Towards Improved Use of Infrared Sounding Data over Land

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1 Introduction

The prime objective of the forthcoming EOS-AIRS and MetOp-IASI instruments is to derive atmospheric temperature and constituent profiles globally including over the land and sea-ice surfaces for numerical weather prediction (NWP). These new instruments make measurements of the upwelling infrared (IR) radiance at high spectral resolution (< 0.5 cm^{-1}). To achieve the objectives of obtaining profiles over land the surface radiative skin temperature or land surface temperature (LST) has to be known to a target accuracy better than 0.5 K and surface spectral emissivity, ε_ν, (SSE) to an accuracy better than 0.01. These parameters can be retrieved from the IASI radiances themselves but an *a priori* knowledge of the surface properties is necessary for a retrieval of both LST and SSE.

Until recently the operational NWP centres have not used the TOVS radiances over land, with the exception of the stratospheric sounding channels, as the data void areas have only been over the oceans and sea-ice. However with the gradual reduction in the radiosonde network in some areas the need to assimilate satellite data over land has become more pressing in order to mitigate this loss of valuable upper air in-situ data. Both cloud-track winds and radiances are of value to constrain the wind and temperature fields respectively. Only the assimilation of radiances over land/ice will be addressed in this report.

Some experiments have been proposed in the framework of the IGOS upper air measurements project to remove all the radiosondes and then to see how well the satellite data can "recover" the lost information. Preliminary experiments over N. America suggested that the degradation of the forecast performance due to the reduction in radiosondes could be greatly lessened by using more satellite data over land. Observing system experiments by Kelly (1997) demonstrated that with 3D Var (and recently reconfirmed for 4D Var) the impact of the radiosondes on the N. Hemisphere tropospheric forecast scores dominates that from all other observation types. The small impact of satellite data over the N. Hemisphere is perhaps not surprising as most of the satellite data measuring the troposphere was not assimilated over land north of 20^{o}N.

In addition to the requirements of NWP radiance assimilation an accurate knowledge of the land and sea-ice surface temperature and emissivity is of importance for many applications including hydrology, calculation of surface fluxes, NWP and climate model surface fields and climate impact studies. The parameterisation of land surface processes in NWP models is becoming increasingly complex and will allow the radiative skin temperature measured by satellites to affect the bulk land surface parameters through models of the surface-air heat fluxes. Seasonal forecasting is a new emerging application where an accurate representation of the land surface properties with no biases is important to ensure realistic forecasts of temperature and precipitation anomalies months ahead.

Many of the issues discussed in this report for the thermal IR part of the spectrum are also common to the microwave (MW) but here as the emissivities are lower the effects are correspondingly greater on the MW radiances (e.g. from AMSU or MHS). The improvement in the representation of the IR surface emissivities needs to be developed in parallel with MW surface emissivity schemes. This report only considers the necessary steps required to make better use of the high resolution IR radiance measurements over land but the MW measurements are also valuable over land due to their lower sensitivity to clouds and so this is also an important area of research.

The plan of this report is as follows. Section 2 describes the framework for assimilating radiance data over land in a NWP model and outlines the requirements. Sections 3, 4 and 5 document the datasets currently available for land surface types and emissivity, the radiative transfer modelling of land surfaces, and the potential retrieval schemes for land surface temperature and emissivity, respectively. Finally, a list of recommendations for further work is given in Section 6.

2 Assimilation of infrared radiances over land

2.1 Formulation of variational assimilation for radiances

The assimilation of radiances or retrievals in a variational assimilation system (e.g.1DVar described by Eyre et al, 1993 or 4DVar described by Rabier et al, 1998a) relies on the minimisation of a cost function *J(x)* where *x* is the atmospheric state vector which represents all the model variables to be analysed. The term *J(x)* represents the degree of fit of *x* both to the observations, *y*, the model background fields x_b (normally from a short range forecast) and any other constraints given by J_c. This can be written as:

$$J(x) = \frac{1}{2}\left(x - x_b\right)^T B^{-1}\left(x - x_b\right) + \frac{1}{2}(y - H(x))^T (O + F)^{-1}(y - H(x)) + J_c \qquad \textbf{(1)}$$

where *H* is the observation operator which transforms the model variables into the appropriate observed variable (in this case radiance) and *y* is the observation vector (e.g. a set of radiances at different wavelengths). *H(x)* includes both the forward model and the spatial and temporal interpolation from the model fields to the observation location and time. *O* is the observation error covariance (including “representativeness” error), *F* is the forward model and interpolation error covariance and *B* is the background error covariance matrices. The superscripts ^{T} and $^{-1}$ denote the matrix transpose and the matrix inverse, respectively. The minimisation is performed to obtain an analysis of the atmospheric state *x* which has the best fit to the background field (first term on the right hand side (RHS) of Equation 1) and the observations (second term on the RHS of Equation 1) taking into account their relative errors. This results in the analysis drawing close to the observations if their errors are small compared to the background errors. Conversely in areas where the background errors are small (e.g. downstream of data dense areas), the observations do not have such a large influence on the resulting analysis. In order to perform the minimisation, the adjoint of the observation operator is required which allows the change in model variables to be computed for a given change in measurement space.

The above formulation holds regardless of the dimensions of *x* so that *x* can be 1-dimensional (e.g. an atmospheric profile), a 2-dimensional model field, a 3-dimensional field (e.g. all the model fields for one time) or 4-dimensional (e.g. model fields for several times). This has led to 1DVar methods for satellite temperature and constituent profile retrievals described in section 5 and by Eyre et. al. (1993). 3DVar systems have been developed for atmospheric data assimilation systems assuming all the observations are at the analysis time (Andersson et al, 1998). 4DVar systems (Thépaut and Courtier, 1991; Rabier et al, 1998b) allow an analysis to be obtained using data taking into account their range of observation times which enables more dynamically consistent analyses to be computed. Such a system is currently operational at the European Centre for Medium Range Weather Forecasts (ECMWF).

For the specific case of radiance assimilation, the first guess radiances from the model, *H(x)*, must be estimated using the interpolated first guess atmospheric temperature and constituent profiles, LST and SSE to compute values with a fast radiative transfer model (see Equation 2 below). These radiances are then compared with the measured radiances and the differences are minimised globally, taking account of all other observations, within the time window (for 4DVar) through modifying the model first guess fields using the adjoint of the observation operators. The first guess profiles from the atmospheric model fields have error characteristics that have been well characterised. However the model LST and SSE first guess values are to date less well characterised. In desert areas for example the radiative skin temperature of the model can be in error by greater than 10K around local noon as illustrated in Figure 1. In comparison over the sea the errors are less than 1 K. For sounding channels with a small sensitivity to the surface an error of surface temperature of 10 K can still lead to errors greater than 0.1 K, which is comparable to the signal we are looking for to adjust the atmospheric profile. To improve the assimilation of radiances the first guess values for LST and SSE need to be better characterised and should be more Gaussian in distribution as assumed in the variational context.

Accurate first guess radiances over land are not only required for assimilation of sounding channel radiances into the NWP analyses but also for quality control of the whole radiance vector at each observation point. If the surface sensing channel first guess and measured radiances are well outside the *a priori* error limits then there may be problems with the sounding channel radiances also due to undetected cloud contamination for example. It is important to identify these suspect soundings before they are assimilated and reject them. The next section describes the results of some preliminary experiments with TOVS to illustrate the potential benefits of assimilating radiances over land.

