"Spectral surface emissivity for use in assimilation of IR radiance data over land"

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I. Introduction

The use of very high spectral resolution satellite measurements over land, as given by AIRS or IASI instruments, will certainly increase in the next few years. Preparatory studies have begun with the creation of appropriate "climatological" maps for surface spectral emissivity (SSE). In this report I will present maps of these quantities and their validation. Emissivity maps were prepared on the base of the new Ecoclimap (Masson et al.2002) vegetation and land cover types and the infrared SSE values from spectral libraries (MODIS, ASTER and JPL) compiled with the ones modelled by Snyder et al. (1998). New emissivity maps were produced separately for 18 wavebands in the infrared spectral range and for each month. The final maps were validated with MODIS channel 31 and 32 land surface emissivity products based on the split-window method. Further validation of this new SSE was performed by quantifying the impact brought by this new emissivity when computing simulated radiances for IR sounder. It was first carried out with the radiative transfer model RTTOV-7 with High-resolution Infra-Red Sounder (HIRS) channel 8 data. A further step has consisted in the validation with Atmospheric Infrared Sounder (AIRS) measurements. Extensive tests of the SSE with the AIRS data are currently performed. To retrieve and assimilate the very fine spectral resolution measurements from advanced IR sounders (IASI/AIRS) we need to have the ancillary information (background) which specifies the behaviour of the variables or constitutes some a-priori constraints. In order to estimate the quality of the background information one need to compute the background error covariance, called B matrix. A first estimate of land surface skin temperature (LST) can be taken from model forecast, and surface spectral emissivity (SSE) can be provided by climatological values depending on the land cover type. To calculate the background error covariance for temperature (vertical profile + surface) the Ensemble method was used. For the emissivity the B matrix is calculated for 12 wavebands, separately for each of the different land cover types. Chosen wavebands fully cover the IASI and AIRS spectral range. The data for emissivity climatological maps (SSE background) were taken from the MODIS spectral library. Additionaly, preliminary experiments with emissivity as a control variable in a 1-dimensional variational assimilation model (1D-Var) have been run.

II. Land surface types and emissivity climatological maps

The new classification of surface types was based on the Ecoclimap a complete surface parameter global dataset (Masson, 2003). In general, areas of homogenous vegetation were represented by 215 ecosystems. They were derived by combining existing land cover maps, climate maps, normalised difference vegetation index (NDVI) inferred from observations of the Advanced Very High Resolution Radiometer (AVHRR) instrument and The Food and Agriculture Organisation (FAO) database of soil texture. Most of these ecosystems were a combination of only one of the following 12 vegetation types (so-called pure ecosystems): bare soil, rocks, permanent snow and ice, crops type C3 (omnipresent except tropical and equatorial belts, and where the corn is intensively cultivated), crops type C4 (applied for crops C3 exceptions), irrigated crops, natural herbaceous (temperate), natural herbaceous (tropics), wetland herbaceous or irrigated grass, needleleaf trees, evergreen broadleaf trees, and deciduous broadleaf trees. Those pure ecosystems with addition to urban areas and water gave us full description of 14 simplified global land cover types, for further emissivity assignments.

Currently in the climatological files for the ARPEGE model, 5 land cover types exist: high vegetation, low vegetation, bare soil, permanent ice and water. ARPEGE cover types were believe to be representative enough to use them for the characterization of the emissivity background errors.

The Infrared Atmospheric Sounding Interferometer (IASI) range (645-2760cm^{-1} 8461 channels) got divided into 18 wavebands with respect to their usefulness for the channel selection (informative bands).

The wavebands have been chosen narrow and dense in areas with high (>0.5) transmittancy running average over 40 channels. This was done in order to follow the variability of the land cover types spectra and to validate the emissivity climatology created from MODIS emissivity maps (channels 31 and 32). The resulting wavebands are: 645-760, 760-805, 805-885, 885-950, 950-1000, 1000-1068, 1068-1135, 1135-1210, 1210-1240, 1240-1968, 1968- 2020, 2020-2064, 2064-2120, 2120-2180, 2180-2450, 2450-2575, 2575-2720, 2720-2760 cm^{-1}.

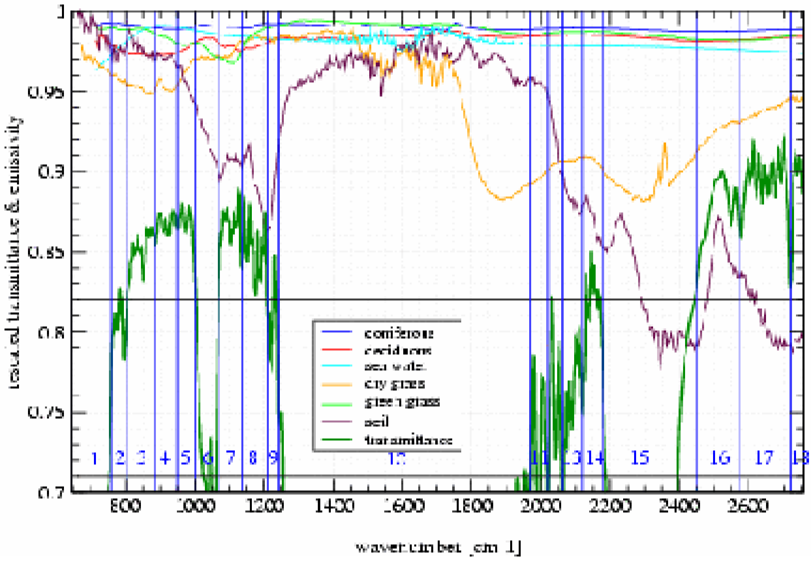


Fig 1 IASItransmittance and emissivity spectra of different land cover types. Transmittance (thick green) is a running average over 40 channels (scaled by 1/3 then shifted by 0.6).

