Convective-scale data assimilation of satellite infrared radiances over the Mediterranean: adaptation of the observation operator to the high-resolution.

Fanny Duffourg, Véronique Ducrocq, Geneviève Jaubert, Nadia Fourrié and Vincent Guidard

National Centre for Meteorological Research CNRM/GAME
(Météo-France/CNRS - National Centre for Scientific Research)
Mesoscale Meteorology Department (GMME)

Abstract

Fine scale phenomena are still badly grasped whereas they are an important challenge to take up. For that reason, some meteorological centres have recently developed numerical weather prediction models with a kilometric mesh that explicitly resolve moist convective processes. With this higher resolution, new problems, particularly in assimilation, have appeared. For example, the model mesh is now smaller than any satellite observation spot. As a consequence, we need to gather model information from different grid points to simulate correctly the brightness temperature measured. This issue is examined more specifically for the newly developed convective scale 3D-Var data assimilation system of Météo-France: AROME. In AROME, satellite observations are simulated thanks to the RTTOV radiative transfer model. The brightness temperature is estimated at the centre of the satellite observation spot using the four closest model columns surrounding this point. This interpolation procedure comes from previous assimilation systems for which the model mesh was larger than the observation spot. But with fine scale data assimilation systems such as AROME (2.5 km), such a procedure is no longer valid as a single AIRS or IASI observation spot covers more than 12 model grid points at nadir. That is why, in this study, we explore different ways of aggregating the model information within a satellite spot in order to better represent the whole atmosphere sounded at once by these instruments. We then compare the different brightness temperatures obtained by using RTTOV with these different aggregating methods. The first results show almost no differences for temperature channels (the differences in brightness temperature are smaller than 0.1 K) but bigger ones (from 0.5 K to 1 K) for water vapour channels in some places where important gradients in the humidity field are present.

Introduction

A number of meteorological centres have recently developed convective-scale numerical weather prediction systems with the specific aim of improving forecasts of high impact weather events. Their kilometric grid-mesh, nonhydrostatic equations and improved microphysics enable the explicit treatment of atmospheric deep convection. The representation of the precipitating systems is thus significantly improved. But this ability to simulate the dynamical and physical processes at a fine scale is not always sufficient to prevent bad forecasts: if some mesoscale key ingredients are missing in the initial conditions, the model cannot then reproduce the precipitating systems. In agreement with these two remarks, case studies focusing on Mediterranean heavy rainfall events have already shown significant improvements using nonhydrostatic convective-scale research models. But these studies have also pointed out the necessity to improve the initial mesoscale conditions (Ducrocq et al. 2002, Guidard et al. 2006 with a 10 km mesh model). This is particularly true for the initial moisture field: Mediterranean heavy rainfall events are very sensitive to the fine scale structure of this highly variable field which presents strong gradients.

Convective-scale assimilation of observations over sea is a way to improve the initial conditions of kilometric scale models. Such improvement is of particular importance in case of Mediterranean heavy rainfall events as they originate from the Mediterranean Sea (Nuissier et al. 2007, Ricard et al. 2007). Over sea, satellite data are nearly the only routinely available observations with a sufficient coverage. With the new infrared sounders IASI (Cayla 2001, Chalon et al. 2001) and AIRS (Pagano et al. 2002, Aumann et al. 2003), we now have high-resolution and very accurate information on temperature and humidity over sea. IASI sounds indeed the atmosphere with an horizontal resolution of 12 km at nadir and a vertical resolution finer than 1 km. The accuracy of its measurements is better than 1 K for temperature retrievals and 10 % below 500 hPa for relative humidity retrievals. The initial analysis may therefore gain a lot from the fine-scale assimilation of such precise information over sea.

However the assimilation of satellite data in a convective-scale data assimilation system is not straightforward as new problems arise with the increase of resolution. In particular, the simulation of brightness temperatures from a high-resolution model for its comparison with observations raises new questions. Indeed, the model mesh is now smaller than any satellite observation spot. As a consequence, we need to aggregate model information from different grid points to simulate correctly the brightness temperature measured, whereas with previous larger-scale assimilation systems we could use a single model column. This is what this work is about, focusing on IASI and AIRS because of their particularly interesting characteristics.

