IASI Retrievals Over Concordia Within the Framework of the Concordiasi Program in Antarctica

Anaïs Vincensini, Aurélie Bouchard, Florence Rabier, Vincent Guidard, Nadia Fourrié, and Olivier Traullé

***Abstract*—The Concordiasi campaign aimed to improve satellite data assimilation at high latitudes and, particularly, the assimilation of the Infrared Atmospheric Sounding Interferometer (IASI) radiances over Antarctica. This study focuses on the IASI data retrieval using a 1-D variational data assimilation system, which was carried out at the Concordia station and within the framework of Concordiasi. The study period lasted from November 20 to December 12, 2009. Radiosonde measurements are utilized to validate temperature and water vapor retrieved profiles. Baseline Surface Radiation Network data and manned measurements in Concordia are used to verify skin temperature retrievals and derive information about cloudy conditions. This study assesses the impact of several parameters on the retrieved profile quality. In particular, the background error specification is crucial. The background error covariance matrix is optimally tuned to provide the best possible retrievals, modifying the shape of these covariances for stratospheric temperatures, computing and maximizing the degree of freedom for signal (DFS). The DFS characterizes how the assimilation system uses the observation to pull the signal from the background. For the study period, the humidity and temperature retrieved profiles are optimally improved compared with background profiles, with the largest reduction in error for the skin temperature.**

***Index Terms*—Antarctica, Concordiasi, Infrared Atmospheric Sounding Interferometer (IASI), retrieval, skin temperature, 1-D variational (1D-Var).**

I. Introduction

ANTARCTICA is relatively data sparse in terms of *in situ* atmospheric measurements, particularly because of very harsh conditions and a high elevation of the Antarctic plateau. The low spatial and temporal density of *in situ* observations at high latitudes was emphasized in previous studies [1]–[3]. Satellite measurements have the potential to fill these data gaps; even if they involve difficulties, they would offer opportunities for future developments. The Concordiasi project was designed in the framework of the fourth International Polar Year [4]. This field experiment occurred during Austral springs 2008–2010. Radio soundings and stratospheric balloons were launched in order to gather additional *in situ* measurements over Antarctica. One of the main goals of the Concordiasi campaign is the improvement of the assimilation of satellite data and, in particular, the validation of Infrared Atmospheric Sounding Interferometer [(IASI); on board of the European polar-orbiting satellite MetOp launched in October 2006] radiance assimilation over the southern polar regions. IASI data should improve numerical weather predictions (NWPs), owing to more accurate real-time analyses, and should help understand climate changes through reanalyses. The use of satellite radiances in data assimilation is impeded by the presence of clouds, which curtail the amount of information received from infrared sounders [5], and by inaccurate estimations of both surface temperature and surface emissivity [6]. However, IASI retrievals of surface temperature and surface emissivity [7], [8] can provide more realistic estimations of these parameters. Within the scope of the Concordiasi campaign, it is necessary to calibrate and validate the use of IASI data, comparing their retrievals with independent data sets such as *in situ* measurements [9]. At present, available data are mainly located on the coast of Antarctica. Inland, only the South Pole station and the Concordia station (located at 75°12′ S, 123°37′ E) are regularly reporting data. Since 2008, additional conventional observations such as radio soundings have been produced at Concordia and at Dumont d'Urville, in the context of Concordiasi. Concordia is ideally located to validate satellite data assimilation. The Antarctic plateau is extremely homogeneous compared to many other locations. This study gives an account of the results of the radiosonde measurements of the Austral spring campaign in 2009, in order to validate the use of IASI observations for temperature and humidity over Concordia. Section II depicts the retrieval data and the retrieval scheme that were used in this study. Optimizations of the retrieval process and results of the 1-D variational (1D-Var) experiments are discussed in Section III. Conclusions are given in Section IV.

II. Setup of the Experiment

A. Infrared Observations and Retrievals

IASI is a high-spectral-resolution sounder that provides accurate information about the atmospheric temperature and the composition of the atmosphere at a high vertical resolution. IASI measures the infrared radiation emitted from the surface of the Earth and the atmosphere. Since the beginning of 2007, IASI data have been available and assimilated in NWP [10], [11]. Clouds have an important radiative impact on infrared radiances and can severely limit the information from advanced sounders [12]. It was thus decided that this study should focus

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on clear-sky conditions, which are determined by *in situ* observations and measurements. Radiances in clear-sky conditions are used to retrieve profiles from the top of the atmosphere down to the surface. In the retrieval process, a difficulty may arise from the high sensitivity to the surface because of the high altitude of Antarctica.

B. Description of the 1D-Var Scheme

Retrievals are performed using a 1D-Var data assimilation scheme with background fields from the NWP Action de Recherche Petite Echelle Grande Echelle (ARPEGE) model of Météo-France developed in collaboration with the European Centre for Medium-Range Weather Forecasts (ECMWF) [13] and with observations from IASI. The 1D-Var code was developed at the Met Office as part of the Numerical Weather Prediction Satellite Application Facility [14]. The 1D-Var scheme consists in retrieving temperature and humidity profiles. For humidity, the natural logarithm of specific humidity is used. Some surface parameters are also retrieved: surface and skin temperatures, surface humidity, and surface pressure.

The 1D-Var scheme is based on the minimization of a cost function which measures the fit of the retrieved atmospheric state to the background variables and to the observations. Let $\mathbf{x_b}$ be a vector of background variables and $\mathbf{B}$ be the associated error covariance matrix. Let $\mathbf{y}$ be a vector of observations and $\mathbf{R}$ be the associated error covariance matrix. The cost function J for the atmospheric state $\mathbf{x}$ is defined by

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x_b})^{\mathrm{T}}\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x_b}) + \frac{1}{2}\left(H(\mathbf{x})-\mathbf{y}\right)^{\mathrm{T}}\mathbf{R}^{-1}\left(H(\mathbf{x})-\mathbf{y}\right) \quad (1)$$

where H is the observation operator that simulates brightness temperatures from atmospheric profiles and $^{\mathrm{T}}$ is the transpose operator.

The minimum of the cost function gives an estimate of the most probable atmospheric state $\mathbf{x_a}$ and is computed by an iterative process. At each iteration, a descent direction is determined, using the value of the cost function gradient

$$\nabla_{\mathbf{x}} J(\mathbf{x}) = \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x_b}) + \mathbf{H}^{\mathrm{T}}\mathbf{R}^{-1}\left(H(\mathbf{x})-\mathbf{y}\right) \quad (2)$$

where $\mathbf{H}^{\mathrm{T}}$ is the adjoint operator of the tangent-linear model $\mathbf{H}$ of H.