Climatological fields of surface spectral emissivity were created respectively to these wavebands. The creation was based on the global new land cover types and vegetation maps with resolution of 0.5 all over the globe (Masson, 2003) and SSE calculated for each of 14 simplified types from separate emissivity spectra of different natural and man-made materials.

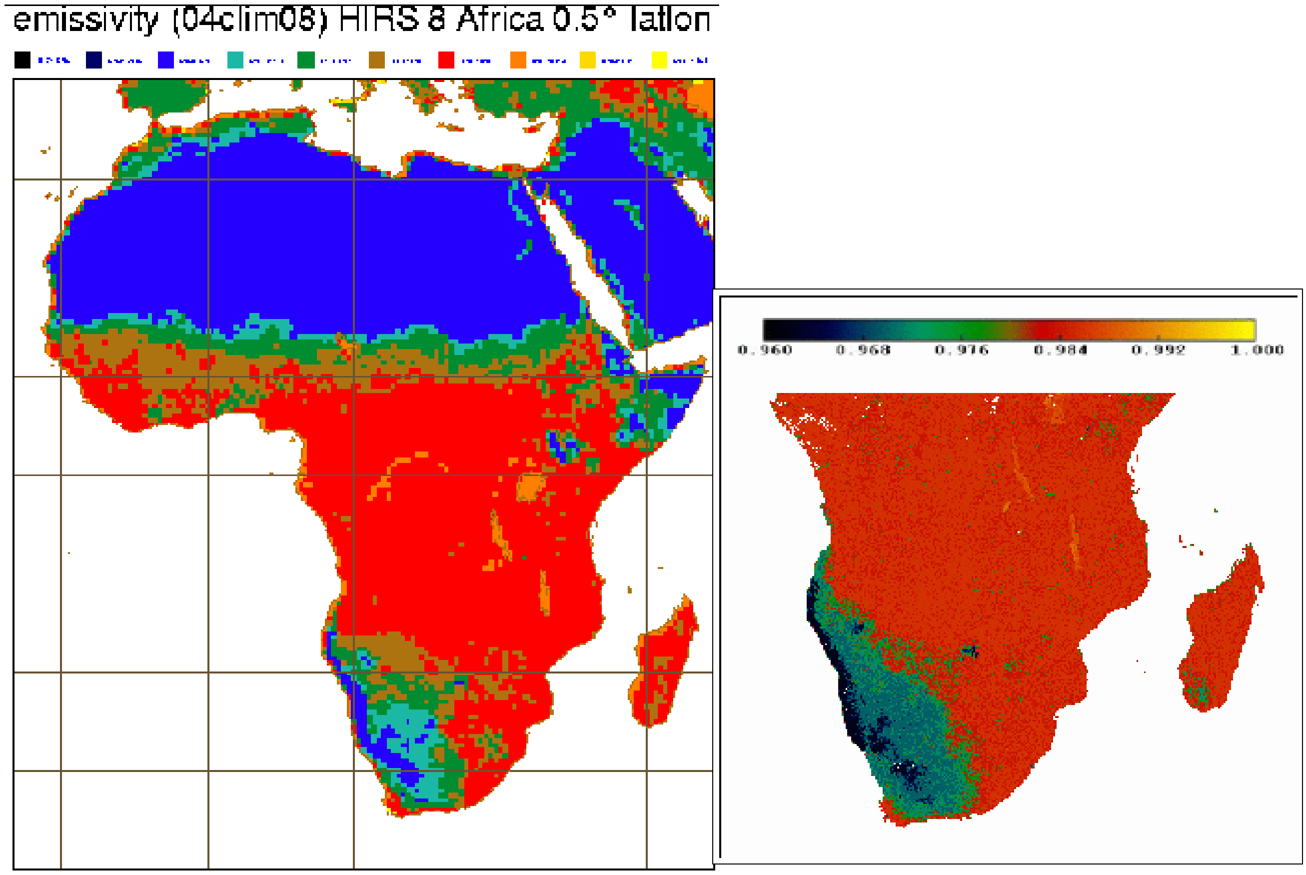
Then, the SSE maps were taken as an input for the modified climatological configuration of the ARPEGE model in which emissivity was interpolated to the final model grid.

III. Validation of the SSE maps

The validation of the spectral emissivity climatological maps has been done in a few steps. Firstly we have compared (subjective) SSE maps for wavebands 805-885 cm^{-1} and 885-950 cm^{-1} with the MODIS emissivity maps for channels 32 and 31 respectively. The next step consisted in testing of the new SSE in the radiative transfer model RTTOV-7 with use of observations of HIRS instrument channel 8, which points to the surface. Finally, tests were performed with real AIRS data in preselected 324 channels (also using RTTOV-7).

