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RESEARCH ARTICLE

Global consistency check of AIRS and IASI total CO_2 column concentrations using WDCGG ground-based measurements

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Abstract This article describes a global consistency check of CO_2 satellite retrieval products from the Atmospheric Infrared Sounder (AIRS) and Infrared Atmospheric Sounding Interferometer (IASI) using statistical analysis and data from the World Data Centre for Greenhouse Gases (WDCGG). We use the correlation coefficient (r), relative difference (RD), root mean square errors (RMSE), and mean bias error (MBE) as evaluation indicators for this study. Statistical results show that a linear positive correlation between AIRS/IASI and WDCGG data occurs for most regions around the world. Temporal and spatial variations of these statistical quantities reflect obvious differences between satellite-derived and ground-based data based on geographic position, especially for stations near areas of intense human activities in the Northern Hemisphere. It is noteworthy that there appears to be a very weak correlation between AIRS/IASI data and ten ground-based observation stations in Europe, Asia, and North America. These results indicate that retrieval products from the two satellite-based instruments studied should be used with great caution.

Keywords CO_2, consistency check, AIRS, IASI, WDCGG

1 Introduction

Carbon dioxide (CO_2), the dominant anthropogenic greenhouse gas and an indicator of climate change, has dramatically increased from a pre-industrial level of 280 ppm (parts per million) to a current value of about 395 ppm, as described by the IPCC Fifth Assessment Report (AR5) (IPCC, 2014). This increase, which is mainly caused by human activities such as the burning of fossil fuels, has raised serious climate and sustainability concerns. It is expected that a further increase of atmospheric CO_2 will significantly alter future climate by affecting the Earth's radiation balance. It is essential to quantify variations in the temporal and spatial pattern of CO_2 concentrations in order to identify and understand sources and sinks at the Earth's surface and to better predict the influence of these factors on climate change.

Ground-based CO_2 observations and satellite measurements have provided the two main data sources for studying the variations in global atmospheric CO_2 concentrations. The World Data Centre for Greenhouse Gases (WDCGG) archives and provides data on CO_2 and other greenhouse gases measured mainly at surface stations. The WDCGG is one of the World Data Centres (WDCs) under the World Meteorological Organization's (WMO) Global Atmosphere Watch (GAW) program and, together with other programs, was created to provide information about variations in CO_2 and other greenhouse gases (WMO GAW Report No.161, 2005).

Several studies have been conducted to define the annual and seasonal changes of CO_2 based on measurements from ground-based stations. As a consistency check for CO_2 measurements from space, several publications have recently compared the Atmospheric Infrared Sounder (AIRS) retrieval products to WDCGG data from five ground-based stations using statistical techniques and have found that the AIRS data were in good agreement with the ground-based measurements (Bai et al., 2010; Zhou et al., 2013).

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While traditional ground-based CO_2 measurements have a high accuracy and are collected continuously, spatial coverage is sparse and in certain areas, such as oceans and most parts of the Polar Regions, measurements are completely absent (Butz et al., 2009; O'Dell et al., 2012). Thus, it is impossible to accurately determine the sources and sinks of CO_2 based solely on ground-based measurements. Satellite sounders with various spatial, temporal, and spectral resolutions provide a unique opportunity to map atmospheric CO_2 globally.

Satellite measurements of global atmospheric CO_2 concentrations can fill the gaps between the ground-based measurements by providing daily global total CO_2 values and other products at a high spatial resolution. As the major satellite-based instruments for long time-series of high data quality, AIRS and the Infrared Atmospheric Sounding Interferometer (IASI) are a new generation of infrared instruments, providing observations using thousands of channels. The larger number of channels and the resulting diverse weighting functions imply that these sensors can achieve a higher resolution than the infrared sensors used earlier such as the High Resolution Infrared Radiation Sounder (HIRS). The ability of AIRS to track seasonal and latitudinal variations of CO_2 in the middle to upper troposphere has been verified by comparisons between AIRS data and NOAA Earth System Research Laboratory/Global Monitoring Division (ESRL/GMD) aircraft measurements carried out in 2005 (Maddy et al., 2008).