The Marquardt–Levenberg descent algorithm is applied to find this minimum. This minimization method is adapted to nonlinear observation operators, as it is the case here (e.g., [15]). This technique is a combination of a Gauss–Newton and a steepest descent minimization technique. The iterative solution of the Marquardt–Levenberg equation is

$$\begin{aligned}\mathbf{x_{n+1}} = \mathbf{x_b} + &\left(\mathbf{B}^{-1} + \mathbf{H}^{\mathrm{T}}\mathbf{R}^{-1}\mathbf{H} + \mathbf{J}'' + \gamma\mathbf{I}\right)^{-1} \\ &\times \big(\mathbf{H}^{\mathrm{T}}\mathbf{R}^{-1}\left(H(\mathbf{x_n})-\mathbf{y}\right) + H(\mathbf{x_n}-\mathbf{x_b})\big) \\ &- \mathbf{J}' + \mathbf{J}''(\mathbf{x_n}-\mathbf{x_b}) + \gamma(\mathbf{x_n}-\mathbf{x_b})\big)\end{aligned} \quad (3)$$

where $\mathbf{x_n}$ is the $\mathbf{n}$th estimate of the atmospheric profile, $\mathbf{J}'$ is the first differential of the additional cost function with respect to $\mathbf{x}$, evaluated at $\mathbf{x_n}$, and $\mathbf{J}''$ is the second differential. Thus, $\mathbf{J}'$ is a vector with the same length as $\mathbf{x_n}$, and $\mathbf{J}''$ is a matrix with the same size as $\mathbf{B}$. γ is the Lagrange multiplier which varies depending on the nonlinearity of the problem and the proximity to the desired solution. The method of Lagrange multipliers provides a strategy for finding the stationary points (maxima, minima) of a differentiable function subject to constraints. When $\gamma = 0$, the equation can be solved with the Newtonian inverse Hessian method. In nonlinear cases, it is possible that the step taken by using the Newtonian method will result in an increased cost function. In this case, the value of γ is increased (thereby reducing the step size) until a point is reached where the cost function decreases (as $\gamma \to \infty$, (3) becomes the method of steepest descent). After an improved solution (i.e., lower cost function) has been found, the value of γ may once again be increased to allow larger steps in the next iteration.

When using the Marquardt–Levenberg minimization, we consider that the convergence has occurred when the normalized cost function gradient is less than the square of the cost function and when γ decreased in the previous iteration.

In this study, the algorithm needs only two iterations to converge for all the presented experiments (the maximal number of iterations allowed by the 1D-Var scheme is set to ten). The background fields are already very close to the final solution.

A radiative-transfer model is required with the 1D-Var scheme and supplies both radiances and tangent-linear and adjoint observation operators. In this study, the Radiative Transfer for the Television Infrared Observation Satellite Operational Vertical Sounder (RTTOV) v8 fast radiative-transfer model [16]–[18] serves as observation operator. It accurately computes brightness temperatures given first-guess model fields of temperature and humidity on 43 fixed pressure levels between 0.10 and 1013.15 hPa. The coefficients for the infrared range of the model are from the kCompressed Radiative Transfer Algorithm database.

Most information on atmospheric temperature is derived from the CO_2 absorption waveband assuming fixed CO_2 concentrations. The fixed mixing ratio of CO_2 that is used in this study is equal to 377 ppmv on all atmospheric levels. In reality, atmospheric CO_2 concentrations show significant spatial and temporal variability. According to Engelen *et al.* [19], the use of a global mean CO_2 value introduces errors in the retrieved temperature profiles of up to 0.85 K compared to a retrieval in which the CO_2 is known precisely. It is possible to reduce these errors to 0.3 K when including CO_2 in the retrieval vector, but this was not attempted in this study. Moreover, they have shown that the use of a monthly zonal mean CO_2 value produces errors of up to 0.35 K in the temperature. A sensitivity study has been realized to determine the impact of the modification of the mixing ratio of CO_2 used in the radiative-transfer calculations. Simulation experiments with a variation of CO_2 values between 362 and 402 ppmv (every 5 ppmv) have been carried out. The mean root mean square (rms) of the difference between observed and simulated radiances, which are derived using the RTTOV model with input from NWP ARPEGE model fields, has been computed for all channels in the CO_2 absorption waveband. These results have not shown significant differences. The value of 377 ppmv will be used in the study because the bias correction is adapted to this value. The current assumption is that variational bias correction (varBC) corrects most of the error, due to the fact that we neglect the spatiotemporal variability of CO_2, in the simulation of the satellite radiances. According to Engelen and Bauer [20], the required bias correction is