2.2 Experiments with TOVS

Recent experiments at ECMWF have demonstrated that medium range (3-7 days) forecasts can be improved over Europe if more of the HIRS channels are used over land as shown in Figure 2. In addition to the stratospheric channels those HIRS channels with only a small sensitivity to the surface were assimilated but with an inflated observation error to reflect the uncertainties in the radiance simulation over land as defined in Table 1. These results suggest there are real benefits to extend the assimilation of TOVS radiances as far as possible over land to improve N. Hemisphere forecasts. Over the S. Hemisphere the improvements are smaller but the increased use of radiance data over the Antarctic landmass and the surrounding sea-ice will potentially contribute to improved analyses and forecasts. The mean differences between the analyses with the additional channels and those without are shown in Figure 3 for the N. Hemisphere.

Further experiments to use more of the TOVS channels which sense more of the surface were unsuccessful due to the first guess surface properties not being close enough to the “truth” as seen by the TOVS window channel radiances as illustrated in Figure 1. Around local noon the retrieved minus model first guess differences can be greater than 10 K.

When the model has a better representation of the surface types and skin temperature it may become possible to use more channels over land.

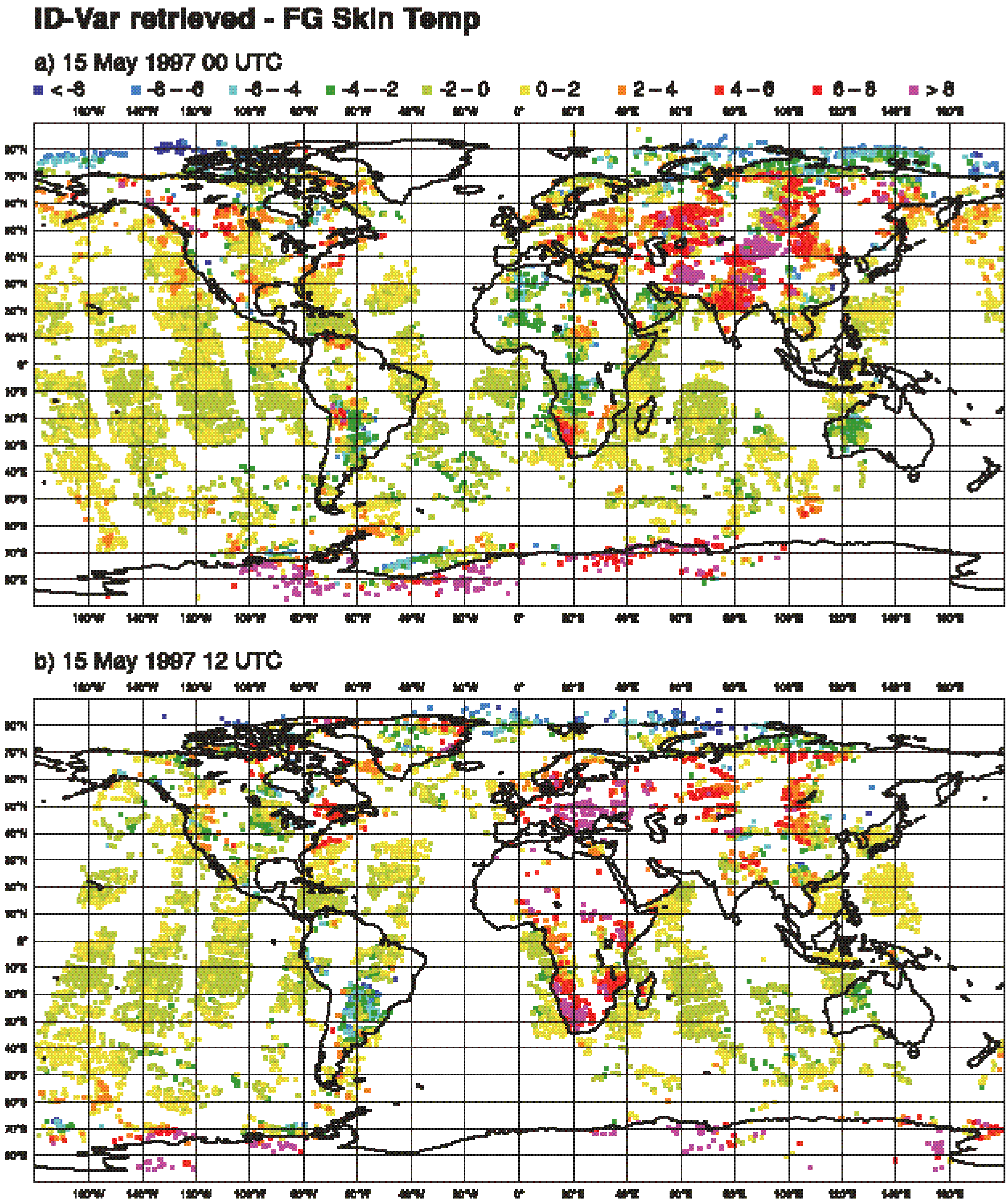

Figure 1. The difference between the retrieved and first guess retrieved radiative surface skin temperatures from 1DVar for two analyses 12 hours apart.

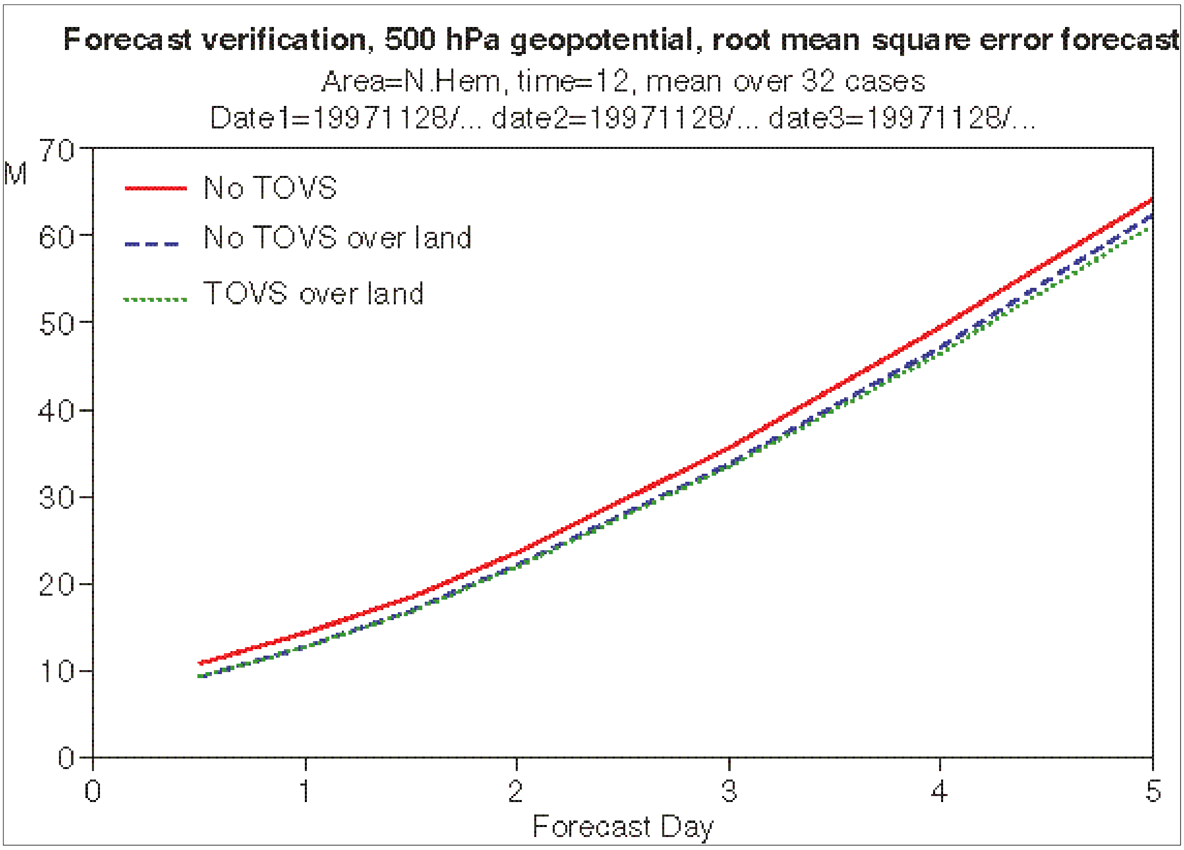

Figure 2. Average of 30 days of forecasts over the N. Hemisphere with no TOVS radiances (solid line), with TOVS radiances over sea and sea-ice and stratospheric channels everywhere (dashed line) and with TOVS upper tropospheric channels as defined in Table 1 used over land (dotted line).