The main purpose here is to evaluate the impact on infrared radiances simulation of using all atmospheric model information contained in the observation spot instead of only the single vertical column situated at the centre of the observation spot. This issue is examined more specifically for the newly developed convective scale 3D-Var data assimilation system of Météo-France: AROME. For that, we develop different ways of aggregating the model information within a IASI or AIRS spot so as to better represent the whole atmosphere sounded at once by these instruments. These new methods as well as the current one will be presented in the first section along with the IASI, AIRS and AROME system main characteristics. Then, the various methods are evaluated statistically and finally the most important differences are characterised thanks to a case study.

IASI and AIRS radiances simulation

IASI and AIRS radiances

IASI (Cayla 2001, Chalon et al. 2001) and AIRS (Pagano et al. 2002, Aumann et al. 2003) are hyperspectral infrared passive sounders, respectively on board the European and the American polar orbiting satellites MetOp and Aqua. They measure the radiation coming out of the atmosphere in thousands of channels in the infrared spectrum. This outgoing radiation is strongly linked with the concentrations of various atmospheric gases, with humidity and temperature. Thus, thanks to their numerous channels (8461 for IASI and

2378 for AIRS) with high spectral resolution (0.25 cm^{-1} for IASI and from 2.2 cm^{-1} at 3.7 μm to 0.5 cm^{-1} at 15.4 μm for AIRS), IASI and AIRS measurements provide very accurate information on temperature and humidity (1 K for temperature retrievals and 10 % below 500 hPa for relative humidity retrievals with 1 km vertical resolution).

IASI and AIRS are nadir-viewing sounders: they scan the atmosphere below the satellite for different look positions along a plane which is perpendicular to the satellite orbit track. When looking at an off-nadir position, the atmosphere is scanned along a slanted line-of-sight. Table 1 gives the maximum angle formed between the line-of-sight and the nadir direction. As IASI and AIRS fields-of-view are respectively 0.825° and 1.1°, the horizontal resolution of their measurements varies with the scan angle. The minimum (at nadir) and maximum (at swath edge) values are given in table 1.

Instrument	Horizontal resolution at nadir (diameter of the circular spot)	Maximum scan angle	Horizontal resolution at swath edge (major and minor axes of the ellipsoidal spot)
IASI	12 km	48.3°	38 km × 20 km
AIRS	13.5 km	49.5°	40 km × 22 km

Table 1: IASI and AIRS geometrical characteristics

The AROME 3D-Var

Such high-resolution and very accurate information on temperature and humidity is very interesting to assimilate in a convective-scale model such as AROME, the newly developed numerical weather prediction system of Météo-France. AROME is to become operational by the end of the year 2008.

This model has a grid mesh of 2.5 km and 41 unequally spaced vertical levels up to 1.36 hPa. Its dynamics is based on non-hydrostatic equations. Many physical processes such as cloud microphysics, deep convection or turbulence are explicitly resolved while shallow convection, radiation, etc. remain parametrized. Cloud processes are particularly well described because of the explicit treatment of cloud microphysics but also thanks to the detailed description of hydrometeors through five different species: liquid water, rain water, cloud ice, snow and graupels.

AROME has its own 3D-Var data assimilation process, cycled every 3 h: each cycle produces 3 h forecasts which are used as background fields for the next analysis in the next cycle. In the AROME 3D-Var, inherited from the ALADIN one (Fischer et al. 2005), satellite radiances (previously converted into brightness temperatures thanks to the Planck function) are directly assimilated, without any previous retrieval. For that, the background and the satellite observations have to be compared directly in terms of brightness temperatures. This is performed by calculating simulated brightness temperatures from the background and by comparing them with the observed brightness temperatures.

Simulation of satellite radiances with the current observation operator

The simulation of satellite brightness temperatures from the background is performed in two main steps, grouped together in the observation operator. The first step aims at forming a model column that represents the atmosphere sounded and the second step is the effective brightness temperature calculation, using the model column formed in the first step.

In the AROME data assimilation process, the brightness temperature calculation is performed with the RTTOV radiative transfer model (Saunders and Brunel 2005).