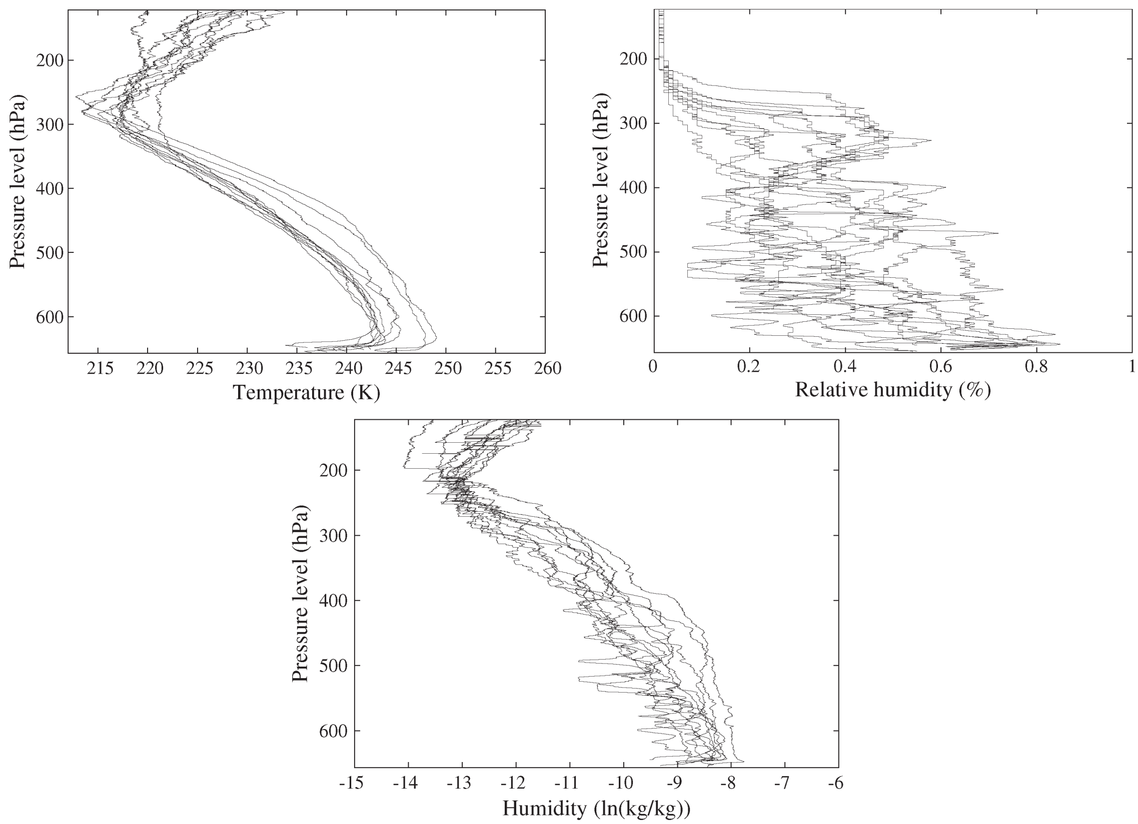

Fig. 1. Radio sounding profiles at Concordia for (top left) temperature, (top right) relative humidity, and (bottom) specific humidity natural logarithm for the 11 clear cases selected for the period of November 20 (0 UTC)–December 12 (0 UTC), 2009. Temperature profiles supplied by radiosondes are completed in the surface by measurements of BSRN.

reduced when using more realistic CO_2 values, and the impact on the analysis quality and forecast scores is mostly neutral.

A realistic climatological ozone profile is used. In this profile, the ozone concentration is smaller than 0.5 ppmv between the surface and 100 hPa and varies between 0.5 and 6 ppmv from 100 to 0.1 hPa. The 170 channels selected in this study are not in the ozone absorption waveband, and they are not very sensitive to ozone.

C. In Situ Observations for Validation

To validate retrievals, *in situ* data are used. Radio soundings measure the vertical profiles of the atmosphere. The radiosonde data also provide a means to directly validate retrievals of temperature and humidity made from the IASI infrared radiances. Other *in situ* measurements come from the Baseline Surface Radiation Network (BSRN), initiated by the World Climate Research Programme. This network aims at providing validation material for satellite radiometry and climate models [21]. BSRN data measure the surface radiation. The skin temperature can be deduced from the observed upward and downward long-wave radiation that is measured by BSRN, according to Planck's law [22]. BSRN data also provide information about cloudy conditions as the high variations of the long-wave downward irradiance depend on the formation or dissipation of clouds. Fig. 1 shows the radio sounding profiles, completed with surface BSRN data, for temperature and the radio sounding profiles for humidity for the cases considered clear in the study. They reveal that, in Concordia, temperature profiles are relatively homogeneous except near the surface (between 630 and 650 hPa) where the temperature gradient is large. Temperature variations of up to 7 K can be observed from 630 hPa to the surface. Relative humidity profiles present larger fluctuations than do temperature and specific humidity, due to its nonlinear dependence to these two parameters. When computing the specific humidity natural logarithm, humidity profiles show a small quantity of water vapor and exhibit more pronounced vertical structures than temperature profiles.

During the Concordiasi campaign in 2009, the Vaisala radiosondes RS92-SGP with a GPS receiver were used. Vaisala reports that the temperature values are accurate to 0.5 K and that the relative humidity values are accurate to 5%. The relative humidity is probably more uncertain when used in Antarctica because of the long response times of radiosonde humidity sensors at low temperatures. According to Vömel *et al.* [23], the Vaisala RS92 humidity sensor is characterized by a large solar radiation dry bias and a minor temperature-dependent calibration error. They have shown that, for soundings launched at solar zenith angles between 10° and 30°, the average dry bias is on the order of 9% at the surface and increases to 50% at 15 km. The dry bias is a function of pressure and is expected to be more significant in tropical than in polar regions, because the tropopause is significantly higher in the tropics, thereby limiting the vertical range in which radiosonde relative humidity data should be considered. Moreover, the observation error standard deviations of radiosondes for temperature at Concordia vary from 0.98 to 1.2 according to altitude. They are smaller than 1 K between the surface and 300 hPa and larger than 1 K above 300 hPa. Thus, we can mainly trust the radiosondes in the troposphere.

Other information about surface parameters and cloudy conditions was collected by Olivier Traullé (Météo-France/Centre National de Recherches Météorologiques-Groupe d'études de l'Atmosphère Météorologique) during his stay at Concordia in November and December 2009. He measured skin temperature owing to a penetration sonde and observed meteorological conditions. BSRN data, together with human observations, provide us with estimations of *in situ* surface temperatures and cloudy conditions.

D. Available Data

The retrievals are realized for the period from November 20 to December 12, 2009. The background profiles are extracted from ARPEGE. The geometry of ARPEGE was modified in order to study polar assimilation. In this stretched model, the center was moved from France to Concordia, leading to a horizontal resolution of 16 km around Concordia and with 60 vertical levels from the surface up to 0.05 hPa, the top of the model [9]. The background profiles are more accurate with this new geometry than with the operational geometry centered in France. The increased resolution over Antarctica improves the representation of steep orography. Moreover, Bouchard *et al.* [9] have shown that the stretched model centered over Concordia permits the increase of the number of data assimilated in the model for Antarctica and the decrease of the rms of the difference between radio sounding and background for the temperature for all altitudes over the area of interest, in comparison with the initial geometry. The surface and the skin temperatures used in the retrievals are the ones supplied by the background profiles. Moreover, past ECMWF studies showed improvements in polar atmospheric analyses in general [24] due to the increase in the number of used observations and the good data coverage over the polar regions (satellite data and radiosondes). Owing to more extensive use of polar-orbiting-satellite data, the magnitude of analysis increments has been reduced, which reflects improvements of both model and data assimilation. Thus, analyses and short-range forecast errors were very significantly reduced between 2001 and 2006. As both the ARPEGE and the ECMWF models have a lot in common, ARPEGE also benefited from these improvements.