The IASI is an ideal sensor for studying the tropospheric CO_2 concentrations caused by biospheric emissions because of its daily, global, and complete spectral coverage across the thermal infrared region. It supplys monthly or weekly products that capture the natural variability of the Earth's surface (Hilton et al., 2012). It is important to validate the reliability of the retrieval products from AIRS and IASI against surface observational data from WDCGG using a variety of statistical methods. The observational records of WDCGG are chiefly related to the near-surface CO_2 concentrations, which closely reflect the column-averaged concentrations. Comparisons with values of satellite-derived CO_2 concentrations transported from the surface to the mid-troposphere also allow for space–time consistency checks despite different observational patterns and values for near-surface and space-based observations.

In this article we hope to clarify the similarities and differences between two kinds of total CO_2 column concentration data retrieved from AIRS and IASI. The results can be applied to climate studies with caution, as there are statistical discrepancies.

This article is organized as follows: Section 2 introduces the CO_2 data obtained from AIRS and IASI satellite observations and WDCGG ground-based measurements, Section 3 describes the statistical and analytical methodology, Section 4 presents the results and discussion, and conclusions are summarized in Section 5.

2 Data

2.1 Satellite observations

Two satellite-derived CO_2 datasets are examined in this study. These particular datasets are chosen because they provide free tropospheric column-averaged concentration information as well as scope for wide horizontal sampling. The first dataset is retrieved from AIRS, which is a cross-track scanning grating spectrometer that measures 2378 channels covering spectral ranges of 649–1136, 1217–1613, and 2181–2665 cm^{-1}. The AIRS instrument also includes four visible/near-IR(Vis/NIR) channels between 0.40 m and 0.94 m, with a 2.3-km FOV(Aumann et al., 2003). AIRS applies a spatial coherence quality assurance (QA) test, and the Level 2 CO_2 standard product consists of the retrievals that satisfy the acceptance criterion (Olsen et al., 2007; Olsen, 2009). Level 2 (L2) CO_2 products are retrieved using a Vanishing Partial Derivative (VPD) algorithm with a spatial resolution of $90\,km \times 90\,km$ (Chahine et al., 2005). Level 3 (L3) CO_2 products are monthly data gridded at a $2.5° \times 2°$ grid cell size and derive from L2 CO_2 products. We use Version 5, Level 3 monthly product data provided by the NASA Goddard Earth Sciences Data and Information Services Center (DISC).

The second dataset is obtained from IASI, which is a cross-track scanning Michelson interferometer that measures 8461 channels in the infrared (IR) range at 0.25 cm^{-1} spacing between 645–2760 cm^{-1}(3.6–15.5 μm). The IASI has 30 ground fields of regard (FOR) per scan, each measuring a 2×2 array of footprints, which corresponds to a ground resolution of 12 km at nadir and a satellite altitude of 819 km (Schlüssel et al., 2005; Hilton et al., 2012). The IASI on Metop-A (Meteorological operational satellite-A) is the first in a series of three identical infrared interferometers planned to provide over 15 continuous years of data. Metop-B was declared fully operational and pronounced to replace Metop-A in April 2013. Metop-C is scheduled for launch toward the end of 2016. The IASI instrument has the potential to provide high-quality data, so it is crucial to characterize the quality of its retrievals.

2.2 Parameters of advanced sounders: AIRS, IASI, GOSAT, and SCIMACHY

AIRS and IASI are IR sounders which mainly work in the thermal infrared spectral region with maximum sensitivity in the middle to upper troposphere (Chalon et al., 2001; Phulpin et al., 2002; Aumann et al., 2003). GOSAT, based on near infra-red sounders (NIR) and SCIMACHY, based on short wave infra-red sounders (SWIR), have almost constant sensitivity to the entire atmosphere column with the maximum value near the surface, and are frequently used to derive the column-averaged dry air mole fractions of CO_2 in the atmosphere (XCO_2) (Bovensmann et al.,

1999; Kuang et al., 2002; Christi and Stephens, 2004; Buchwitz et al., 2005a, b; Kuze et al., 2009; Wang et al., 2012). For more details among these four sounders, please refer to the Table 1 below.

The NIR/SWIR sounders cannot collect data during night time, thus IASI and AIRS as IR sensors are crucial to provide data to construct a consistent long-term time series of atmospheric CO_2 observations from space (Wang et al., 2012). Since all of the instruments mentioned above operate in the optical spectral region (< 16 μm), their abilities to monitor atmospheric CO_2 are significantly limited by the presence of clouds. AIRS and IASI's performances are expected in places where radiometric measurements will be operable, like collecting data from areas where there is clear or partly cloudy sky. IASI's global coverage of the sounding system is ensured by the simultaneous use of the microwave sounder AMSU-A (Advanced Microwave Sounding Unit A). The AIRS spectrometer is designed to operate synchronously with the microwave instruments AMSU-A1 and AMSU-A2. Therefor, IASI/AIRS are much more suitable for checking global consistency than other sounders like GOSAT or SCIMACHY. For this reason we choose AIRS and IASI for checking their consistency with WDCGG.