MODIS

The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on board NASA's Terra satellite routinely retrieves land surface products, and SSE among them. The method used for retrieval of emissivity maps which were used for our initial comparison was the 'split-window' technique, using MODIS bands 31 (centered at 900cm^{-1}) and 32 (833cm^{-1}). These data are avaliable at 1 km spatial resolution, and temporally divided into groups: individual swath data, 1-day average and 8-day average. Fig.2 presents an example of comparison of the surface spectral emissivity climatological map for the month of August against the MODIS SSE composite of individual



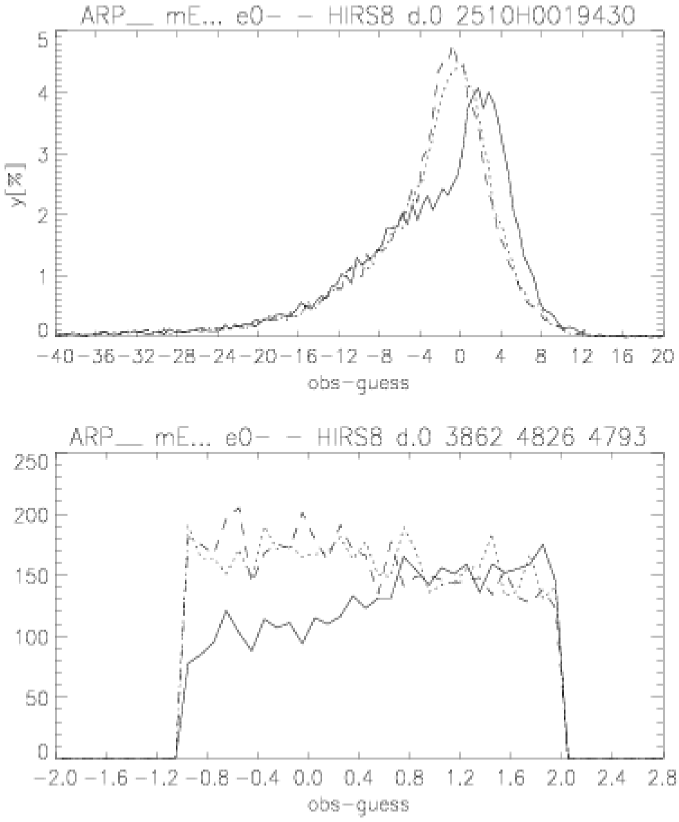
swaths for the 20 of August 2000. One can note a good correspondence between the emissivity fields.

Fig.2 On the left side - climatological map of the SSE for the month of August, and on the right one the SSE composite map retrieved from MODIS band 31 measurements. Both figures have the same colour scale.

MODIS data are free of charge and can be accessed from the webpage referenced in bibliography.

HIRS-8

As already mentioned, this new SSE was also tested against observations of the HIRS instrument, for channel 8. This channel is centered at 900cm^{-1} with half-power bandwidth equal to 35cm^{-1}. It corresponds very well to MODIS band 31, is very sensitive to surface parameters and it can be used to detect cloud contamination. As we work with surface data, there is a strong requirement that the radiances we use were measured in clear sky conditions. Tests have been done on the differences between measured and the forecasted brightness temperatures (obs-guess) in this channel window.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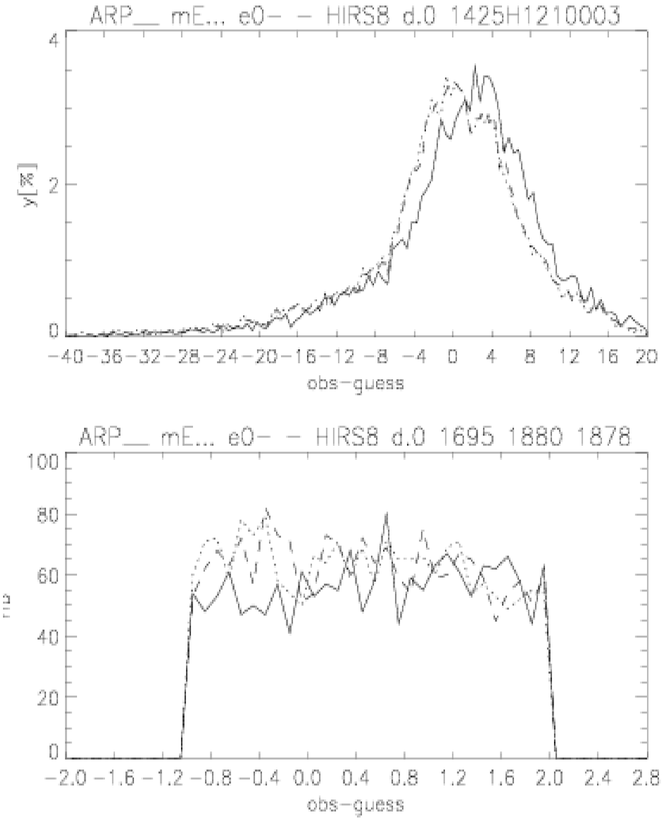
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a)