Usually, radio soundings are launched at 12 UTC from Concordia, but during the field campaign additional radiosondes were launched at 0 UTC when the MetOp satellite was over Concordia. Thus, data from radio soundings launched at 0 UTC are used, and background profiles are supplied for the same hour. Retrieved profiles will be compared with radiosonde data as in the work of Gettelman *et al.* [25], in which one of the aims was to validate relative humidity measurements over Concordia from the Atmospheric Infrared Sounder (AIRS). Moreover, it was shown that it is possible to reproduce quite accurately IASI measurements with adequate radiosonde measurements and radiative-transfer models [26]. A good-quality reference data set infers that sonde measurements should have an extremely low bias and a high accuracy of relative humidity. In this study, radio soundings are taken as a reference, but it should be noted that they can induce additional errors in the final results.

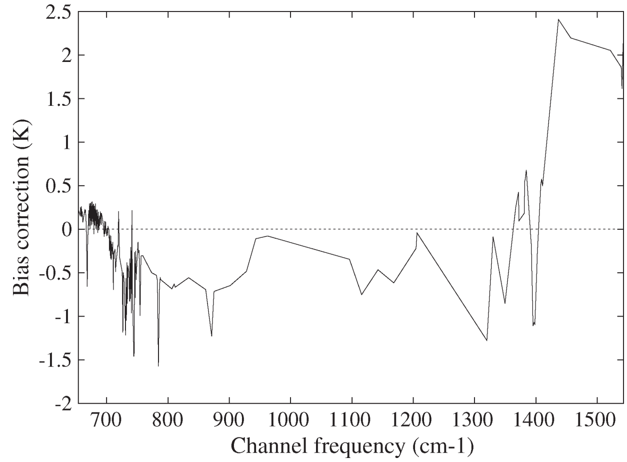

Fig. 2. Bias correction applied to each channel in average over the cases studied in this paper.

Space and time colocation criteria allow us to select IASI data nearest to the radio sounding time and closest to Concordia. For the considered period, IASI pixels are, on average, 37 km away from Concordia, and there is a time lapse of 25 min with the radio sounding launching time. In 2009, 11 cases were considered clear according to human observations and BSRN data. Only these clear cases are presented in this study.

III. 1D-Var Experiments

A. Setup and Optimization

The study investigates the clear cases for the period November to December 2009. IASI can provide observations from 8461 channels, but observations from only 170 channels are used in this study [9]. The selection of channels is based not only on statistics of the difference between observations (brightness temperatures) and background but also on the shape of the weighting functions. Channels are chosen when the rms of the difference between observations and guess is small, with a low bias and a low standard deviation. Spectral channels sensitive to constituents that exhibit strong but unknown spatiotemporal variability are avoided, as it is the case for carbon monoxide, methane and ozone (the selected channels are only chosen in the atmospheric windows, in the CO_2 and H_2O absorption wavebands). These channels are relatively free of interferences of trace gases. Moreover, IASI data are bias corrected, and our varBC accounts for most of the errors related to the observation operator. The emissivity over land is fixed at the value of 0.98 for all wavenumbers. The surface emissivity is relatively constant in Antarctica according to existing emissivity atlas, as the global infrared land surface emissivity database developed by Seeman *et al.* [27]. In order to improve retrievals, several 1D-Var input parameters had to be optimized. IASI data were bias corrected owing to an adaptive bias correction for satellite radiances. The varBC scheme is calculated in ARPEGE and reduces biases between satellite observations and their model equivalent using geometric and flow-dependent predictors to remove systematic errors in satellite radiance data [28], [29]. Three types of predictors are used for IASI: a global offset applied to each channel, a scan angle correction based on the nadir-viewing angle, and an air-mass correction (based

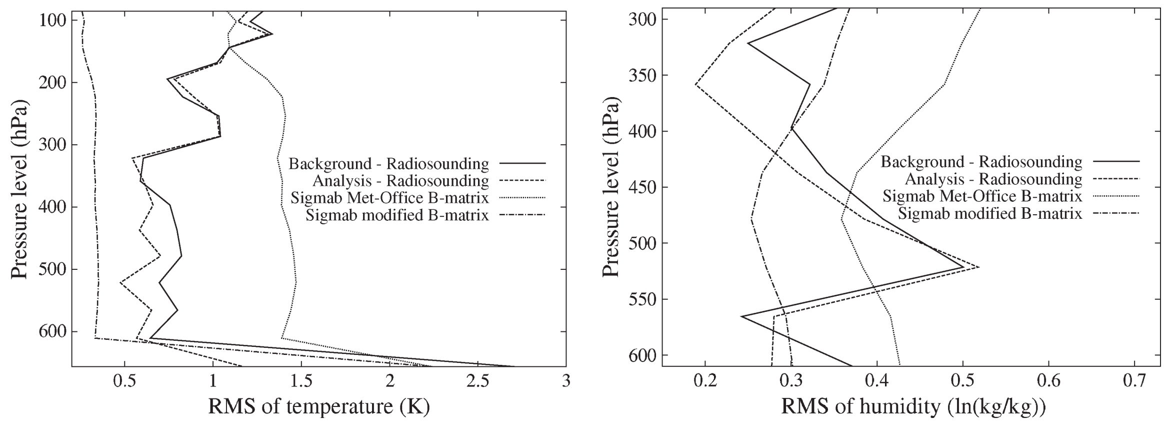

Fig. 3. RMS errors with respect to radio soundings for (first panel) temperature and (second panel) specific humidity natural logarithm for (solid line) background profiles and (dashed line) retrieved profiles for clear cases in November and December 2009. The modified B-matrix is used. Background error standard deviations are represented for the (dotted line) Met Office B-matrix and the (dashed–dotted line) B-matrix after modifications. For temperature, surface rms errors are calculated from BSRN data.

on the thicknesses of the four atmospheric layers of 1000–300, 200–50, 10–2, and 50–5 hPa). Other predictors are additionally used for other instruments (surface wind speed, total column of water vapor, and surface temperature). In the global model ARPEGE, this varBC is refined at each analysis time, using coefficients computed during the previous assimilation as a first guess. Fig. 2 shows the bias correction of IASI data. This bias correction is globally negative between -1.5 K and 0.5 K for channels between 654 and 1410 cm^{-1} but is positive for stratospheric temperature channels and larger than 1.5 K for water vapor channels between 1436 and 1542 cm^{-1}. As the bias correction is only supposed to remove the observation component of the bias, it cannot be expected to be zero.