Channel Number	**4DVAR data usage**	**Clear (^{o}K)**	**Cloudy (^{o}K)**	**Sea-ice (^{o}K)**	**Land (^{o}K)**
1	All	1.40	1.40	1.40	1.40
2	All	0.35	0.35	0.35	0.35
3	All	0.30	0.30	0.30	0.30
4	Clear only	0.20	-	0.20	*0.20*
5	Clear only	0.30	-	0.30	*0.30*
6	Clear only	0.40	-	0.80	*0.80*
7	Clear only	0.60	-	1.20	-
8	*Clear only*	*1.00*	-	*2.00*	-
9	-	-	-	-	-
10	Clear only	0.80	-	1.60	-
11	Clear only	1.10	-	1.10	*1.10*
12	Clear only	1.50	-	1.50	1.50
13	Clear only	0.50	-	1.00	-
14	Clear only	0.35	-	0.70	-
15	Clear only	0.30	-	0.60	-
16	FG only	-	-	-	-
17	FG only	-	-	-	-
18	FG only	-	-	-	-
19	FG only	-	-	-	-
21	QC check	-	-	-	-
22	All*	0.30	0.30	1.00	-
23	All*	0.22	0.22	0.22	*0.22*
24	All	0.25	0.25	0.25	0.25
25	All	0.60	0.60	0.60	0.60
26	All	1.00	1.00	1.00	1.00
27	All	1.80	1.80	1.80	1.80

* Only clear radiances used for latitudes $< 30^{o}$

Table 1. TOVS observation errors (O+F) assigned in 1DVAR at ECMWF. The errors used in 4DVar are 1.5 times these values. Figures in italics are the extension to the use of radiances over land.

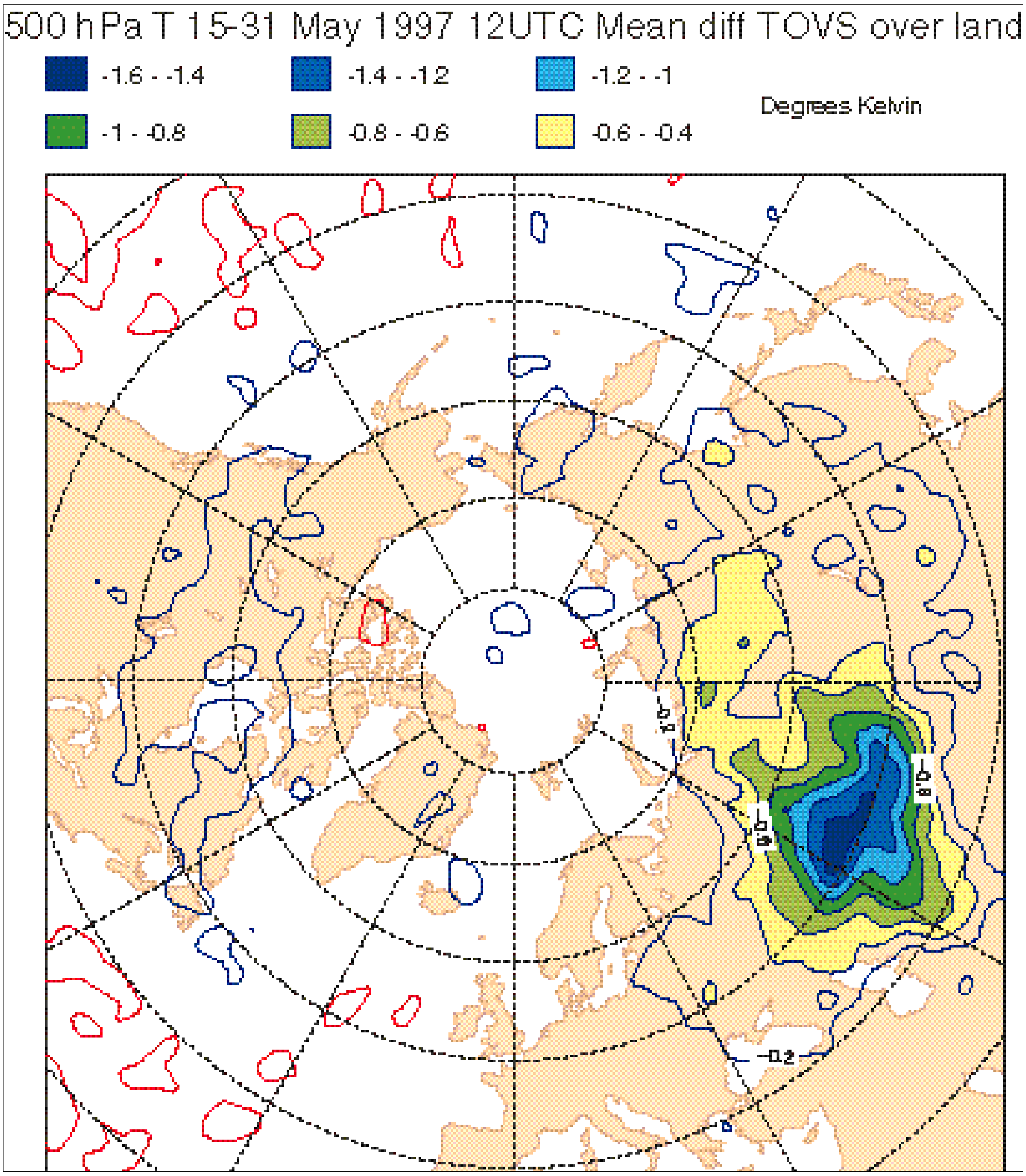

Figure 3. Mean difference for period 15-31 May 1998 for 500hPa temperature between analyses with extra TOVS channels over land and those with only stratospheric channels used.

3 Datasets of land surface type and emissivities

3.1 Land surface types

There are several detailed datasets of land use and land cover that have been produced by the US Geological Survey for several decades but these are too detailed for the purposes of parameterising land surface emissivity for global NWP.

The NASA EOS/MODIS research programme is promoting studies into LST retrieval algorithms and, as a result, one of their activities is to formulate a set of surface radiative models for different surface types as outlined by Snyder et al. (1998) which is an excellent reference paper for surface emissivity datasets and the modelling issues. This project together with the International Geosphere-Biosphere Program (IGBP) has defined fourteen different emissivity classes listed in Table 2. The global coverage of some of the classes is listed in Table 3. Each class combines other distinct biospheric surface types into one class. The emissivity model developed by Snyder et al. (1998) is then applied to each class to generate a range of emissivity spectra for each class. This range is generated by varying the many factors which affect the emissivity for example the viewing angle, water content, chemical composition, structure and roughness, vegetation density and growth state. This allows one to estimate the mean, maximum and minimum surface emissivities at each wavelength for each of the 14 classes. The viewing angle and soil moisture (based on the recent precipitation) are variables that NWP models can represent but many of the other factors will have to remain parameterised. An example of the spectra for 2 different classes (bare soil and ice/snow) is shown in Figure 4. If a NWP model includes these classes as a surface field then this kind of information can provide a valuable first guess emissivity and associated error for a SSE retrieval and radiance assimilation.