In this study, we used Level 2 IASI retrievals product data provided by the NOAA National Environmental Satellite, Data, and Information Service (NESDIS) Center. The IASI CO_2 products are retrieved from NOAA's Comprehensive Large Array-data Stewardship System (CLASS) (http://www.class.ngdc.noaa.gov). For IASI Level 2 product, the columns of N_2O, CH_4, and CO_2 are retrieved using artificial neural networks (ANN) trained with synthetic radiances (using RTTOV) and a collection of trace gas profiles from the MOZART model (Chalon et al., 2001). Additional details about IASI Level 2 products can be found in the IASI Level 2 Product Guide.

As for the resolution of IASI, the elementary (or effective) field of view (EFOV) is the useful field of view at each scan position. Each EFOV consists of a 2×2 matrix of instantaneous fields of view (IFOV). Each IFOV has a diameter of 14.65 millirad (mrad). Each IFOV corresponds to a ground resolution of 12 km at nadir and a satellite altitude of 819 km. The 2×2 matrix is centered on the viewing direction (IASI Level 2 Product Guide). Details of the IASI's data are show in Table 2; all these values and information are from its head files of IASI level 2 products.

2.3 Ground-based measurements

For this study, WDCGG ground-based measurement data are selected. WDCGG, first established in 1990, has been operating for more than 20 years. The data center gathers, archives, and provides data on CO_2, CH_4, CFCs, N_2O, O_3, and associated gases such as CO and NO_x for the atmosphere and oceans, as observed by GAW and other programs. The WDCGG data are based on a total of 132 CO_2 measurements at 114 stations. Monthly mean data from air sample observations at stationary platforms, collected from September 2008 to December 2010, are used in this article. The locations of the stations used in this study are shown in Fig. 1.

Table 1 The parameters of advanced sounders: AIRS, IASI, GOSAT, and SCIMACHY

Parameter	Advanced Sounder			
	AIRS	IASI	GOSAT	SCIMACHY
Available trace gases in the troposphere	CO_2, CH_4, O_3, CO, H_2O, SO_2	CO_2, CH_4, O_3, CO, H_2O, SO_2, N_2O	CO_2, CH_4, O_2, O_3, H_2O	O_3, O_4, N_2O, CH_4, CO, CO_2, H_2O, SO_2, HCHO
Sensor	Infrared Sensor (IR)	Infrared Sensor (IR)	Near Infrared Sensor (NIR)	short wave Infrared Sensor (SWIR)
Instrument type	Grating Spectrometer	Interferometer	Cloud and Aerosol Imager and near infrared/ SWIR radiometer	NIR channel 8 from nadir measurements
Observation strategy	Nadir	Nadir	Nadir, target	Limb, nadir
Spectral range/μm	3.74–4.61 6.20–8.22 8.80–15.4	3.62–5.0 5.0–8.26 8.26–15.5	0.758–0.775 1.56–1.72 1.92–2.08 5.56–14.3	0.24–0.44 0.4–1.0 1.0–1.7 1.94–2.04 2.265–2.38
Nominal altitude/km	705	819	666	790
Local time	13:30	21:30	13:00±0:15	10:00
Nominal launch date	May 2002	October 2006	January 2009	March 2002
Lifetime/year	7	5	5	7

Table 2 IASI Level 2 products name-lists and the units (with NetCDFdata format)

Type	Units	Type	Units
The index of the AMSU FOV	none	Microwave surface class	none
UTC Milliseconds since Jan 1, 1970	msec	Microwave surface emissivity	none
Retrieval latitude values for each AMSU FOV	degrees North	Number of MW spectral points AMSU FOV	none
Retrieval longitude values for each AMSU FOV	degrees East	Number of surface emis hinge points per AMSU FOV	none
View angle for each AMSU FOV	degrees	Number of cloud emis hinge points per AMSU FOV	none
Satellite height above each AMSU FOV	km	Number of cloud layers per AMSU FOV	none
Column averaged CO_2 per AMSU FOV	ppm	Quality flags for retrieval	none
Solar zenith angles for each AMSU FOV	degrees	Ispare diagnostics array from retrieval	none
Ascending_Descending	none	Rspare diagnostics array from retrieval	none
Surface height	meters	Cloud top pressure	mb
Land fraction	none	Cloud top fractional coverage	none
Surface pressure	mb	Pressure	mb
Skin_Temperature	Kelvin	Effective_Pressure	mb
Skin temperature from MIT retrieval	Kelvin	Effective_Pressure	Kelvin
Skin temperature from the first guess	Kelvin	Temperature from MIT retrieval	Kelvin
		Temperature from the first guess	Kelvin