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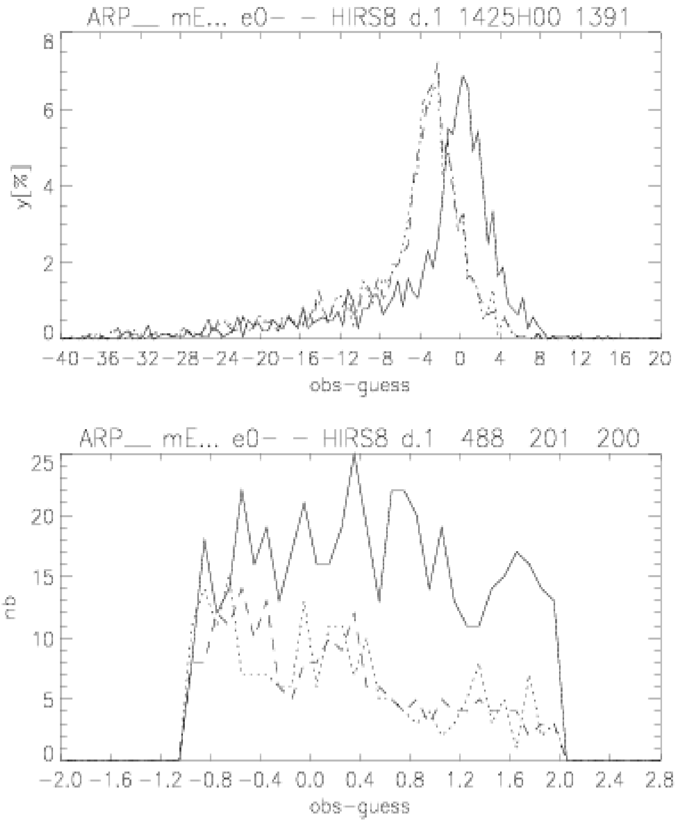
c)

d)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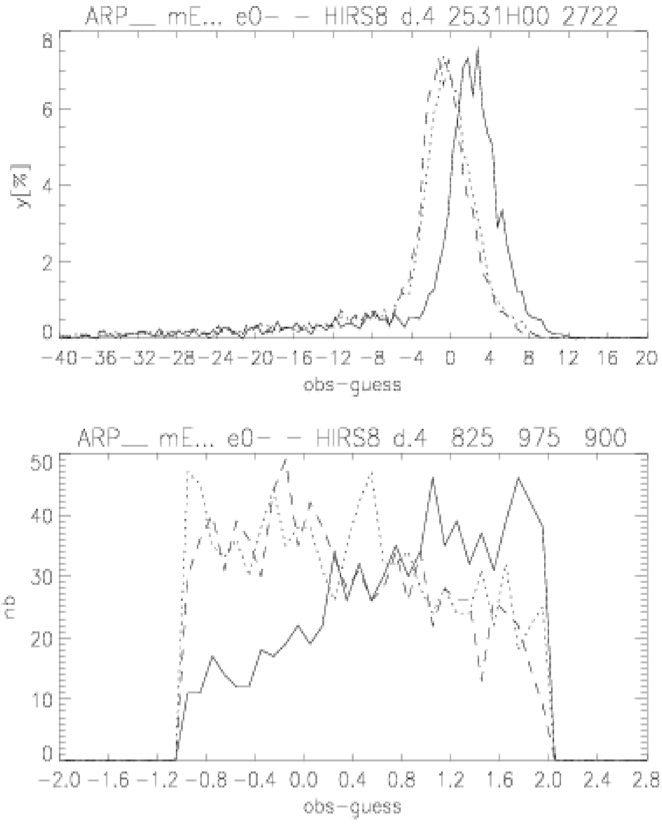
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Fig.3 Histograms of obs-guess values for different days and domains. a) and b) are cumulated over the whole globe, c) over Europe and d) over Africa. Temporal ranges are: a) 25-31.12.2002 cycle 00z, b) 14-25.06.3002 cycle 12z, c) as"b" but cycle 00z, d) as "a". Upper graphs shows distribution of obs-gues values for the whole sample, while the bottom ones only show 'not cloudy' points. Solid line corresponds to used ARPEGE emissivity, dotted one to the new SSE, and dashed line represents the results with RTTOV-7 emissivity.

As a forecasted brightness temperature (Tb) we use the brightness temperatures calculated in RTTOV-7 from atmospheric state vector taken from the 6hour ARPEGE model forecast. This state vector is a vertical atmospheric profile containing the temperature and humidity at 43 pressure levels, surface air and skin temperature, surface pressure and surface spectral emissivity. A cloud test to eliminate the cloudy points we applied on channel 8, assuming that for clear sky conditions the difference between measured and the forecasted Tb lies in between -1 and 2K and is not latitude dependent.

To evaluate the quality and usefulness of the new climatology for emissivity, we compared the values of obs-guess with the RTTOV-7 run for different values of surface emissivity for the same state vector. As a first reference run, the emissivity from ARPEGE was used, i.e. SSE=0.93 for dry land, 0.99 for moist land and partial snow cover and 1.00 for ice-caps and full snow cover. The second one was RTTOV7 run with its own emissivity value, i.e. SSE=0.98 everywhere for land. All the tests were performed on the same sample of initial profiles. On Fig.3 the top graphs represent histograms of the full range of obs-guess values, and the bottom ones - the number of cloud free or small obs-guess points in each sample. The solid line is the ARPEGE reference, the dotted one corresponds to the new SSE, and the dashed one to the RTTOV reference. Note the values written in the titles of the bottom graphs: they are the number of profiles for which obs-guess values pass the 'cloud test' for the three emissivity used. The various panels a) to d) correspond to the various areas and times of day.