Currently, the model column representing the sounded atmosphere is estimated at the centre of the satellite observation spot by interpolating the four closest model columns surrounding this point. This procedure, hereafter referred to as **Tb1column**, comes from previous assimilation systems for which the model mesh is larger than the observation spot. It is however very rough for a 2.5 km resolution model: a single IASI or AIRS observation spot covers more than 12 AROME grid points at nadir, about a hundred at swath edge, and all these points contribute similarly to the measure (the instrument point spread function is quasi-uniform over the spot).

Adaptations of the observation operator to the convective-scale

We have modified the observation operator to aggregate the model information within the satellite spots.

A first modification affects the representation of the sounded atmosphere. We now compute the mean of all the model columns located in the observation spot and use this mean model column as representative of the sounded atmosphere to estimate the brightness temperature with RTTOV. This new operator is called hereafter **Tbspot1**.

In order to be further close to the way of how the instrument measurement is achieved, we also average the brightness temperatures estimated for each model column in the spot rather than estimate the brightness temperature from an averaged model information. This third version of the observation operator, called **Tbspot2**, is however much more computing time consuming which is an important drawback for an operational use.

Statistical evaluation of the new observation operators

Evaluation method

We will now evaluate the impact of these modifications of the observation operator. For that, IASI and AIRS brightness temperatures are simulated using the three observation operators at each clear AROME grid point situated over the Mediterranean Sea. We consider that a grid point is clear if the model contains less than 10^{-6} kg of hydrometeors per kg of air in the whole sounded atmosphere. These simulations are performed for all AROME analyses (every 3 hours) of September 2007. The brightness temperatures are calculated only for tropospheric channels because there are not enough AROME levels in the stratosphere to ensure a good representation of the radiative transfer in this part of the atmosphere. For AIRS, the calculations are performed for all the tropospheric channels that are not blacklisted in the data assimilation process of the ECMWF's Integrated Forecasting System. For IASI, we also compute only the tropospheric channels that are not blacklisted in the ECMWF's IFS for the temperature band. For IASI water vapour band, we compute all the tropospheric channels. With all these data, we compute statistics of the brightness temperature differences between calculations using the three observation operators presented above.

For reference, the instrument noise is also evaluated in terms of Noise Equivalent Differential Temperature (NEDT). For IASI we took the NEDT values at 280 K given in Blumstein (2007), for AIRS the values at 250 K given in Pagano et al. (2002 and 2003) and, for each channel, we computed the NEDT values at the mean brightness temperature over the month and at the mean brightness temperature plus or minus the brightness temperature standard-deviation over the month (to get an idea of the variation of the instrument noise).

To maximize the potential differences between the calculations using the various operators, the brightness temperatures are simulated for the maximum scan angle and therefore the maximum size of observation spot.

Differences between the various observation operators

Differences between Tbspot1 and Tb1column

Figures 1 and 2 show the standard-deviations of the brightness temperature differences between calculations using simply averaged (Tbspot1) and punctual (Tb1column) model information, together with the instruments Noise Equivalent Differential Temperature (NEDT).