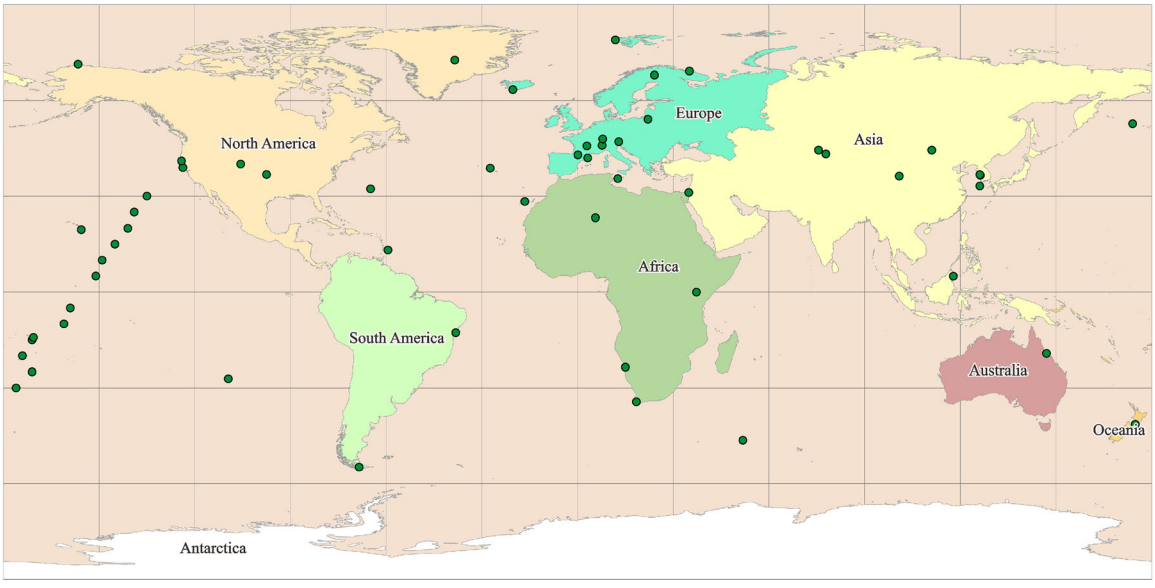

Fig. 1 Geographical distribution of WDCGG ground-based stations (green dots), selected for consistency check with IASI and AIRS total CO_2 datasets.

3 Methodology

The evaluation indicators include correlation coefficient (r), relative difference (RD), root mean square errors (RMSE), and mean bias error (MBE). The correlation coefficient is the most important and useful statistical parameter to evaluate a relationship between two variables. In order to reduce the number of samples, the t-distribution is used to test the significant correlation coefficients. The correlation coefficient is calculated by Eq. (1):

$$r_{xy} = \frac{\sum_{i=1}^{N}(x_i-\overline{x})(y_i-\overline{y})}{\sqrt{\sum_{i=1}^{N}(x_i-\overline{x})^2\sum_{i=1}^{N}(y_i-\overline{y})^2}}, \quad (1)$$

where N is the number of samples, x_i represents the value of x for the sample i, i.e., the CO_2 data measured at ground-based stations, y_i represents the value of y for the sample i, i.e., the retrieved CO_2 value from one of the satellite

datasets, $\bar{x}$ is the mean value for all x_i, and $\bar{y}$ is the mean value for all y_i. The relative difference (RD) is calculated by Eq. (2):

$$\mathrm{RD}_i = \frac{y_i - x_i}{x_i} \times 100\%, \quad (2)$$

where y_i and x_i represent the retrieved CO_2 values from satellite and ground-based observations, respectively, for sample i. The RMSE is often used to quantify the difference between an estimated value and the actual measured value. In this study, RMSE is calculated by the following equation (Eq. (3)):

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - x_i)^2}. \quad (3)$$

The MBE is calculated by the following equation (Eq. (4)):

$$\mathrm{MBE} = \frac{1}{N}\sum_{i=1}^{N}\mathrm{RD}_i, \quad (4)$$

where RD_i is the relative difference for the sample i.