The results are not obvious to interpret, they do not show clearly and unambiguously the general improvement of the estimated Tb converted by the radiative transfer model with the use of the new surface emissivity. We compared the number of profiles for which the difference: observed Tb and estimated one in RTTOV, had stayed in the range -1 to 2K ('cloud test'). What we can observe is that for the period of 25.12.2002-10.01.2003 use of new SSE considerably improves the values of simulated brightness temperature in comparison with the ones obtained with the use of the SSE from the ARPEGE model (on fig.3a dotted and solid lines). On the contrary for the period of 14-25.06.2003, especially over Europe, the use of the surface emissivity from the global model gave the best results (fig.3c). One explanation of that could be the unusally hot and dry summer in that region this year. The state of vegetation was not similar to the 'climatological' one. It means that instead of green grass and crops there were dry ones. As one can see on fig.1 the difference between dry and green grass emissivity spectra in band nr.4 (corresponding to HIRS channel 8) was significant. So, as the result SSE=0.93 (as it is in ARPEGE) appeared to be better for that unusual period than the new SSE with values between 0.973 and 0.987. Also there was noticed dependence between low emissivity areas and value of SWI (soil wetness index) taken from ARPEGE model. For the next tests we wanted to use SWI additionally to land cover type in estimation of local emissivity value, but for technical reasons it is not yet possible. Considering Tb calculated with the use of SSE=0.98 (RTTOV default value for land) as a reference, seems that that the new SSE did not improve very much the estimation of brightness temperature. In some cases the difference in the number of 'good' points was negligible (fig.3abc), in others it could reach up to 8 percent (fig.3d).

Table 1. Comparison of the number of 'good points' with use of new SSE against emissivity from RTTOV-7 and ARPEGE, for all periods together for different domains.

	globe	Europe	N America	S America	Africa	Asia	Australia
RTTOV-$7_{0.98}$	2.9%	1.7%	2.2%	-3.10%	10.8%	3.7%	4.3%

ARPEGE	16.5%	12.8%	11.6%	-2.4%*	30.3%	12.9%	50.3%*

In table 1 are presented results of the comparison test for all tested periods together, for different domains. The values mean by how many more "good points" were for Tb estimation in radiative transfer model with the use of the new SSE. Negative values (as it is for South America) mean that in average (over all tested periods) new SSE was giving worse Tb. The comparison against ARPEGE emissivity, as for South America as for Australia (*) could be neglected because of low resolution of the ARPEGE model on that areas (it has stretched geometry).

In general one can say that the use of new SSE decreased the difference between measured and the simulated brightness temperatures, or stayed neutral. But there could exist exceptions while some extreme, long term atmospherical conditions appeared. Moreover some additional tests on just clear sky profiles could give more detailed ideas about the new SSE behaviour.

AIRS

For the validation of the new SSE with AIRS measurements, the same strategy was applied, with a different cloud detection and channel selection. The AIRS cloud detection scheme was based on multichannel data, and it has been found to be quite sensitive to small clouds only partially filling the field of view, optically thin cloud and stratiform cloud with a top temperature near identical to the surface (Smith,2003). So, it was more accurate with comparison to the 'cloud test' applied to HIRS 8 data. Additionally the AIRS imager was also used to detect clouds. As a result the validation of the new surface emissivity has started on profiles for purely clear sky conditions.

As the Atmospheric Infrared Sounder is an instrument with very high spectral resolution the use of all 2378 channels is not practical and efficient. So thinning of the data was advised and a subset of 324 channels was prepared by NOAA AIRS Science Team. These channels were grouped into the 18 earlier mentioned bands, but because of some differences in spectral coverage of IASI and AIRS instruments, the wavebands number 11, 12, 13, 14 and 18 were out of AIRS range. Additionally in ARPEGE 1D-VAR satellite radiances assimilation there was no ozone analysis included, so channels from bands 5, 6, 7 and partially 9 were blacklisted from the assimilation process (i.e. they do not enter the analysis). The other problem was caused by 'solar contamination' in the short wavelength part of the spectrum. Channels touched by this problem could be used by night, but then the AIRS imager could not be used to detect clouds.

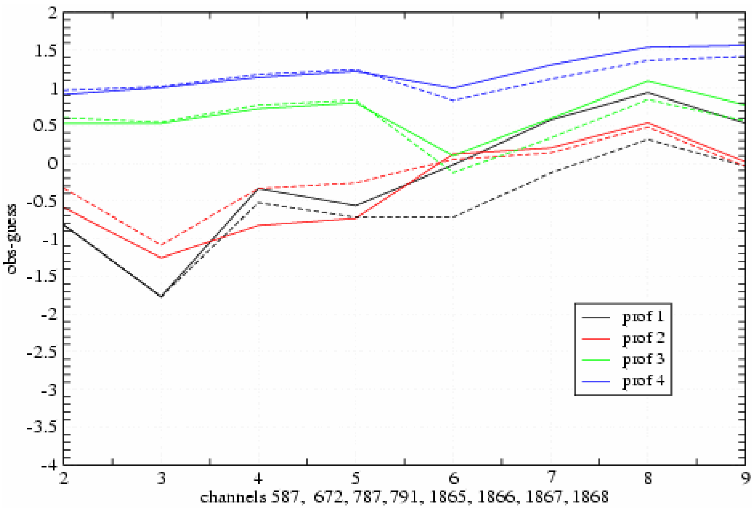


Fig 4 Obs-guess values of Tb for 8 selected channels in 2 bands. Continuous line refers to SSE=0.98 (RTTOV, reference), the same colour but dashed line corresponds to new SSE.

As a consequence we rejected also the wavebands 16, 17 and partially 15. From the remaining bands we also excluded the ones with low transmittancy values (these channels were not seeing the surface), namely number 1, 10 and also 2. Finaly only two full bands remained: 3 (four channels) and 4 (four channels), and partially band 9 (one channel) and 15 in the longwave part. Considering the usefulness of the bands we neglected band 9 because of a lack of channels to compare with and

to analyse the impact of the SSE. From waveband 15 we kept four longwave channels pointing to the levels closest to the surface.
Summarizing, for SSE validation with the AIRS data and subsequently in 1D-VAR we could use three bands 3, 4 and 15, with 12 channels. As we intend to use the same wavebands for 1D-VAR, the new B matrix has been calculated just for these bands, and very high correlation was found between adjacent bands 3 and 4, and almost zero correlation of these two bands with band number 15. For simplicity reason (diagonal B) we merged wavebands number 3 and 4 as the average emissivity values in those were relatively close. And the result was, that finally we would use 8 channels: four from merged bands 3 and 4, and four from band 15.