More research needs to be carried out to better define the individual classes, their geographical location and temporal variations. This should include use of MODIS data to define the geographical coverage and investigate variations with viewing angle, etc. Also consideration should be given as to whether the 14 classes defined in Table 2 are also appropriate for the MW surface emissivity. Snow and ice for instance have different signatures in the MW.

Emissivity class	**IGBP classes**
Gr Ndle Forest	Evgrn Ndle Forest, Gr Dcd Ndle Forest
Sn Ndle Forest	Sn Ded Ndle Forest Evgrn Bdlf Forest, Gr Dcd Bdlf Forest
Gr Bdlf Forest	Gr Mixed Trees and Shrubs
Sn Bdlf Forest	Sn Ded Bdlf Forest, Sn Mixed Trees and Shrubs
Gr Woody Savanna	Gr Woody Savannas, Gr Crop Tree Mosaic, Growing Bdlf Crops
Sn Woody Savanna	Sn Woody Savannas, Sn Crop Tree Mosaic
Gr Grass Savanna	Gr Savannas, Gr Grasslands, Gr Dense Shrublands Growing Grass Crops, Gr Crop Grass Mosaic
Sn Grass Savanna	Sn Savannas, Sn Grasslands, Sn Dense Shrublands, Sn Crop Grass Mosaic
Gr Sparse Shrubs	Gr Sparse Shrublands
Sn Sparse Shrubs	Sn Sparse Shrublands
Water	Wetlands, Water Bodies
Organic Bare Soil Arid Bare Soil	Organic Bare Soils, Idle Bdllf Crops, Idle Grass Crops Arid Bare Soil, Rocks
Snow, Ice	Snow, Ice

Key:

Ndle	Needle
Bdlf	Broadleaf
Evgrn	Evergreen
Gr	Green
Sn	Senescent
Dcd	Deciduous

Table 2. Fourteen proposed emissivity classes and the corresponding IGPB classes and states

ISLSCP land cover type	Global yearly coverage
Ice and snow	10%
Grasslands	17%
Shrubs, Desert, and Bare Soil	20%
Broadleaf and Mixed Forest	17%
Tundra and Cultivated land	20%
Coniferous Forest	16%

Table 3. Percentage annual coverage of each of six cover types for the ISLSCP classification system and monthly snow cover data. If any non-snow class had an average snow depth of more than 5 cm for a month it was counted as snow. Although these classes do not coincide with the IGBP classes, the table shows that only 20% of the globe-year is the bare soil classes with the most variable emissivity. Not included in this table are sea and inland water.

3.2 Surface emissivities

Experimental data on SSE is not widely available from the literature. One of the most comprehensive datasets (Salisbury and D'Aria, 1992, 1994; Salisbury *et al.* 1994) relates to about 80 samples of soils, rocks, different vegetation types and snow/ice within the 2-14 μm spectral range with a resolution about 2 cm^{-1}. Information on the spectral and angular dependence of SSE can also be found in Takashima (1988), Labed (1990), Labed and Stoll, (1991), Nerry *et al*., (1988) and Kannari (1990). Nevertheless, as explained by many authors, the emissivity spectral measurements for all natural surfaces (within the spectral ranges covering atmospheric windows) remains incomplete.

One potentially useful area of research concerns understanding the relationship between emissivity and some vegetation parameters (e.g. NDVI, Van de Griend and Owe, 1993). Based upon these analyses it is possible that the modelling of SSE using relevant databases as a first guess background can be performed.

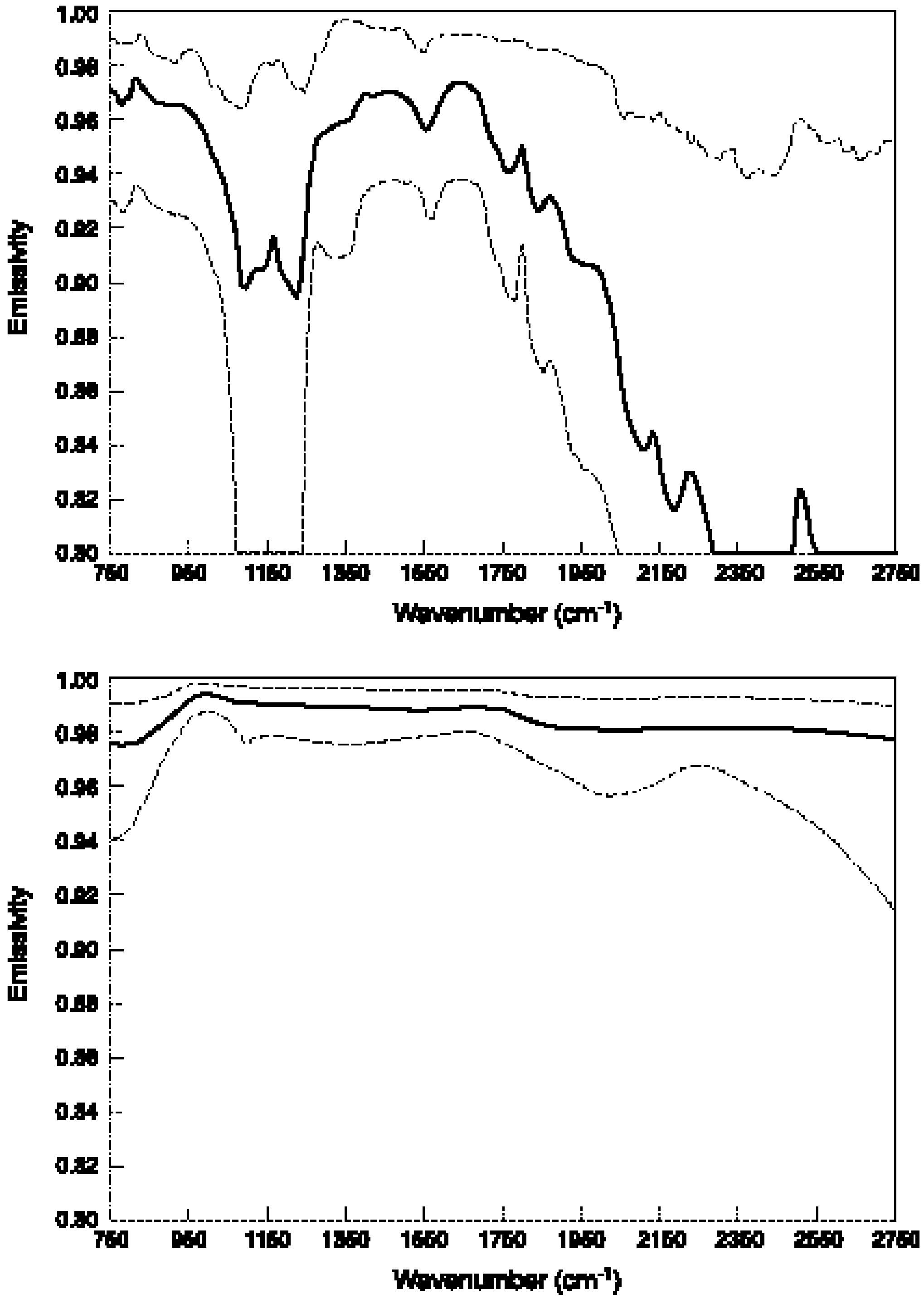

Figure 4. Mean spectral emissivity and max/min limits for arid bare soil (top panel) and for ice and snow (lower panel) from Snyder et. al. (1998).