The B-matrix used as a reference in this study was supplied by the 1D-Var package of the Met Office. This matrix is commonly used in the data assimilation community and was found to produce better retrievals than the ARPEGE B-matrix (not shown), even if background fields from ARPEGE are used in this study. The Met Office B-matrix has the following characteristics: The errors for upper-air temperature and humidity are assumed to be uncorrelated with each other, and the other correlations are specified, including errors between upper-air fields and surface variables. The observation error covariance matrix $\mathbf{R}$ is the operational R-matrix of ARPEGE. This matrix is diagonal, and observation error standard deviations are constant for each subset of channels (0.9 K for surface channels, 0.45 K for channels sounding the tropospheric temperature, 0.45 K and 0.55 K for channels sounding the stratospheric temperature, and 3.6 K for water vapor channels). This matrix is applied globally to IASI radiances and will be assumed to be valid over Antarctica.

In this study, only the variance errors of the B-matrix are adjusted in order to improve analyses, considering observation variance errors as fixed. Fig. 3 shows that the variance errors of the B-matrix are overestimated. Indeed, the standard deviation of background errors σ_b, that is to say, the estimated accuracy of background temperature and humidity, is too large compared to the rms of the differences between background and radio soundings. It is possible to find a pair of coefficients dividing the B-matrix covariances on temperature and humidity that provides better retrievals. In order to determine these coefficients, the degree of freedom for signal (DFS) is computed. The DFS characterizes how the assimilation system uses the observations to pull the signal from the background [15]. Its value is given by

$$DFS = \mathrm{Tr}(\mathbf{I} - \mathbf{A}\mathbf{B}^{-1}) \tag{4}$$

where $\mathbf{A}$ is the retrieval error covariance matrix and $\mathbf{I}$ is the identity matrix. $\mathbf{A}$ is defined by $\mathbf{A} = \mathbf{B} - \mathbf{B}\mathbf{H}^{\mathrm{T}}(\mathbf{H}\mathbf{B}\mathbf{H}^{\mathrm{T}} + \mathbf{R})^{-1}\mathbf{H}\mathbf{B}$, where $\mathbf{H}$, $\mathbf{B}$, and $\mathbf{R}$ are the matrices defined previously.

The pair of coefficients dividing the B-matrix covariances and maximizing the DFS gives more accurate analyses in comparison with radio soundings. Fig. 4 shows the DFS isolines computed for several pairs of coefficients dividing temperature and humidity covariances. Each DFS value in Fig. 4 corresponds to the sum of the DFS computed for temperature and the DFS computed for humidity. Only isolines where DFS is higher than 3.6 are plotted. The maximal DFS is obtained when the temperature covariances are divided by 17.5 and the humidity natural logarithm covariances are divided by 2, with DFS values equal to 1.96 for temperature and 2.03 for humidity. In Fig. 3, the background error standard deviations are plotted for the original B-matrix from the Met Office and the modified B-matrix. On average, these standard deviations decrease when using the modified B-matrix, with values ranging from 1.32 K to 0.32 K for temperature and from 0.43 to 0.31 ln(kg/kg) for specific humidity. The modification of the B-matrix corresponds to a translation of the background error standard deviations (Fig. 3). The modified B-matrix does not permit the background error standard deviations to follow exactly the vertical profile of the rms of the difference between background and radiosonde. However, this matrix is, overall, satisfactory as the background errors are appropriately found to be slightly smaller than these rms values. The standard deviations of background errors seem to be well estimated as regards to the surface parameters (surface and skin temperatures) when compared to measurements, and consequently, their values are unchanged. The following analyses are obtained using this modified B-matrix, and the results in terms of rms are presented in the following. We can notice that the optimization

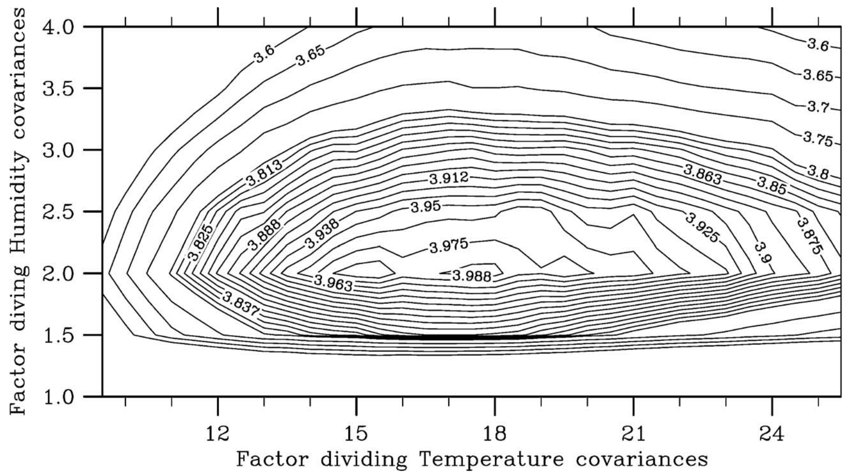

Fig. 4. DFS isolines depending on coefficients dividing temperature and humidity covariances when using the Met Office B-matrix and the operational R-matrix of ARPEGE. Only isolines where DFS is higher than 3.6 are plotted. DFS is computed for each couple of multiplying factors $(10 + n \times 0.5;\ 1 + m \times 0.5)$ $\forall (n, m) \in [0, 31] \times [0, 6]$.

of the background error covariances significantly improves the analyses. The DFS calculation permits determining the pair of coefficients for which the B-matrix provides the best results in terms of rms. The background error covariances are better estimated, and so, the analyses better fit the radiosondes. The mean rms of the difference between analyses and radiosondes is improved by 0.2 K for temperature with the optimized B-matrix in comparison with the initial B-matrix of the Met Office. The improvement is only 0.04 ln(kg/kg) for water vapor.