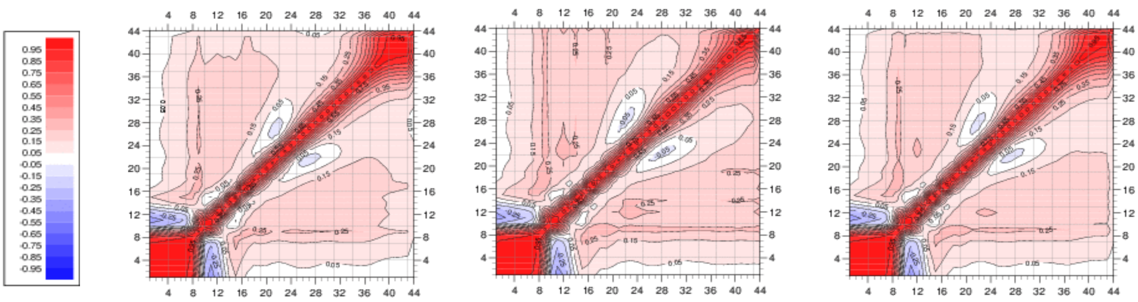
First validation tests were performed for 4 randomly chosen profiles over land. As it can be seen on fig.4 introducing the new SSE values for separated channels in wavebands improved the estimation of the brightness temperatures from the atmospheric state vector especially for band 15. The integer values of x axis from 2 to 9 correspond respectively to AIRS channels: 587, 672, 787, 791 (merged bands 3 and 4) and 1865, 1866, 1867, 1868 (band 15). Further tests will be performed on a larger sample of profiles.

IV. Background error statistics

To retrieve and assimilate the very fine spectral resolution measurements from advanced IR sounders (IASI/AIRS) we need to have the ancillary information (background) which specifies the behaviour of the variables or constitutes some a-priori constraints. In order to estimate the quality of the background information one need to compute the background error covariance, called B matrix. This matrix is one of the most important elements of the data assimilation system - it determines the filtering and the propagation of the observed information. We were estimating the B matrices for temperature profile with LST and for emissivity. The details are described below.

Temperature

As a background (first guess) for temperature we use the 6h forecast from the ARPEGE (cy22t1) model, and to estimate the background errors with Ensemble method we made gridpoint calculations. It means that the ensemble of forecasts was projected onto ARPEGE gridpoint space (truncation T199) and interpolated onto 43 RT-IASI levels. The final ensemble is composed of 10 independent 3d-var analysis experiments for the month of May 2001. For consecutively numbered members were calculated the differences between the background fields for each 6h cycle from 5th to 30th of May 2001, so the statistics were based on 234 background differences.



Correlations for T over LAND correlations for T over SEA global correlations for T

Fig.5 Correlations for T for 43 RTTOV levels + surface skin temperature, for different areas (based on ARPEGE grid).

From them we calculated the background error covariances, separately averaged over gridpoints of land, sea and globally. The vertical correlations between all levels derived from the obtained matrices are shown on the Figure 5. The surface is the 44th level.

The correlations for high atmosphere levels do not look realistic, the reason for that is the extrapolation from 31 ARPEGE levels to 43 in the radiative transfer (RT) model. In the stratosphere RT has 14 levels and ARPEGE only 3, next 15 RT levels (stratosphere and upper troposphere) correspond to 12 in the forecast model. Just for the lower troposphere (below 500 hPa) an equivalent spanning of levels between ARPEGE and RT-IASI is satisfactory: 16 model levels refer to 14 of RT.

The global B matrix generally used in RT-IASI was calculated at ECMWF (J.-N. Thepaut), also using the Ensemble method, but the interpolation to 43 RT-IASI levels was from 60 levels in the IFS model, which allow a better description of the high atmosphere. Because none of the B matrices is experimental and we wanted to keep the land surface characteristics and remove "noise" from the top of the atmosphere, we decided to mix both matrices - the present one for land and the ECMWF one. A "transition matrix" combining them was used.