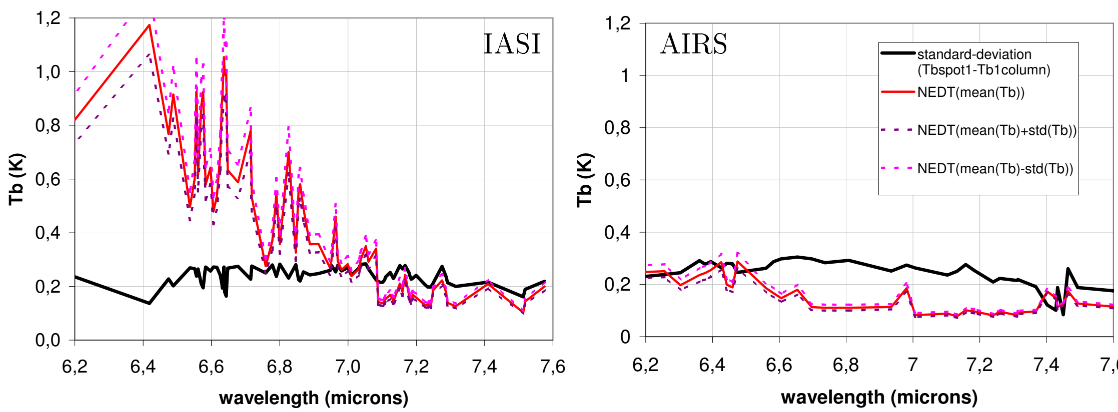


Figure 1: Standard-deviation of the brightness temperature differences between calculations using Tbspot1 and Tb1column and instrument Noise Equivalent Differential Temperature (NEDT) for IASI and AIRS water vapour channels.

We can see on figure 1 that the standard-deviations of the brightness temperature (Tb) differences between calculations using Tbspot1 and Tb1column are larger than the instrument noise for all AIRS water vapour channels and for IASI water vapour channels peaking under 350 hPa (wavelengths between 7 μm and 7.6 μm). Therefore, for all these channels, there are significant differences between the simple new observation operator Tbspot1 and the current one Tb1column.

However, the differences between Tbspot1 and Tb1column are negligible for temperature channels (cf. fig. 2 for IASI).

For each temperature and water vapour channel, the average of the brightness temperature differences is very close to 0 K: no new biases have been introduced.

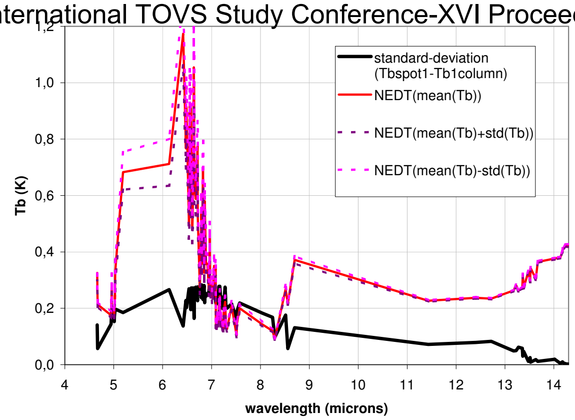


Figure 2: Same as figure 1 for all IASI channels.

Differences between Tbspot1 and Tbspot2

Figure 3 is similar to figure 1 but for the differences between the two new observation operators (Tbspot2, where the brightness temperatures are estimated for each model column in the observation spot before being averaged, and Tbspot1, where the model information within the observation spot is averaged before applying the radiative transfer). Figure 4 shows scattering plots comparing the brightness temperature differences between calculations using Tbspot2 and Tb1column and the brightness temperature differences between calculations using Tbspot1 and Tb1column.

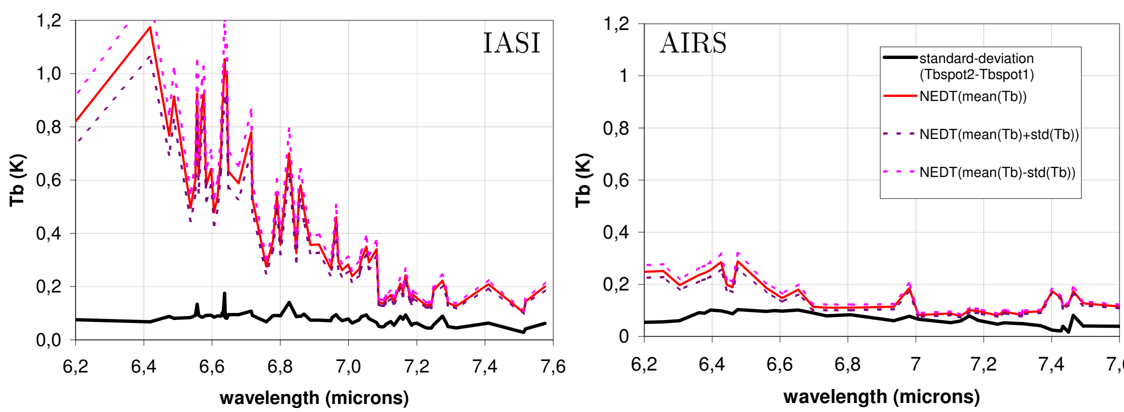


Figure 3: Standard-deviation of the differences between calculations using Tbspot2 and Tbspot1 and instrument Noise Equivalent Differential Temperature (NEDT) for IASI and AIRS water vapour channels.