4 Results and discussion

4.1 Consistency check of spatial variations between AIRS/IASI and WDCGG

The accuracy of retrieval products from space not only depends to a large degree on the method and algorithm used, but also appears to reflect both geographical environment and human activities (Zhou et al., 2013). Figure 2 shows that seven inland WDCGG stations, with corresponding regions of CO_2 data products from space (Table 3), show lower correlation coefficients. Two other maritime stations are also close to 0.5, assuming 0.5 to be the lower threshold limit. The reasons for these results could be attributed to the following aspects. First, the surface variation from ocean to land has a marked impact on the precision of the data retrieved from space. Temperature, water vapor, and O_3 have great influence on the sensitivity of the atmospheric CO_2 data retrieval from the satellite observations. Water vapor is the most important factor in the tropical regions, whereas temperature creates a major interference for midlatitude and subarctic regions (Zhou et al., 2014). Second, for *in situ* measurements, the irregular turbulent transportation by the complex underlying surface, human activities, and adverse synoptic patterns disturb the effectiveness of the existing surface observations. The weaker relationship between CO_2 data products from space and *in situ* observation in heterogeneous terrestrial environments probably could be understood.

The analogy with this study has been presented by Olsen: the results showed that the land/ocean difference in the north-south gradient of the CO_2 concentration was greater than two times (11.2 ppm vs. 4.7 ppm) (Olsen and Randerson, 2004). Grieco et al. (2013) carried out a comparison in his study, to compare the IASI and AIRS retrieved CO_2 content averaged over the whole period of July 2010 for observations above the Mediterranean Sea. It is evident that the AIRS CO_2 products map display all the elements of random behavior and the IASI is in agreement with both the cycle and trend. Hence, the consistency check between satellite data and WDCGG ground-based observations with a large sample sizes can provide a more robust result as compared to the use of a single data source alone.

For the majority of stations located between 55°S and 80°N, the correlation coefficients vary from 0.1 to about 0.9. Statistical results indicate that 23% of the correlation coefficients between IASI and ground-based WDCGG observations are below 0.5, 48% are between 0.5 and 0.8, and 29% are above 0.8 (Fig. 3(a)). In contrast, 44% of the correlation coefficients for AIRS and ground-based WDCGG observations are below 0.4, 43% range between 0.4 and 0.8, and 13% are above 0.8.

From the variation of the two kinds of correlation coefficients with latitude, it can be found that correlation coefficients decrease with increasing latitude between AIRS and ground-based observations in the Northern

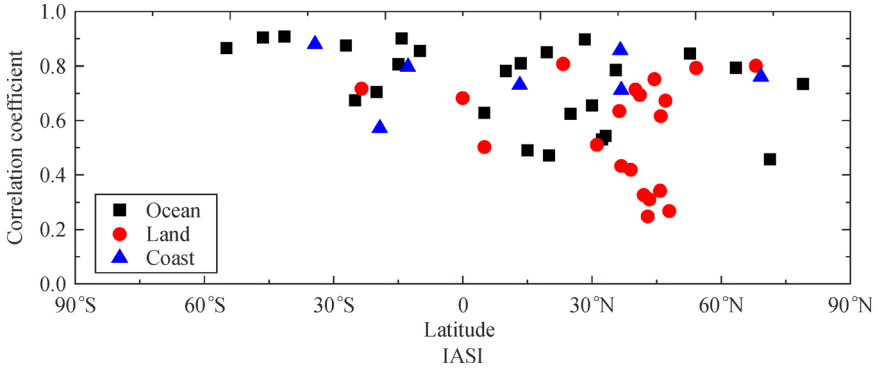

Fig. 2 Correlation coefficient variations for IASI products and WDCGG stations plotted against latitude.