4 Radiative properties of land surfaces

Firstly, it is important to emphasise the definition of the land surface properties is inherently difficult to represent since what is sensed by satellite does not necessarily correspond to the *in-situ* or laboratory measurements. In addition, for a surface with a varying orography, even the concept of an *average* skin temperature may be meaningless. However, with the assumption of a uniform surface and a plane parallel atmosphere in local thermodynamic equilibrium, the atmospheric radiative transfer equation can be written as:

$$\mathrm{R}(n,q) = e_s(n,q)\, t_z(n,q) B(n,T_s) + \int_z^{+\infty} B(n,T(h)) \frac{\P t(n,h,q)}{\P h} dh + \Omega_s(n,q) t_z(n,q) R\downarrow(n,q) \quad \textbf{(2)}$$

where *R(n,q)* denotes spectral radiance, *B* denotes the Planck function, *h* the altitude variable, ν the wavenumber and *t(n,h,q)* is the transmittance from level *h* to space at incidence angle θ and t_z the total transmittance from ground level at a height *z* to space. The spectral surface emissivity, $e_s(n,q)$, and the skin temperature, T_s for a surface at a height *z* are the surface parameters which must be specified in order to compute a top of atmosphere radiance *R*(ν,θ). The surface to space transmittance $t_z(n,q)$ and layer transmittance *t(n,h,q)* must also be known. *R*↓(ν,θ) is the downwelling atmospheric radiance at the surface and Ω_s(ν,θ) is the combination of the specular and diffuse surface reflectance called the hemispherical reflectance.

For IASI, the first and third terms on the RHS of equation 2 are negligible for the regions of the spectra used for sounding where the atmosphere is opaque. They become significant in the "window" regions of the spectra (i.e.. 10-12 μm and 3.7 μm) where estimates of $e_s(n,q)$, T_s and Ω_s(ν,θ) are required as these terms dominate over the second term. The estimation of t_z , *t(h)* and *R*↓(ν,θ) can all be made using a fast radiative transfer model such as the RTIASI model developed at ECMWF.

The relationship between $e_s(n,q)$ and Ω_s(ν,θ) can be given by:

$$\Omega_s(n,q) = (1 - e_s(n,q)) + \Omega^{diff}(n,q) \qquad \textbf{(3)}$$

where the first term on the RHS of equation 3 is the specular reflectance and Ω^{diff}(ν,θ) the diffuse reflectance.

Section 3 describes some possible sources of date to define the likely range of $e_s(n,q)$, and Ω^{diff}(ν,θ) which can be used in equation 2 and 3 depending on the surface type. If the assumption is made that the diffuse reflectance can be neglected relative to the specular reflectance then one can simply show the sensitivity of each of the HIRS surface sensing channels to surface emissivity. This depends on the atmospheric profile and incidence angle to define the magnitude of the downwelling surface radiance *R*↓(ν,θ).

Results using the RTTOV RT model show for a 5% change to the surface emissivity the effect on the HIRS channel radiances is shown in Table 4. This clearly shows the lower sensitivity of the radiances to the surface for tropical profiles due to the higher water vapour absorption. The difference between profiles is less for the higher frequency window channel (2200 cm^{-1}). To date the operational radiative transfer models which include surface effects have assumed specular reflection only but more sophisticated models are necessary especially for the MW.

HIRS channel number	**Centre (cm^{-1})**	**Tropical (^oK)**	**Arctic (^oK)**
5	714	0.00	0.02
6	732	0.01	0.14
7	750	0.07	0.92
8	899	1.19	2.28
10	796	0.39	1.26
11	1361	0.00	0.07
12	1481	0.00	0.00
13	2191	0.34	0.25
14	2207	0.13	0.03
15	2236	0.03	0.00

Table 4. Response of HIRS brightness temperatures to change in surface emissivity of 5% for two atmopsheric profiles.

5 Retrieval of land surface parameters

5.1 Introduction

This section considers the methods of the LST and SSE retrieval from high resolution IR radiance measurements. The physical retrieval methods described make use of IASI data in a set of channels (micro-windows) and are based on the following concepts:

1. Utilisation of the split window type technique for a removal of the atmospheric attenuation effect

2. Retrieval of LST and SSE from the IASI data using *a priori* data on SSE and LST data

3. Retrieval of SSE using constraints for individual channels based on IASI measurements and emissivity modelling data

The issues summarised in the following sections are:

a) The concise description of existing methodology for the retrieval of the LST and SSE from thermal IR multi-spectral radiance data available from current space borne IR imagers or sounders such as AVHRR, ATSR, HIRS2, etc.

b) The preliminary analysis and assessment of the potential of IASI data to retrieve the LST and SSE

c) The identification of the critical areas and problems regarding the development and implementation of efficient schemes for the LST and SSE retrieval from cloud free IASI data (stand alone and/or combined with information from other sources).

5.2 Outline of existing retrieval methods and problems

5.2.1 Split window methods

The prospect of extracting the LST and SSE information from thermal IR multi-channel radiance measurements in the window spectral range has been a subject of numerous investigations during the last decade, see for example comprehensive reviews in (Becker&Li, 1995; Prata et al, 1995). In the majority of the studies the various versions of the well-known SWM have been used for LST retrieval from NOAA AVHRR data. Let us consider in more detail the background of this approach and its validity with regard to the LST derivation.

The measurements of the outgoing IR radiances in the atmospheric windows at 3.7 μm and 10.5-12.5 μm available from the HIRS/2 and AVHRR instruments on board the NOAA satellites provide a tool for a retrieval of the surface temperature (ST) data. The cloud-free IR brightness temperatures are converted to the surface brightness temperatures through removal of the atmospheric radiance attenuation effects, caused by the absorption of the water vapour and other gaseous constituents. If the AVHRR data are available, then the SWM is commonly used to retrieve the ST. The SWM employs the linear combination of the brightness temperatures measured in the AVHRR IR channels 3, 4 and 5. The basis for the split window technique or its extension (like a multi-channel approach for ST determination) is the difference in atmospheric attenuation for the channels used. The SWM gives accurate results over the sea surface for the retrieval of sea surface temperature (SST), see for example Uspensky and Soloviev (1998) and Barton (1995). This is due to the fact that the SST is homogeneous over large areas and close to the air temperature, T_a, near the surface and that the emissivity of the sea surface is constant over large areas and close to unity.

This is not the case for the land surface. Firstly, the spatial and temporal variations of the LST are more pronounced than those for the SST and the LST may not be close to T_a. Secondly, the land SSE is generally less than unity over the 10.5 - 12.5 μm range. It depends on the surface soil characteristics, vegetation state and therefore varies both spatially and temporally.

The calculations of the AVHRR data information content with respect to LST in Uspensky and Sutovsky (1991) demonstrate that it is possible to produce reliable LST estimates over homogeneous areas provided the SSE values in spectral bands of the AVHRR channels 4 and 5 are known accurately. In particular one can estimate LST with a standard deviation better than 1 K if the SSE values are known with an accuracy better than 0.01. These requirements regarding the accuracy of the SSE are similar to those reported in Becker and Li (1990a). The algorithms for the LST estimation from the measurements in the AVHRR channels 4 and 5 are the standard SWM algorithms, but the coefficients used are of "local" nature, i.e. dependent upon the local values of SSE . Various versions of SWM algorithms and the results of their verification can be found in Caselles *et al*. (1997) Li and Becker (1993) and Sobrino *et al*. (1991, 1994, 1996).

The comparisons between the LST estimates derived from AVHRR data and collocated ground based observations have resulted in the values of RMS differences within 2 - 4 K for different samples (Uspensky, Sutovsky,1991; Becker, 1995). A similar level of accuracy is realised for the LST estimates derived from TOVS (HIRS/2) data although cloud detection is more difficult for HIRS. An obvious way to improve the reliability of the LST retrievals is to determine the SSEs at the sounding point with adequate accuracy. The issue is how to extract information on SSE: from IASI data alone and/or getting some information from emissivity models.