The differences between the two new observation operators are globally negligible (cf. fig. 3) even if Tbspot1 sometimes gives slightly larger - and probably overestimated - differences with Tb1column than Tbspot2, in particular when we have large differences with Tb1column (cf. fig. 4). As a consequence, the more realistic observation operator Tbspot2 being too much computing time consuming for an operational and real time use, from now on, we choose to work only with the simpler one, Tbspot1.

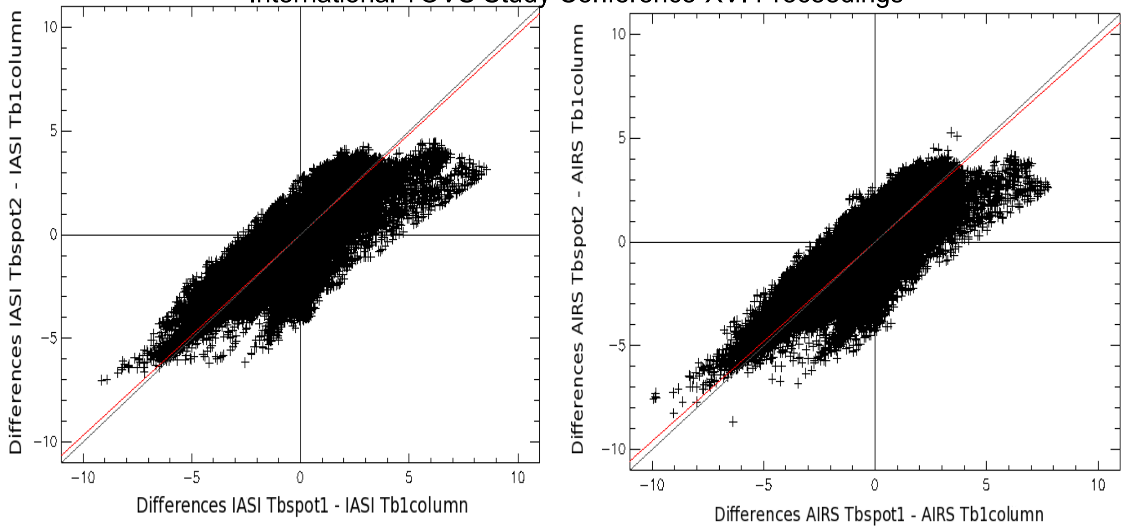


Figure 4: Scattering plots comparing the brightness temperature differences between calculations using Tbspot2 and Tb1column (ordinate) and the brightness temperature differences between calculations using Tbspot1 and Tb1column (abscissa) for all IASI (on the left) and AIRS (on the right) water vapour channels studied.The regression line is in red and the line y=x is in black.

Characterization of the most important differences

We have seen previously that using the simple new observation operator Tbspot1 instead of the current observation operator Tb1column may modify significantly the simulated brightness temperatures. Figure 5 shows that the importance of these modifications varies a lot with time and that their variations are consistent for the different channels. Thus, some specific situations with specific meteorological structures aggregate the most important differences between calculations using the various operators while in other situations, the differences are much smaller.