Table 3 Low correlation coefficients for ground-based observations and retrieval products from IASI over inland areas

Station name	Latitude	Longitude	Altitude/m	Country	Correlation coefficient
Southern Great Plains	36.78°N	97.5°W	314	USA	0.43319
Point Arena	38.95°N	123.72°W	17	USA	0.41907
Begur	41.97°N	3.23°E	13	Spain	0.32707
Pic du Midi	42.9372°N	0.1411°E	2877	France	0.24789
Plateau Assy	43.25°N	77.87°E	2519	France	0.3104
Puy de Dome	45.7719°N	2.9658°E	1465	France	0.34257
Schauinsland	47.92°N	7.92°E	1205	Germany	0.26769

Hemisphere, the values fall significantly north of 40°N. However the IASI correlation coefficients do not show a similar tendency with latitude, except for a slight downward trend from 55°S to 80°N. This variation tendency implies that accuracy of the retrieval products from space not only is restricted by the method and algorithm used, but also appears to be under the influence of both the geographical environment and human activities, which also indirectly impact the quality of data retrieved.

Relative to Fig. 3(a), the MBE (⩽0.5%) for both IASI

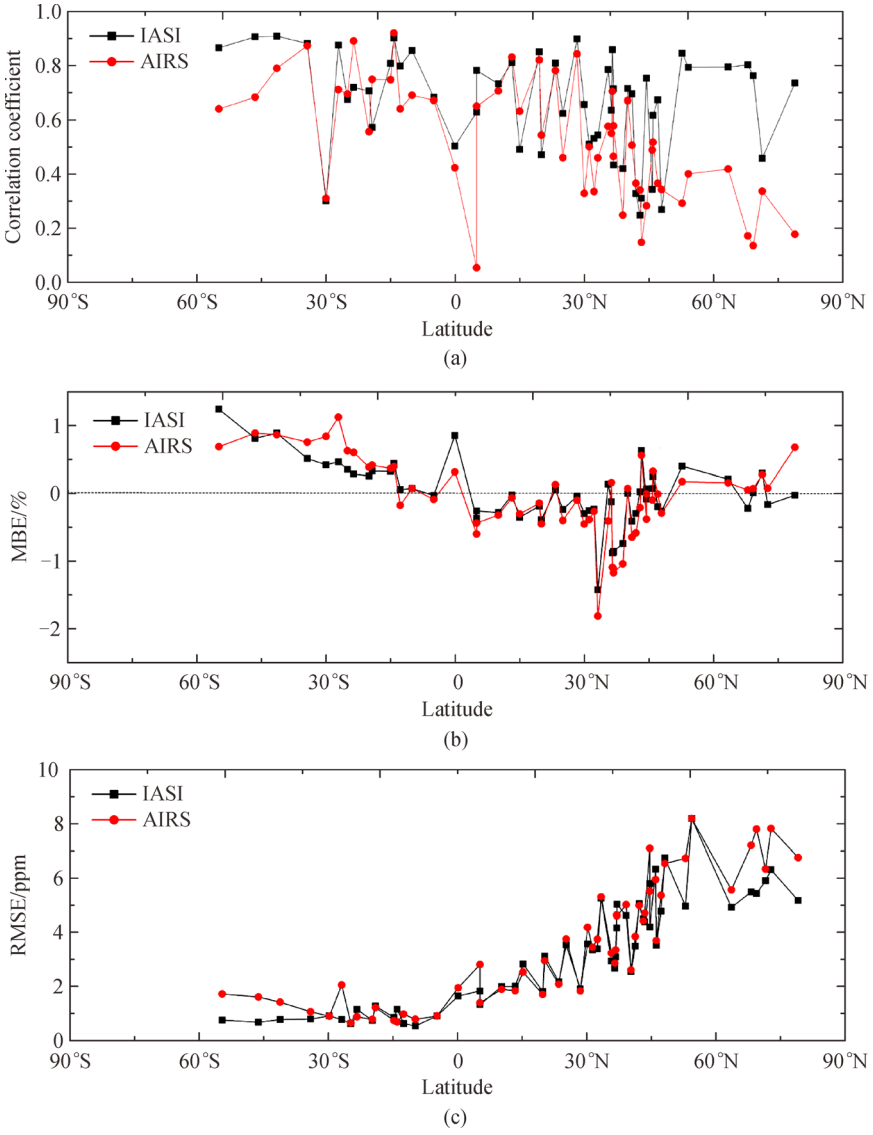

Fig. 3 Variations in (a) correlation coefficient, (b) MBE, and (c) RMSE with latitude for the AIRS, IASI, and WDCGG data.

and AIRS shows a decreasing consistency between the satellite-retrieved data and ground-based observations for 55°S–30°N, after which an increasingly undulant trend emerges (Fig. 3(b)). Figure 3(c) shows the RMSE for the two kinds of data gradually increases with latitude and reaches 8 ppm at about 50°N. Above 50°N, IASI shows a smaller deviation from the WDCGG CO_2 station data, although both sets of retrieved values begin to decrease from 50°N to 85°N (Fig. 3(c)).