5.2.2 Physical retrievals

Another approach for temperature and constituent profile retrieval or radiance assimilation is to retrieve an effective emissivity value of the product εT_s, where the effective emissivity is assumed to be a constant over the spectral range considered. According to this pragmatic definition of effective emissivity and skin temperature, this allows vertical profiles to be derived which are consistent with the observations. However, once temperature and water vapour profiles have been retrieved, we can turn our attention to a larger portion of the window region (e.g. 800-900 cm^{-1}) and try to discriminate between the two terms separately i.e. emissivity and skin temperature through the spectral dependence of ε. Linearising the radiative transfer equation with respect to emissivity and skin temperature, we have:

$$R(n,q) = R_g(n,q) + t_z B(n,T_{gs})(e(n,q) - e_g(n,q)) + t_z e_g(n,q)\frac{\partial B}{\partial T}\Big|_{T=T_{gs}}(T_s - T_{gs}) \qquad \textbf{(4)}$$

where T_{gs}, e_g are guess values for skin temperature and emissivity (the index *g* indicates first guess values). In principle, the linearised equation above may form the basis for a retrieval scheme for an effective emissivity and an effective skin temperature, in the sense that they fit the observations. However, the simple use of the above equation may give unphysical results for the emissivity (greater than one, or less than zero). In addition, the Jacobian coefficients in the above equation may coincide with an error term because they depend mostly on the wavenumber through the Planck function and this is a smooth dependence. The consequence is an extremely ill-posed inverse problem. This problem may be only partly alleviated by considering a very large interval for ν. With this in mind. a possible retrieval strategy is to restrict the analysis to a few values of the spectral emissivity, i.e. to divide the spectral interval into 4 to 5 bins, and assume a constant emissivity for each bin. Afterwards, an iterative, constrained inversion could be performed where the constraint of emissivity between 0 and 1 is explicitly taken into account. In practice, the constrained inversion could be performed using a Landweber approach which has been proven to be particularly efficient for severely ill-posed problems.

This scheme could be particularly suited for IASI, since first guess information for skin temperature, temperature and water vapour profiles needed for the calculation of the transmittance function may be derived by IASI radiances in different spectral ranges. Note that the problem is linear for the emissivity, so that a rough first guess for ε should be enough.

However, while this procedure is realistic for the estimation of sea surface temperature, its validity for land surfaces has to be verified. It is not yet clear if, by feeding back the inversion for water vapour and temperature profiles with this new effective emissivity and skin temperature, we may improve the accuracy of the final products.

Using TOVS data it is possible to derive the LST/SSE estimates within the framework of general meteorological parameter assimilation where a first guess is available from a forecast model (e.g. TOVS 1DVar retrieval). Referring to Equation 1, if the vector *x* is a 1-

dimensional single atmospheric profile including surface parameters then x_b will be the model first guess profile and surface variables and $H(x)$ is the radiative transfer model. y in this case is the vector of TOVS radiances for one observation point. The minimisation is then performed to adjust the background profile, x_b, to give the optimal fit to the radiances taking into account the respective error covariances of the background profile and radiance measurements plus forward model. The important parameters for the retrieval of surface parameters are the background errors related to the surface temperature and emissivities and their correlations with the atmospheric profile variables. The1DVar retrieval of radiative surface skin temperature assuming a value of unity for the SSE is performed operationally in the ECMWF assimilation to provide a more accurate estimate of the radiative skin temperature for the 4DVar assimilation.

5.2.3 Summary

To summarise the problems concerning the LST and SSE retrievals in the context of the development of future methods the following factors should be taken into account:

- Non-blackness of the land surface, i.e. the SSE may be substantially lower than unity and may be imperfectly known for many generic surfaces; in addition, the SSE values generally have large spectral and spatial variations (due to the inhomogeneities of natural surfaces); to derive LST to the required accuracy one needs to have an accurate knowledge of SSE.

- The LST has a large spatial variability (it varies over small areas in particular, such as within a IASI pixel) which leads to the necessity of defining a relationship between the satellite-derived (i.e. pixel-averaged) estimates and *in situ* point LST observations for validation purposes.

- The difference between the LST and air temperature near the surface (screen temperature at 2m height) may be significant.

- The surface upwelling radiance at the TOA is determined by both LST and SSE as well as by atmospheric attenuation. Even though the atmospheric attenuation can be effectively removed from the measurements it is not possible to separately derive the LST and the SSE from passive IR multi-channel radiance data without incorporation of the ancillary information on the SSE because the number of unknowns always exceeds the number of measurements.

- The coupling between the LST and SSE effects complicates the separate derivation of desired quantities from the satellite measurements under consideration.

5.3 Derivation of LST and SSE from IASI data

It has been demonstrated by many authors that the use of the AVHRR data alone coupled with the algorithms similar to the SWM provides for the LST retrieval an RMS accuracy no better than 2 to 4 K. The principal source of gross retrieval errors is the non-blackness of the surface and insufficient knowledge on the SSE. According to theoretical estimates the errors in SSE knowledge of the order of 0.01 may result in the retrieval errors as large as about 2 K. Addition of *a priori* information on SSE leads to an improvement of LST retrieval accuracy. New prospects are arising from the forthcoming high spectral resolution IR measurements like IASI and AIRS. Considering the benefits of using the IASI radiances, the LST retrieval can be considered as solving two unkowns:

- The elimination of atmospheric attenuation effects from the measurements within the spectral window regions

- The correction for non-unit emissivity effects by separating the coupled LST and SSE input in the measurements

The correction for the atmospheric attenuation effects can be performed more accurately using a set of measurements within a considerable number of the temperature and humidity sounding channels. This provides the information required to take these effects into account. The second correction concerns the availability of a large number of relatively "transparent" channels which may be combined with *a priori* information on the SSE (in the form of constraints) which facilitates the evaluation of LST and SSE. It should be performed by separating the LST and SSE effects in the measurements.

As the problem of simultaneous retrieval of the LST and SSE from the IASI data is always ill-posed we need to incorporate ancillary information on the SSE into the retrieval algorithms and as a result to remove the uncertainty in the solution of the inverse problem. Such information may comprise the specification of the relative or absolute values for the emissivity in individual spectral channels (Kahle and Alley, 1992), as well as the admission of the hypothesis that the emissivity does not change in several adjacent channels or in two different time frames (Watson, 1992). Several methodologies have been proposed for mapping the SSE from satellite data (mainly with regard to AVHRR measurements). Some of them utilise special temperature independent spectral indices such as TISI (Becker and Li, 1990; Uspensky, 1992) and the alpha-residuals (Kealy and Hook, 1993) extracted from the original satellite measurements (the last are derived from the satellite data using Wien's approximation of Planck's law, i.e. they are not accurate enough for the IR longwave range). According to validations with real AVHRR data (Li and Becker, 1993; Uspensky and Scherbina, 1993, 1998) the application of the technique similar to the TISI analysis enables one to estimate the SSE values for AVHRR window channels and then to employ the local SWM for LST derivation. It should be noted that the implementation of the methods described revealed some problems, especially the insufficient robustness of the algorithms and physical reliability of retrieved SSE. Some other approaches worthy of mention are based on empirical relationships between the emissivity and vegetation index such as NDVI (Van de Grierd and Owe, 1993; Valor and Caselles, 1996; Caselles et al, 1997; Romanov and Gutman, 1997). In the studies by Valor and Caselles (1996) and Caselles *et al.* (1997) some shortcomings of the above approaches were identified: the complexity of the algorithms makes them difficult to use in an operational way; the "local" nature of relations used and the different spatial resolution of data involved and the increase of retrieval errors when the model approximations are not sufficiently valid.