B. Results

Fig. 3 shows the rms of the differences between background and radio soundings and between analysis and radio sounding with respect to pressure. Retrieval errors for temperature and humidity are globally smaller than background errors. For temperature, the surface rms errors are calculated from BSRN data. There are no available surface data for specific humidity. On average, for temperature, the rms error decreases by 0.14 K between 650 and 100 hPa after the analysis, with a decrease of 0.25 K between the surface and 290 hPa and a decrease of 0.009 K between 290 and 80 hPa. For specific humidity, between the surface and 520 hPa, the rms of the difference between analysis and radio sounding is almost equal, on average, to the rms of the difference between background and radio sounding. The rms errors after the analysis decrease by 0.06 ln(kg/kg) on average between 520 and 300 hPa. It is important to notice that radio soundings are used as a reference but are not absolutely reliable because of measurement errors. Some of the error between radiosondes and background or IASI retrievals can be attributed to biases in the radiosonde measurements as mentioned in Section II-C. However, other errors can arise from the representivity error due to mismatch between the orography described by the model and the actual orography (as seen by IASI). This error is small because the Concordia station is on a wide plateau and the size of the nadir IASI observation spot is 12 km and around 100 km on the edges. Moreover, only the closest IASI pixel from the ARPEGE grid point near Concordia is used and not an average of several pixels.

In terms of brightness temperatures, the rms of the differences between IASI observations and brightness temperatures from the 1D-Var retrievals is significantly reduced compared to the rms of the differences between IASI observations and brightness temperatures calculated from the background profile (Fig. 5). Moreover, Fig. 5 shows that the observation error standard deviations of the R-matrix are well estimated compared to the rms of the differences between IASI observations and retrievals. They seem to be underestimated in the window channel (from 773 to 1204 cm^{-1}), but the errors come mainly from the background in this waveband, due to a poor specification of skin temperature.

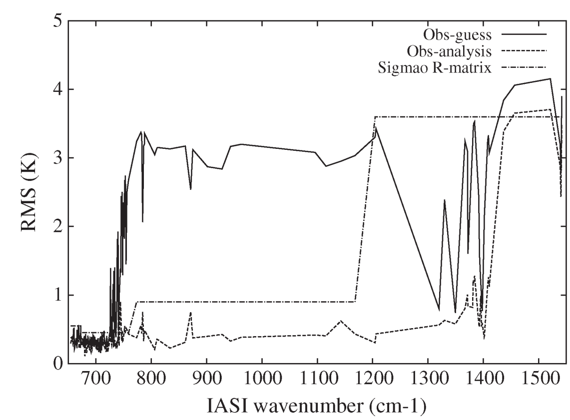

Fig. 5. RMS errors for brightness temperature (solid line) before and (dashed line) after analysis compared with IASI observations depending on the IASI wavenumber. Observation error standard deviations are represented for the (dashed–dotted line) operational R-matrix of ARPEGE.

In the study of Gettelman *et al.* [25], AIRS retrievals of humidity and temperature were compared to radiosondes launched over Concordia in December 2003 and January 2004. These radiosonde measurements have been corrected for most known biases. Satellite data for temperature are of a very high fidelity to the mean differences between AIRS and the radio soundings (less than 1 K at all levels, with AIRS colder than the radiosonde). Humidity is highly biased relative to radiosonde observations. AIRS specific humidity differs from 10% or less from radio soundings near the surface up to 500 hPa but from 50% or more just below the tropopause (300–400 hPa). Thus, there is an upper tropospheric moist bias in the AIRS retrievals relative to the corrected radiosonde profiles. In this study, results with IASI sounders are very similar. The bias between the IASI-retrieved temperature and radiosonde temperature is less than 1 K at all levels (except for the surface because of a wrong estimate of the background skin temperature), and IASI is globally colder than the radiosondes. The bias between specific humidity retrievals and radiosondes is 15% or less near the surface up to 550 hPa and is 15% or more between 300 and 500 hPa. Thus, the two sounders give very similar results even if the measurement campaigns did not occur during the same Austral spring.

Jacobians are the derivatives of the brightness temperatures with respect to atmospheric parameters at different levels of the radiative-transfer model. Temperature and humidity Jacobians are calculated with the 1D-Var scheme and give information about the sensitivity of IASI channels to atmospheric parameters. The shape of these Jacobians can explain the characteristics of the retrieved profiles. Fig. 6 shows the Jacobians of temperature (respectively humidity) for the 170 assimilated channels. The aspect of the curves representing temperature (humidity) Jacobians has minima around 380 and 200 hPa (a minimum around 530 hPa) which is in agreement with the altitudes at which the rms is reduced during the 1D-Var process (Fig. 3). Jacobians for skin temperature [Fig. 6(c)] show a high sensitivity to surface wavebands and also to water vapor wavebands.

C. Discussion About Skin Temperature Retrievals

The improvement in terms of skin temperature is particularly striking. Fig. 7 shows a better fit of skin temperature retrievals to *in situ* observations (manual measurements and BSRN data) compared with background skin temperature. During the months of November and December 2009, the rms errors between *in situ* measurements and retrievals are 1.18 K for BSRN data and 1.07 K for human observations, whereas the rms scores between *in situ* measurements and background skin temperature are 2.71 K for BSRN data and 3.11 K for manual measurements.

D. Results for a Second Period: January 2010

Retrievals have also been computed for the period of January 2010 with the same $\mathbf{R}$ and $\mathbf{B}$ matrices. Background and radio sounding data are supplied at 12 UTC. According to BSRN data, seven cases have clear-sky conditions. As previously, space and time colocation criteria permit selecting IASI data. For the 2010 period, IASI pixels are further away than those for the previous 2009 period. They are, on average, 71 km away from Concordia, and there is a time lapse of 1 h 39 min with the radio sounding launching time. Calbet *et al.* [26] showed that the spatial colocation is not very important to the radiance matching but that temporal colocation is essential. Because of the time lag between IASI data and radio soundings, retrieved profiles do not strictly fit the radiosondes. However, skin temperature retrievals still fit significantly the BSRN skin temperature compared with the background skin temperature (Fig. 7). The rms score between background skin temperature and BSRN data is equal to 5.87 K versus 1.70 K after analyses.