4.2 Consistency check of seasonal variations between AIRS/IASI and WDCGG

To evaluate the long-term trends of the total CO_2 column concentrations, the monthly mean RD for retrieved CO_2 values versus ground-based observations from August 2008 to December 2010 are shown in Fig. 4. For a consistency check, different latitude zones are shown separately for the Northern and Southern Hemispheres. The statistical results indicate that the amplitude of RD fluctuations in the Northern Hemisphere for both AIRS and IASI gradually decreases with latitude and shows obvious seasonal characteristics. We tend to attribute these phenomena to CO_2 flux transportation from different latitude zones in the Northern Hemisphere. Regular photosynthesis in middle and high latitudes results in a greater amplitude of RD fluctuations because of obvious seasonal changes, however the amplitude weakens gradually in the tropical regions of low latitudes. The highest values for monthly mean CO_2 near the surface occur in winter, because reduced plant photosynthesis and fossil fuel combustion result in an accumulation of CO_2 near the surface. With the coming of spring (April and May), the RD begins to increase gradually, CO_2 retrieval values from space gradually rise, and the values near the surface fall by flux transportation. This vertical exchange of CO_2 will continue as the climate gradually warms until the maximum retrieval value appearance from space in summer. The same argument explains why the highest values of RD occur in July to September: CO_2 retrieval values attain the maximum in the upper troposphere and lower stratosphere (UT, LS) by flux transportation because the minimum value of CO_2 concentrations near the surface is caused by enhanced carbon fixation.

It is therefore easy to understand why the RD is gradually reduced from autumn until the minimum in winter: CO_2 values from ground-based observations gradually increase after July through September with weakening carbon fixation, whereas CO_2 values retrieved from space begin to decrease again. It is obvious that the seasonal cycle of CO_2 is driven by biospheric respiration and transportation (Gerbig et al., 2003; Tiwari et al., 2006).

In the Southern Hemisphere, RD showed small amplitudes compared with the Northern Hemisphere by the terrestrial biosphere in the vast ocean.

4.3 Abnormal regions

It is noteworthy that there was a significant difference in the correlation coefficients between the AIRS/IASI retrieval products and the CO_2 recordings for ten of the WDCGG stations (Table 4). These differences are apparent for stations in Europe, Asia, and North America. The consistency check results for these correlation coefficients imply that the retrieval products from both AIRS and IASI for these regions should be used with great caution (Table 4).

5 Conclusions

In this article, the reliability of CO_2 retrieval products from AIRS and IASI relative to WDCGG ground-based measurements are examined employing frequently used statistical methods.

Both the CO_2 retrieval data and the corresponding

Table 4 Abnormal correlation coefficients for ground-based observations and retrieval products from IASI and AIRS for ten stations in Europe, Asia, and North America

Station name	Latitude	Longitude	Altitude/m	Country	Correlation coefficient	
					IASI	AIRS
Danum Valley GAW baseline station	4.97°N	117.83°E	426	Malaysia	0.627492	0.053252
Pacific Ocean (30°N)	30°N	135°W	10	N/A	0.655413	0.327731
Tae-ahn Peninsula	36.72°N	126.12°E	20	Republic of Korea	0.712489	0.464544
Ulaan Uul	44.45°N	111.08°E	914	Mongolia	0.751756	0.281842
Shemya Island	52.72°N	174.08°E	40	USA	0.843974	0.291524
Puszcza Borecka/Diabla Gora	54.15°N	22.07°E	157	Poland	0.791776	0.400088
Heimaey	63.4°N	20.28°W	100	Iceland	0.792858	0.418004
Pallas-Sammaltunturi	67.97°N	24.12°E	560	Finland	0.800925	0.17097
Teriberka	69.2°N	35.1°E	40	Russian Federation	0.761182	0.135397
Zeppelinfjellet (Ny-Alesund)	78.9°N	11.88°E	475	Norway	0.734377	0.176992