As a summary of the above results, the following conclusions and recommendations can be drawn:

1) The models and approaches described (proposed mainly for the AVHRR data) enable useful ancillary information for the SSE to be obtained (such as *a priori* specification of the SSE values or some quantitative constraints), which may be rather effectively incorporated into the SSE retrieval algorithms, and thus (in spite of the shortcomings) to positively influence the accuracy of the LST retrieval.

2) An attempt to expand some of these approaches with application to IASI data inversion procedures (in order to improve the feasibility of the retrieval products) seems reasonable. There are good reasons to believe that the incorporation of the constraints extracted from the IASI-derived indices like TISI may lead to the regularization of the original inverse problem and hence to the LST accuracy improvement.

Two basic approaches can be distinguished among different options for the LST and SSE indirect measurement: a joint (simultaneous) retrieval of the atmospheric and surface parameters based upon the solution of multi-component inverse problem (Timofeev et al, 1997) which is equivalent to a 1DVar type of retrieval (see above) and the physical multi-spectral window method similar to (Nalli and Smith, 1997; Trotsenko et al, 1998). The essential component of both methodologies consists of the incorporation of the ancillary information which specifies the SSE behavior or constitutes some a priori constraints. In this context it seems fruitful to start from the approach reported in (Timofeev et al, 1997), which utilises the optimal parametric presentation for the SSE (i.e. its correspondent decomposition using an empirical orthogonal basis formed by the eigenvectors of the *a priori* covariance matrix for the emissivity).

Preliminary results for the second strategy (Trotsenko et. al. 1998) can be concisely summarised as follows:

1. The retrieval algorithm exploits the information in a set of pre-selected transparent channels (micro-windows) and must provide the correction for atmospheric attenuation and for non-blackness of the surface. The efficiency of the first correction crucially depends on the selection of the appropriate set of channels. The goal of such a selection is to design a retrieval algorithm similar to the split window technique and as a result to provide maximum insensitivity to the knowledge of the atmospheric water vapour and temperature profiles required for the atmosphere attenuation assessment.

2. The second kind of correction implies the incorporation of ancillary information on the emissivity "spectra" into the retrieval algorithms. It is important to note that our intention is to minimise the use of ancillary or *a priori* information on SSE (both in the form of SSE specification for several spectral channels or in the form of simplifying assumptions as well as quantitative constraints). Therefore it is desirable to seek the retrieval method which would be based on the use of some additional relationships between emissivities in different spectral regions directly extracted from the satellite measurements involved (for example, the emissivity ratio in two contiguous channels related to the radiance ratio or special indices like TISI, etc.).

3. The modelling of the SSE behaviour for the spectral regions of interest and for generic surfaces is of vital importance for this work. Being of fundamental importance for many applications the emissivity spectra modelling constitutes a complicated task. The relevant SSE models have to be based upon theoretical modelling and observed emissivity spectra (obtained either from field experiments or from laboratory measurements) as outlined in Section 3.

6 Further work

A list of suggestions for further work are given below to enable improved use of IR radiances over land:

(a) Derive an updated land surface classification database for IR (and MW) emissivities database using MODIS data.

(b) Investigate correlation between NDVI index (or something similar) and average (spectral) emissivity.

(c) Enhance emissivity measurements of representative surfaces and link them to the classifications in (a).

(d) Carry out simulation studies for various forms of vegetated areas and homogenous landscapes in order to transfer lab/in-situ point measurements to scales observed from space.

(e) Analysis of real (e.g. HIRS, AVHRR, IMG, AIRS, HIS, AIRES) radiances over land surfaces. In order to attain the above mission objectives and to meet in particular the stringent accuracy requirement for LST derivation (1 K) the following activities need to be undertaken:

(f) Development of the algorithms and software for the LST and SSE derivation from cloud-free IASI data.

(g) Verification and validation tests of the schemes developed in (f) for LST and SSE retrievals from IASI radiances.

7 Acronyms

AIRS	Atmospheric Infrared Sounder
AMSU	Advanced Microwave Sounding Unit
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
ECMWF	European Centre for Medium Range Weather Forecasts
EOS	Earth Observation System
HIRS	High Resolution Infrared Radiation Sounder
IASI	Infrared Atmospheric Sounding Interferometer
IGBP	International Geosphere-Biosphere Program
IGOS	Integrated Global Observing Strategy
IR	Infrared
ISLSCP	International Satellite Land Surface Climatology Project
LST	Land Surface Temperature
MetOp	Meteorological Operational Satellite
MHS	Microwave Humidity Sounder
MODIS	Moderate Resolution Imaging Spectrometer
MW	Microwave
NASA	National Aeronautics and Space Administration
NDVI	Normalised Difference Vegetative Index
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
RHS	Right-Hand Side
RMS	Root-Mean-Squared
RTIASI	Radiative Transfer Model for IASI
SSE	Surface Spectral Emissivity
SST	Sea Surface Temperature
ST	Surface Temperature
SWM	Split Window Method
TIROS	Television Infrared Observing Satellite
TISI	Temperature Independent Thermal Infrared Spectral Index
TOA	Top Of Atmosphere
TOVS	TIROS Operational Vertical Sounder

8 References and bibliography

Andersson, E., J. Haseler, P. Unden, P. Courtier, G. Kelly, D. Vasiljevic, C. Brankovic, C. Cardinali, C. Gaffard, A. Hollingsworth, C. Jakob, P. Janssen, E. Klinker, A. Lanzinger, M. Miller, F. Rabier, A. Simmons, B. Strauss, J-N. Thépaut and P. Viterbo, 1998: "The ECMWF implementation of three-dimensional variational assimilation (3D-Var). III: Experimental results". *Quart. J. Roy. Meteor. Soc.,***124***, 1831-1860.*

Andersson, E., Pailleux, J., Thépaut, J-N., Eyre, J.R.,McNally, A.P., Kelly, G.A. and Courtier, P., 1994: "Use of cloud cleared radiances in three/four dimensional variational assimilation". *Quart. J. Roy. Meteor. Soc.,* **120,** *627-653.*

Barton, I.J., 1995: "Satellite derived SST's: current status". *J. Geophys. Res.*, **C5**, 8777-8790.

Becker, F. and Z.-L. Li, 1991: "Complementary of temperature independent thermal infrared spectral indices (TISI) and NDVI : compared properties and combined use for soil and vegetation discrimination". *Colloque Int. sur les mesures physiques et les signatures en teledection*, ESA SP-319, 475-480.

Becker, F. and Z.-L. Li., 1990: "Temperature independent spectral indices in thermal IR bands". *Remote Sens. Env.*, **l32**, 17-33.

Becker, F. and Z.-L. Li., 1990: "Towards a local split window method over land surfaces". *Int. J. Remote Sens.*, **11**, N3, 369-393.

Becker, F. and Z.-L. Li., 1995: "Surface temperature and emissivity at various scales: definition, measurement and related problems". *Rem. Sens. Rev*., **12**, 225-253.

Caselles, V., C. Coll and E. Valor., 1997: "Land surface emissivity and temperature determination in the whole HAPEX-Sahel area for AVHRR data". *Int. J. Remote Sens.*,**18,** 5, 1009-1027.