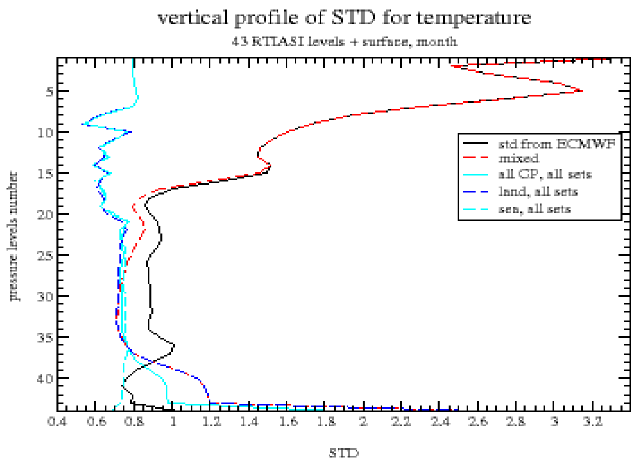
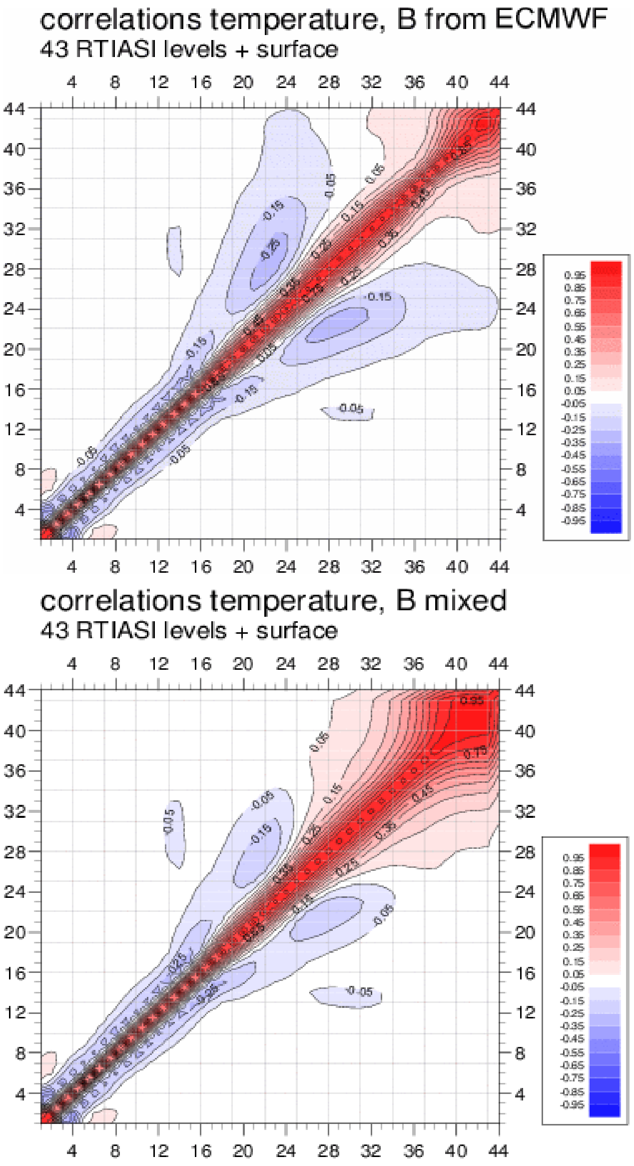


Fig.7 Vertical profiles of STD for temperature. 43 RTTOV levels + surface.



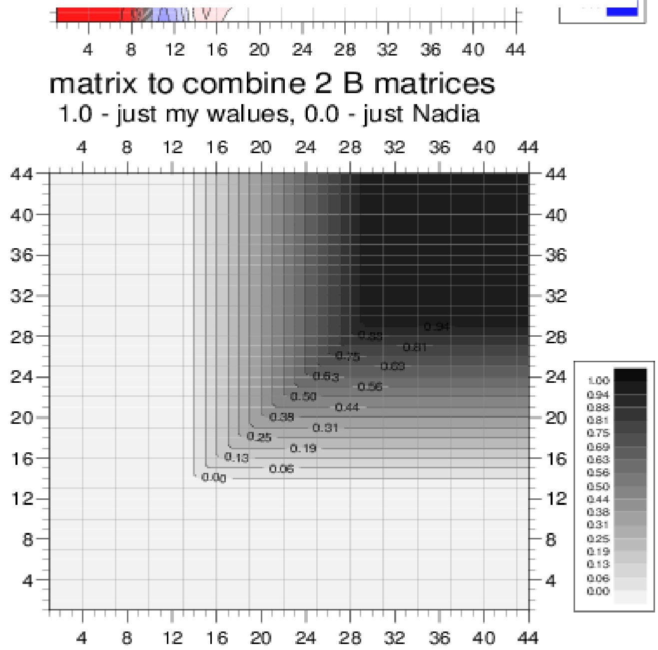


Fig.6 Creation of the final B matrix for land. The ECMWF B matrix was actually the matrix calculated by J-N Thepaut.

For the first 14 RT levels it keeps just the ECMWF covariance, above the 29th level just mine, and in-between a mixture of both matrices, with a linearly growing ratio (with a step of 6.25\%). The original matrices, the transition matrix and the final one are shown on Figure 6. Created in such a way, the matrix is non singular, and 1d-var tests with this matrix have given positive results.

Also to give idea about the values of calculated covariance, Figure 7 presents vertical profiles of standard deviations (STD, square-root of B diagonal) for temperature.
In blue are gridpoint calculated values : dark blue corresponds to the values for the land and dashed light blue to the sea ones. Black curve is the ECMWF temperature standard profile and in dashed red is the profile derived from "combined" matrix.

Emissivity

As it was mentioned before the estimation of the emissivity covariance matrices has been based on 5 ARPEGE land cover types as there has not been enough emissivity spectra samples to built separate background error covariance (B) matrices for each of new 14 types. Emissivity data (laboratory measurements) were taken from the MODIS and ASTER spectral libraries. We obtained from there : 5 sea-water samples, 9 samples of ice and snow, 128 samples of different kinds of soils, 24 samples of high vegetation (trees) and 5 samples of low vegetation. "Sample" means the infrared emissivity spectrum of some plant or material (range: 600-3000 cm^{-1}).

