in the midlatitudes. Due to a best sensitivity to the lowest layers of the troposphere when surface temperature is larger, the performances of the product in term of bias and rms is better in summer and for the morning pixels. For the tropics, the number of stations measuring ozone is less important, and then the statistics are less robust. The first results obtained show significant negative bias in the lower troposphere and significant positive bias in the upper troposphere, and then compensation effect on the entire troposphere.

6. REFERENCES