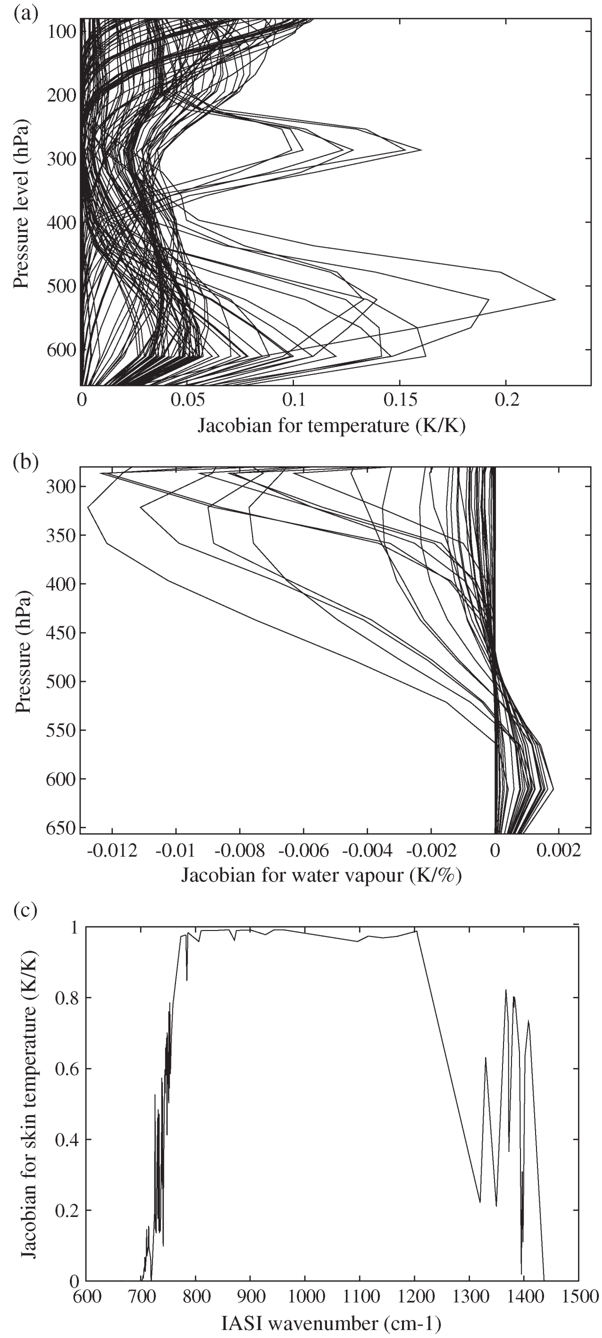

Fig. 6. (a) Temperature and (b) water vapor Jacobians of the 170 selected IASI channels at different levels of the RTTOV radiative-transfer model. The Jacobian for skin temperature, as a function of IASI wavenumber, is shown in panel (c).

E. Impact of Background Skin Temperature on Retrievals

Previous studies revealed that an accurate skin temperature could improve retrievals (e.g., [6]). To have a better background skin temperature, the method presented by Karbou *et al.* [30] is used here. During the first analysis, IASI surface channel 1194 (943.25 cm^{-1}) is selected and supplies a skin temperature that is used as a guess during another retrieval process (it replaces the background skin temperature). This channel 1194 is assimilated in the 1D-Var process. However, the use of a skin temperature retrieved from IASI instead of values taken from ARPEGE background states has no major impact on the retrieved profiles

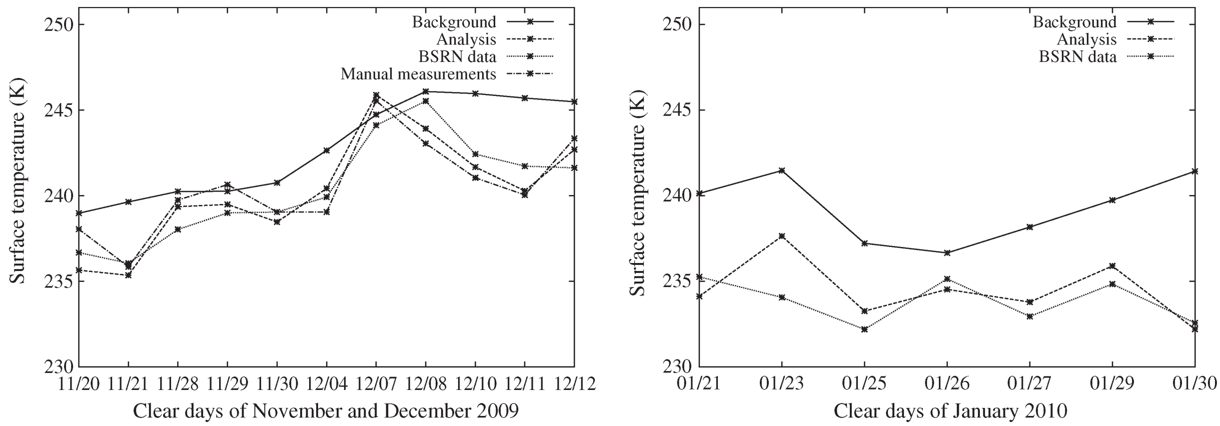

Fig. 7. Surface temperature for clear cases in (first panel) November and December 2009 and in (second panel) January 2010 for (solid line) background and (dashed line) analyses and compared with *in situ* measurements: (Dotted line) BSRN data for the two periods and (dashed–dotted line) manual measurements for November and December 2009.

in this study. The DFS for temperature drops from 1.96 with background skin temperature to 1.79 with IASI-retrieved skin temperature, which indicates that the IASI assimilated channels contain a lot of information about skin temperature, which is consistent with Fig. 6(c). For both skin temperatures, the retrieved profiles of specific humidity are very similar, and the DFS is equal to 2.08 with background skin temperature and to 2.03 with IASI-retrieved skin temperature.

F. Modification of Background Error Standard Deviations for Stratospheric Temperatures

Fig. 3 shows that the background error standard deviations are badly estimated for stratospheric temperatures. These standard deviations do not follow the shape of the curve of the rms of the differences between background and radiosonde between 80 and 320 hPa. Thus, the Met Office B-matrix was modified to better follow the vertical shape of these rms values, as shown in Fig. 8 (second panel). This new matrix is called B'. Background error standard deviations of the B-matrix are not modified for tropospheric temperatures, humidity, and surface parameters. When modifying the upper atmospheric temperatures in the background error covariance matrix, the off-diagonal elements of the B-matrix are modified to take the new background error standard deviations into account. The correlation matrix is not modified. As before, the covariance errors of the B'-matrix are overestimated compared to the rms of the differences between background and radio soundings. It is possible to find a pair of coefficients, determined by the maximization of the calculated DFS, which can be used to divide the covariances of temperature and humidity for the B'-matrix. Fig. 8 (first panel) shows the DFS isolines computed for several pairs of coefficients dividing temperature and humidity covariances. The pair of coefficients for which the DFS value is maximal provides the best retrieval. Each DFS value in Fig. 8 corresponds to the sum of the DFS computed for temperature and the DFS computed for humidity. As for the use of the Met Office B-matrix, the maximal DFS is obtained when the temperature covariances are divided by 17.5 and the humidity natural logarithm covariances are divided by 2, with DFS values equal to 2.49 for temperature and 2.06 for humidity. In Fig. 8 (second panel), the background error standard deviations are plotted for the original B'-matrix and the modified B'-matrix. On average, these standard deviations decrease when using the modified B'-matrix, with values ranging from 1.91 K to 0.46 K for temperature (no modification for specific humidity). As before, the background error standard deviations for surface parameters (surface and skin temperatures) are unchanged.