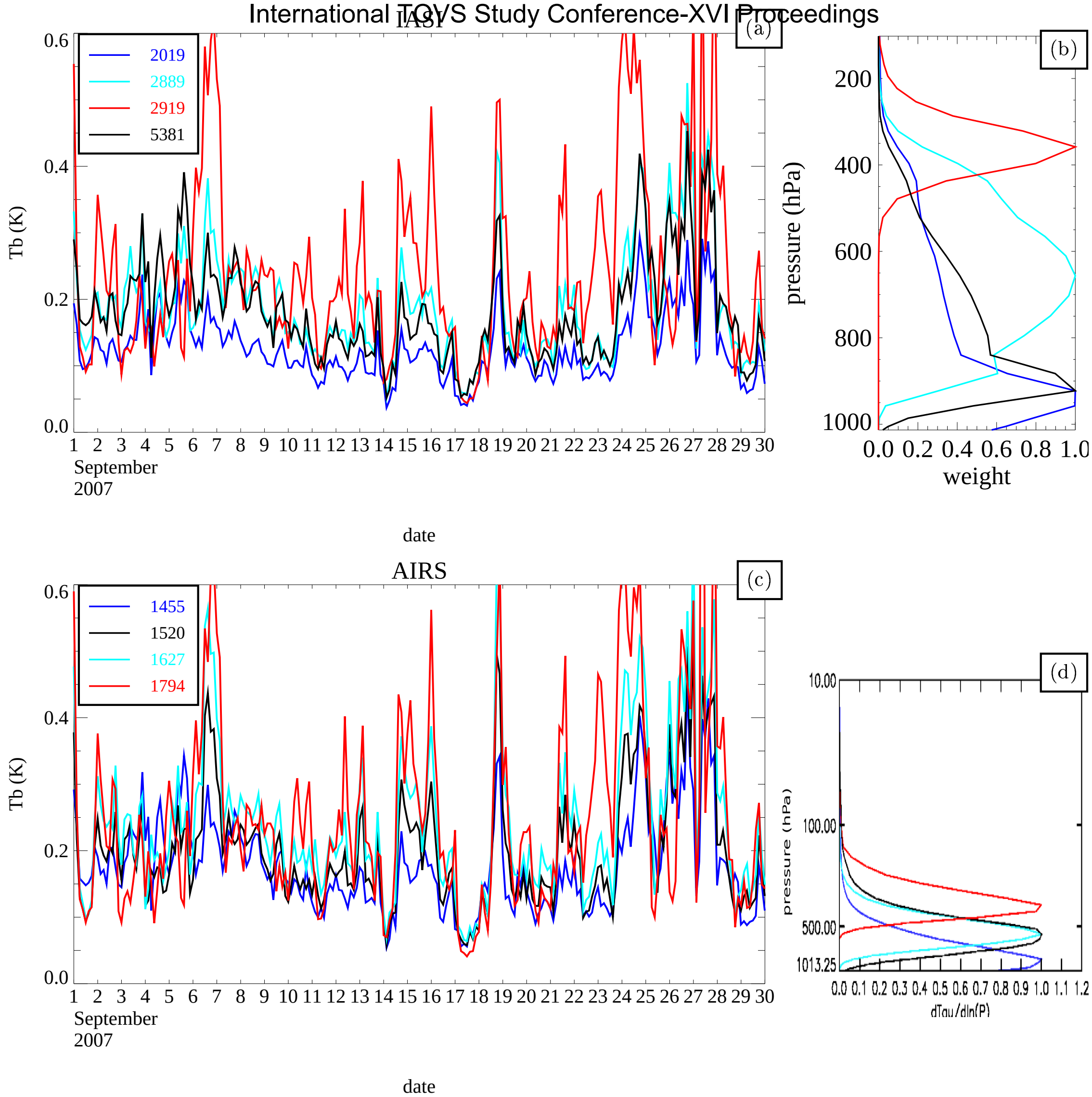


Figure 5: Time series over September 2007 of the standard-deviation of the brightness temperature (Tb) differences between calculations using Tbspot1 and Tb1column for the 4 IASI 2019 (8.7 μm), 2889 (7.32 μm), 2919 (7.28 μm) and 5381 (5.03 μm) (a) and the 4 AIRS 1455 (7.49 μm), 1520 (7.31 μm), 1627 (7.01 μm) and 1794 (6.4 μm) (c) water vapour channels, whose weight functions are shown on the right (b for IASI and d for AIRS).

Conclusions and outlooks

Aggregating the model information within the satellite spot, as it is done in the new observation operators Tbspot1 and Tbspot2, instead of using a single central model column (Tb1column) leads to significant differences in the simulated brightness temperatures for water vapour channels only (peaking under 350 hPa for IASI). These differences are particularly important in some specific meteorological situations. The study of these situations (not displayed here) shows that the most important differences appear in the places where fine-scale humidity gradients occur: with the new observation operators, the fine-scale model humidity variations are filtered which is not the case with the current observation operator Tb1column.