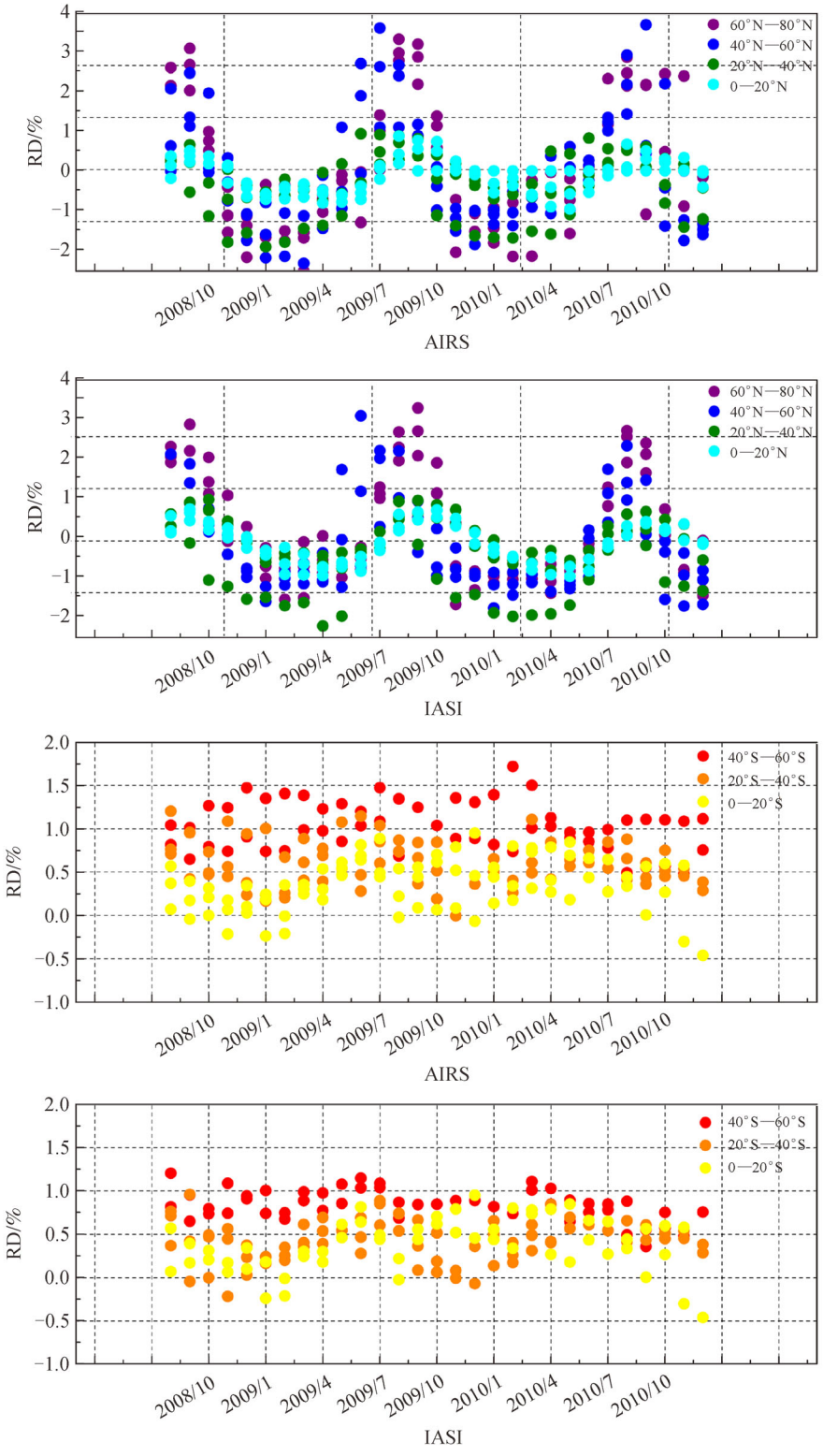

Fig. 4 Monthly mean RD between AIRS/IASI and WDCGG for the retrieved CO_2 concentrations versus the ground-based observations in the Northern and Southern Hemispheres from August 2008 to December 2010.

ground-based measurements correlate well within a region between 55°S and 30°N. In addition, the MBE and RMSE also indicate satisfactory accuracy. However, for stations located north of 30°N, correlation coefficients, MBE, and RMSE show significant differences between the two satellite-based measurements, probably caused by human activities. The seasonal CO_2 maximum in the UT and LS is caused by an accumulation of CO_2 in the boundary layer due to plant photosynthesis, fossil fuel combustion, and vertical transportation. The observed seasonal fluctuation of monthly mean RD is brought about by a hysteresis effect creating synchronous differences at different altitudes.

The consistency check for some of the correlation coefficients imply that data from AIRS and IASI retrieval products for several regions should be used with great caution.

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