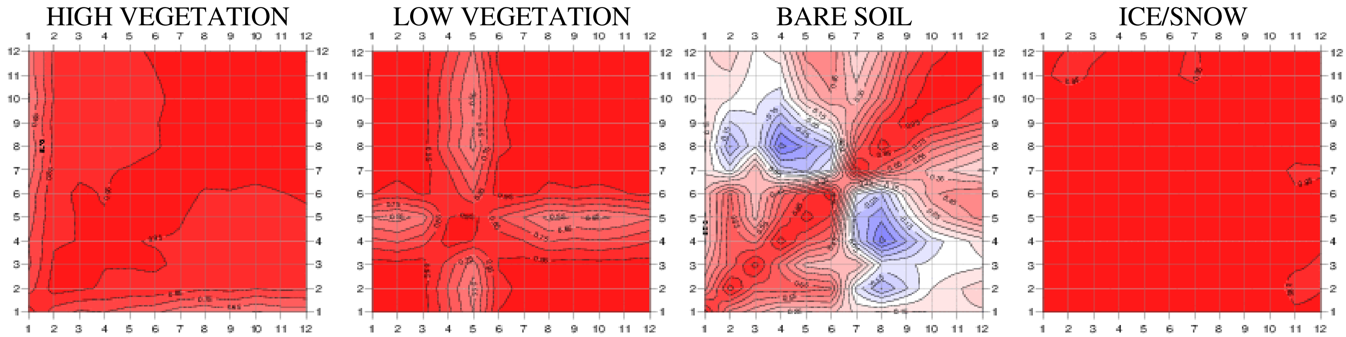


Fig.8 Correlations of SSE for 12 spectral wavebands, separate for each land cover type.

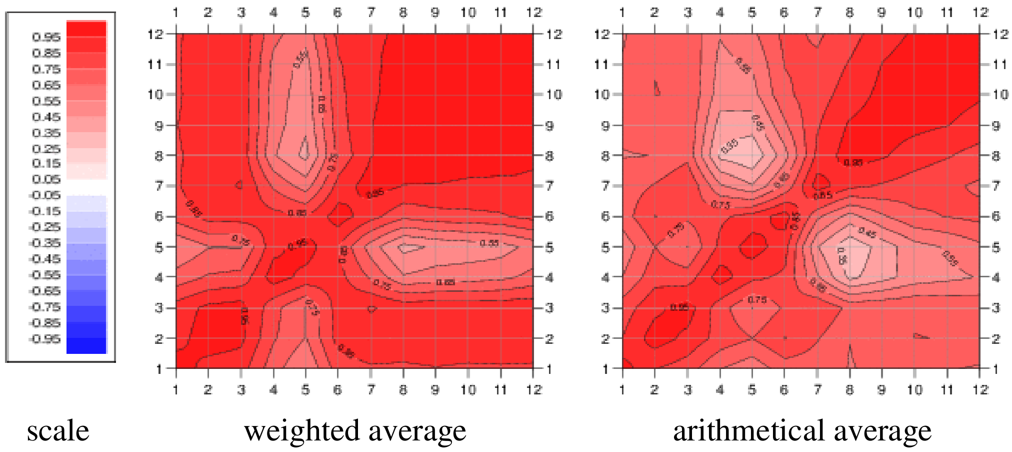


Fig.9 Global correlations derived from covariances averaged over all land cover types.

Unfortunately samples do not have the same spectral resolution, so instead of interpolating all spectra to the same resolution and then calculating statistics, we decided to estimate first the mean emissivity value per waveband and per sample, and average them for each land cover type. Next, in each waveband we calculated the differences for each land type, and afterwards emissivity covariances for all 12 "previous" bands. Calculation of statistics were done for -log(1-SSE). On the figures below are correlations for separated land cover types (Fig. 8), and global ones (Fig. 9) created with and without respect to the percentage of each land type at the global scale.

SSE of high vegetation and ice show very strong correlations between all wavebands. It is caused by the low variability of their spectra with wavenumber. The exactly opposite case is for bare soil emissivity and partially for low vegetation. For bare soil, surface spectral emissivity can change from 0.77 to 1.0 in IR IASI range (645-2760cm^{-1}); for low vegetation it can change from 0.88 to 0.98. The weights (percentage of the globe covered by each surface type) were taken from the ARPEGE grid : sea water - 53.4%, ice/snow - 1.4%, high vegetation - 13.5%, low vegetation - 29.2% and bare soil – 2.5%.

IV. Perspectives

Summarizing, the new emissivity maps based on the Ecoclimap are consistent with MODIS SSE maps retrieved with the 'split-window' method for bands 31 and 32. Usage of the local surface spectral emissivity (the closest point to the position of profile) in radiative transfer model RTTOV-7 with HIRS 8 data have not clearly shown that the estimation of the brightness temperature from atmospheric profile were really improved with comparison to the default SSE value for RTTOV-7, but were usually better than with the emissivity currently used in ARPEGE. In the case of Tb simulated with ARPEGE SSE being the reference, the increase of the number of 'good' points while using the new surface emissivity reaches up to 25% globally for certain tested days.

Preliminary results for AIRS data showed that we could expect Tb values simulated in RTTOV-7 with new SSE closer to the measured ones. But the validation on more numerous sample of profiles is still required. Also the work on 1D-VAR (a scheme of 'one-dimentional variational analysis') must be continued on the inversion of radiances and emissivity retrieval. Up to that moment the introduction of spectral emissivity as a control variable have been applied and first tests performed. Additionaly for more advanced tests we do plan perform senstitivity studies with new background error covariances matrices, especially the one for T, with explicit correlations between Ts and atmospherical T.

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