Averaging before applying the radiative transfer (Tbspot1) or after (Tbspot2) leads in most cases in no significant differences. The new observation operators both simulate brightness temperature fields at a scale which is more comparable with IASI and AIRS measurements than the current observation operator. This may avoid the rejection of some observations or too large analysis increments. This will be verified in a future work by estimating if the brightness temperatures simulated with the new observation operators are really closer to the real IASI and AIRS measurements. This will help in deciding the possible implementation of Tbspot1 in the 3D-Var AROME assimilation scheme.

References

Aumann H., M. Chahine, C. Gautier, M. Goldberg, E. Kalnay, L. McMillin, H. Revercomb, P. Rosenkranz, W. Smith, D. Staelin, L. Strow and J. Susskind, 2003: AIRS/AMSU/HSB on the Aqua mission: design, science objectives, data products, and processing systems. *IEEE Trans. Geosci. Remote Sens.*, **41(2)**, 253-264.

Berre L., S.E. Stefanescu and M. Belo Pereira, 2006: The representation of the analysis in three error simulation techniques. *Tellus*, **58A**, 196-209.

Blumstein D., 2007: In-flight performance of the infrared atmospheric sounding interferometer (IASI) on METOP-A. *Presentation in SPIE conference Atmospheric and Environmental Remote Sensing Data Processing and Utilization III: Readiness for GEOSS*, San Diego, CA, USA.

Cayla F., 2001: L'interféromètre IASI, un nouveau sondeur satellitaire à haute résolution. *La météorologie 8ème série*, **32**, 23-39

Chalon G., F. Cayla and D. Diebel, 2001: IASI: an advanced Sounder for Operational Meteorology. *Proceedings of the 52nd Congress of IAF*, Toulouse, France.

Ducrocq V., D. Ricard, J.-P. Lafore and F. Orain, 2002: Storm-scale numerical rainfall prediction for five precipitating events over France: on the importance of the initial humidity fiels. *Wea. Forecasting*, **17**, 1236-1256.

Fischer C., T. Montmerle, L. Berre, L. Auger and S.E. Stefanescu, 2005: An overview of the variational assimilation in the ALADIN/France numerical weather prediction system. *Quart. J. Roy. Meteor. Soc.*, **613**, 3477-3492.

Guidard V., C. Fischer, M. Nuret and A. Dziedzic, 2006 : Evaluation of the ALADIN 3D-Var with observations of the MAP campaign. *Meteorol. Atmos. Phys.*, **92**, pp.161-173.

Joiner J. and P. Poli, 2005: Note on the effects of horizontal gradients for nadir-viewing microwave and infrared sounders. *Quart. J. Roy. Meteorol. Soc.*, **131**, 1783-1792.

Nuissier O., V. Ducrocq, D. Ricard, C. Lebeaupin and S. Anquetin, 2008: A numerical study of three catastrophic precipitating events over Western Mediterranean region (Southern France). Part I: Numerical framework and synoptic ingredients. *Quart. J. Roy. Meteor. Soc.*, **134**, 111-130.