Fig. 8 (second panel) shows the rms of the differences between background and radio soundings and between analysis and radio sounding with respect to pressure. On average, for temperature, the rms error decreases by 0.16 K between 650 and 100 hPa after the analysis, with a decrease of 0.24 K between the surface and 290 hPa (against 0.25 K for the modified B-matrix) and a decrease of 0.073 K between 290 and 80 hPa (against 0.009 K for the modified B-matrix). Thus, the use of the modified B'-matrix provides more accurate retrievals for stratospheric temperatures and retrievals of similar accuracy for tropospheric temperatures, compared with the results obtained with the modified B-matrix. On average, the modified B'-matrix permits decreasing the rms of the differences between analysis and radio sounding by 0.03 K compared with the modified B-matrix. For the two matrices, the results for specific humidity are very similar.

IV. Conclusion

The IASI sounder has a large potential for the observation of meteorological conditions over Antarctica. It supplies data at this location lacking in *in situ* measurements. The analysis of IASI radiances at Concordia has permitted to better estimate the temperature and the specific humidity at Concordia in comparison with the additional radio soundings launched during autumn 2009 (Austral spring). It was found that, because the standard background error variances were badly specified for stratospheric temperatures, the B-matrix had to be modified to better follow the vertical shape of the rms of the differences between background and radiosonde between 80 and 320 hPa. Subsequently, an optimization of the background error covariances was undertaken by maximizing the DFS in the temperature and humidity profiles. The improvement due to the background error modification was measured quantitatively by improvement in the analyses fit to collocated radiosonde data.

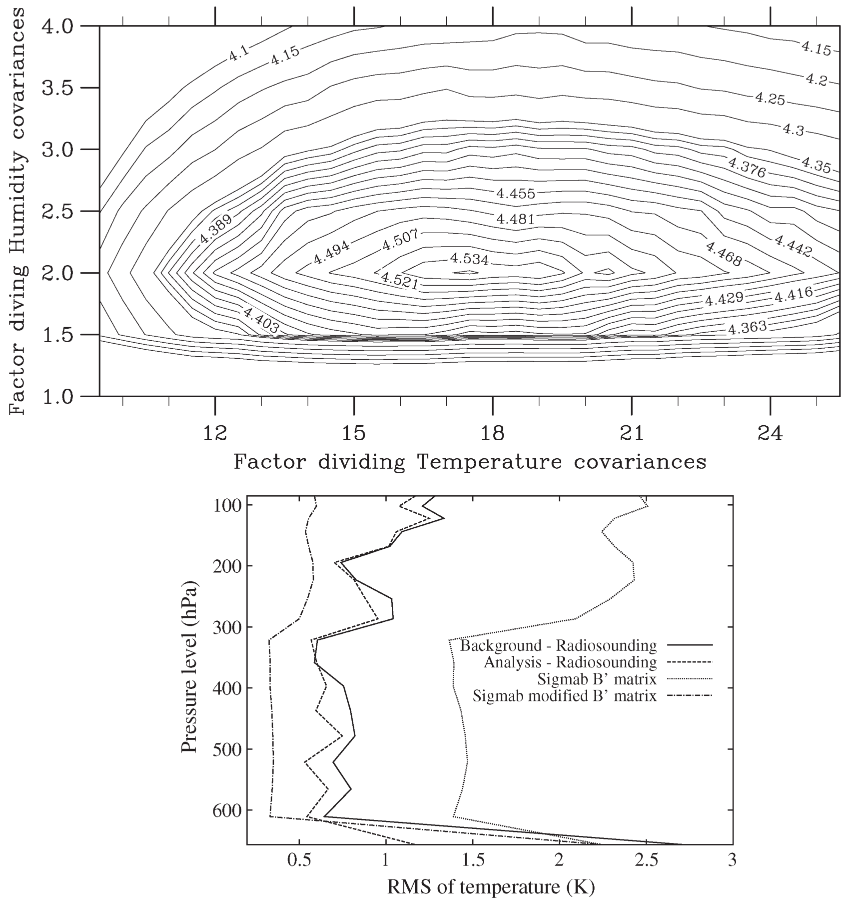

Fig. 8. (First panel) DFS isolines depending on the coefficients dividing temperature and humidity covariances when using the operational R-matrix of ARPEGE and the B'-matrix, which is the B-matrix for which the background error standard deviations have been modified for stratospheric temperature to better fit the vertical profile of the rms of the difference between background and radiosonde. Only isolines where DFS is higher than 4.1 are plotted. The figure on the second panel shows the rms errors for temperature retrievals compared with radio soundings for clear cases of November and December 2009, when using this new matrix B', divided by the coefficients permitting to have the better DFS. The background error standard deviations are represented for the B'-matrix and the B'-matrix after division of its covariances.

This configuration of the B-matrix provided the best possible retrievals. Analysis–radio-sounding rms errors significantly decreased compared with background–radio-sounding rms errors. IASI was also found to be very informative for surface conditions. Retrieved skin temperatures reproduced measured surface data (BSRN and manual measurements) with good fidelity with an rms error around 1.2 K. However, only 11 cases with clear-sky conditions were assimilated. Clouds have an important radiative impact on infrared radiances, and a difficulty in the detection of clouds comes from the use of a wrong surface model and a wrong skin temperature. The Advanced Very High Resolution Radiometer is a radiation-detection imager that can be used to determine both cloud cover and surface temperature. Therefore, it can inform about the cloudiness in IASI pixels which could help detect clouds with more accuracy. An improvement of snow model, which would improve the surface temperature, is another challenge to have a better system.

In order to further validate IASI data over the whole southern polar region, 19 high-altitude balloons able to drop sondes were launched in Austral spring 2010. These 640 dropsondes record the vertical profile of the atmosphere in points that are inaccessible by other means. Thus, this Concordiasi field experiment provided additional validation data that will improve the use of polar-orbiting-satellite data over the whole Antarctic continent and, in particular, the use of IASI radiances.

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