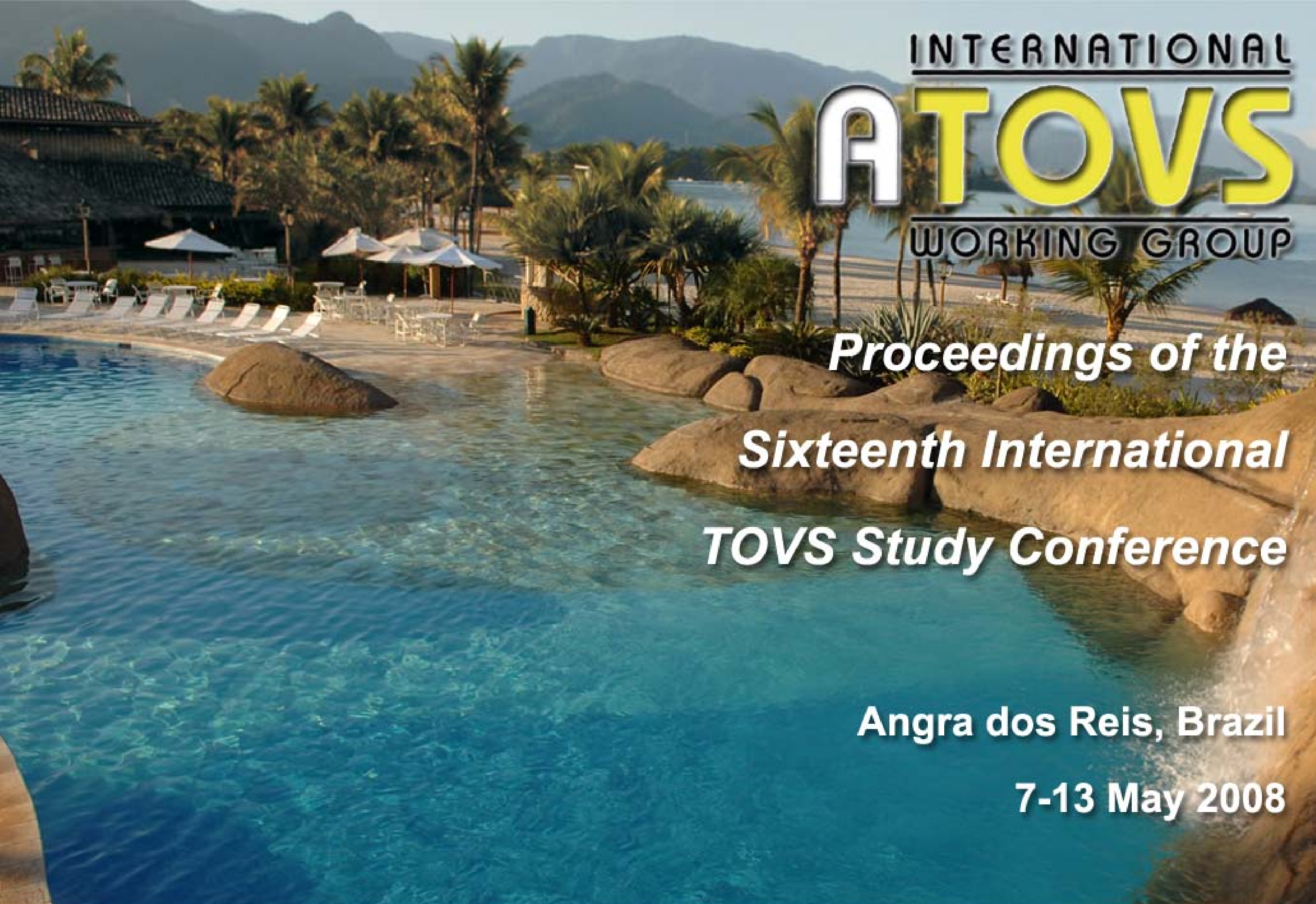
Pagano T., H. Aumann, S. Gaiser and D. Gregorich, 2002: Early calibration results from the Atmospheric InfraRed Sounder (AIRS) on Aqua. *Proceedings of the SPIE's Third International Asia-Pacific Symposium on Remote Sensing of the Atmosphere, Ocean, Environment and Space*,Hangzhou, China.

Pagano T., H. Aumann, D. Hagan and K. Overoye, 2003: Prelaunch and in-flight radiometric calibration of the Atmospheric InfraRed Sounder (AIRS). *IEEE Trans. Geosci.*

Remote Sens., **41(2)**, 265-273.

Ricard D., V. Ducrocq, R. Bresson and L. Auger, 2007: Mesoscale environment associated with Mediterranean heavy precipitating events. Preprints, *12th Mesoscale Processes Conference*, Waterville Valley, NH, USA.

Saunders R. and P. Brunel, 2005: RTTOV_8_7 Users Guide, *NWP SAF Report*.



INTERNATIONAL

ATOVS

WORKING GROUP

Proceedings of the Sixteenth International TOVS Study Conference

Angra dos Reis, Brazil

7-13 May 2008

Sharing ideas, plans and
techniques to study
the earth's weather and climate
using space-based observations