Eyre, J.R., Kelly, G.A., McNally, A.P., Andersson, E. and Persson, A., 1993: "Assimilation of TOVS radiance information through one-dimensional variational analysis". *Quart. J. Roy. Meteor. Soc.,* **119,** *1427-1463.*

Eyre, J.R.,1996: "Variational assimilation of remotely-sensed observations of the atmosphere". *ECMWF Research Dept. Tech. Memo.* 221 *(available from ECMWF librarian).*

Kahle, A.B. and R.E.Alley, 1992: "Separation of temperature and emittance in remotely sensed radiance measurements". *Rem. Sens. Environ.*, **42**, 107-111 (1992).

Kannari, Y., H.Watanabe and A.Iwashita, 1990: " Validation of TIMS data with the comparison of field spectra and rock analysis". *Proc. second TIMS workshop.* JPL 90-55, 37-46.

Kealy, P. and S. J. Hook, 1993: "Separating temperature from emissivity in thermal IR multi-spectral sounder data: implication for recovering LSTs". *IEEE Trans. on Geosci. and Rem. Sens.*, **31**, 1155-1164.

Kelly G.A., 1997: "Influence of observations on the operational ECMWF system". *W.M.O. Bulletin,* **46,** *336-341.*

Kelly, G.A., Tomassini, M. and Matricardi, M., 1996: *Proc. Third International Winds Workshop Ascona, Switzerland 10-12 June 1996. EUM-P18 105-116.*

Labed, J. and M.P. Stoll, 1991: "Spatial variability of land surface emissivity in the thermal IR band: spectral signature and effective surface temperature"., *Rem. Sens. Environ.*, **38**, 1-17.

Labed, J., 1990: "Approche experimentale des problemes l'emissivite et la temperature de surface, ainsi qu' leur variabilite spatio-temporelle dans le cadre de la teledetection spatiale dans l'infrarouge thermique". *These de doctorat, Univ. Strasbourg Institut Physique de l'environnement terrestre teledetection*, 143pp.

Li, Z.-L. and F. Becker, 1993: "Feasibility of land surface temperature and emissivity determination from AVHRR data". *Remote Sens. Environ.*, **43**, 67-85.

Nalli, N.R. and W.L. Smith., 1997: "Improved remote sensing of sea surface skin temperature using a physical retrieval algorithm". *IRS'96: current problems in atmospheric radiation*, 647-650.

Nerry, F. J.Labed and M.P.Stoll., 1998: "Emissivity signatures in the thermal IR band for remote sensing: calibration procedure and method of measurements". *Appl. Opt.*, **27**, N4, 758-764.

Ottle, C. and D.Vidal-Madjar, 1992, "Estimation of land surface temperature with NOAA-9 data". *Remote Sensing of Environ.*, **40**, 27-41.

Prata, A., V.Caselles et al., 1995: "Thermal remote sensing of LST from satellites: current status and future prospects". *Rem. Sens. Rev.*, **12**, 175-224.

Rabier, F., Mahfouf, J.-F., Fisher, M., Jarvinen, H., Simmons, A., Andersson, E., Bouttier, F., Courtier, P., Hamrud, M., Haseler, J., Hollingsworth, A., Isaksen, L., Klinker, E., Saarinen, S., Temperton, C., Thépaut, J.-N., Unden, P. and Vasiljevic, D., 1997: "Recent experimentation on 4D-Var and first results from a simplified Kalman filter"., *ECMWF Technical Memorandum 240.*

Rabier, F., Mahfouf, J.-F., Fisher, M., Jarvinen, H., Simmons, A., Andersson, E., Bouttier, F., Courtier, P., Hamrud, M., Haseler, J., Hollingsworth, A., Isaksen, L., Klinker, E., Saarinen, S., Temperton, C., Thépaut, J.-N., Unden, P. and Vasiljevic, D., 1998b: "The ECMWF operational implementation of four-dimensional variational assimilation". *Quart. J. Roy. Meteorol. Soc. (in press).*

Rabier, F., Thépaut, J-N. and Courtier, P., 1998a: "Extended assimilation and forecast experiments with a four-dimensional variational assimilation system". *Quart. J. Roy. Meteorol. Soc. (in press).*

Romanov, P. Yu. and G.G. Gutman, 1997: "Estimation of land surface emissivity using synergy of AVHRR and ground based measurements". *IRS'96: current problems in atmospheric radiation*,1037-1041.

Salisbury, W. and D. M. D'Aria, 1992: "Emissivity of terrestrial materials in the 8-14 μm atmospheric window". *Remote Sens. Environ.*, **42**, 2, 83-106.

Salisbury, W. and D. M. D'Aria, 1994: "Emissivity of terrestrial materials in the 3- 5 μm atmospheric window". *Remote Sens. Environ.*, **47**, 345-361.

Salisbury, W., D. M. D'Aria. and A. Wald, 1994: "Measurements of thermal infrared spectral reflectance of frost, snow and ice". *J. Geophysical Res.*, **99**, 24235-24240.

Snyder, W.C., Wan Z., Zhang Z., and Feng, Y-Z, 1998: "Classification-based emissivity for land surface temperature measurement from space". *Int. J. of Remote Sensing*, **19,** *2753-2774.*

Sobrino, J.A., C. Coll and V. Caselles., 1991: "Atmospheric correction for LST using NOAA-11 AVHRR channels 4 and 5". *Remote Sens. Environ*., **38**, 19-34.

Sobrino, J.A., Z.-L. Li et al., 1994: "Improvements in the split window technique for LST determination". *IEEE Trans. on Geosci. and Rem. Sens.* **32**, 2, 243-253.

Sobrino, J.A., Z.-L. Li et al., 1996: "Multi-channel and multi-angle algorithms for estimating sea and land surface temperature with ATSR data". *Int. J. Rem. Sens.* **17**, 11, 2089-2114.

Stoll, M., 1991: "Land surface temperature and emissivity retrieval from passive remote sensing measurements". *Proc. third TIMS workshop*. JPL 92-14, 10-19.

Stoll, M., T.Phulpin and T.Schmugge, 1993: "Intercalibration of two airborne thermal infrared radiometers: TIMS and PRT5. Application to land surface temperature retrieval". *Int. J. Rem. Sensing.,* **14**, 13, 2463-2481.

Takashima, T. and K.Masuda, 1988: "Averaged emissivities of quartz and Sahara dust powders in infrared region". *Rem. Sensing. Env.* **26**, 301-302.

Thépaut, J-N and Courtier, J-N., 1991: "Four dimensional variational data assimilation using the adjoint of a multi-level primitive equation model". *Quart. J. Roy. Meteorol. Soc.*, **117,** *1225-1254.*

Timofeev, Yu. M. et al., 1997: "On determination of the temperature and emissivity of land surface from space". *IRS'96: current problems in atmospheric radiation,* 639-642.

Trotsenko, A.N., A.B.Uspensky et al., 1998: "Derivation of surface skin temperature and emissivity from high resolution IR radiance measurements". *To be submitted to J. of Earth Research from Space.*

Uspensky, A.B. and G. I. Scherbina., 1993: "Land surface temperature and emissivity estimation from combined AVHRR /TOVS data". *Proc. of 6th AVHRR data users meeting, Belgirate, Italy, 29 June – 2 July*, EUM P12, 109-116.

Uspensky, A.B. and G. I. Scherbina., 1998: "Derivation of land surface temperatures and emissivities from satellite IR window measurements". *Adv. Space Res.*, **21**, 3, 433-437.

Uspensky, A.B. and V.I. Soloviev, 1998: "The current state and prospects of development methods for sea surface temperature derivation from space". *J. Earth Obs. Rem. Sens.* **1**, 102-112.

Uspensky, A.B. and V.M. Sutovsky, 1991: "Towards the remote sensing of land surface temperature from AVHRR data". *Proc.5th AVHRR data user's meeting. Tromso, Norway, 25-28 June 1991*, 367-374.

Uspensky, A.B., 1992: "Derivation of land surface temperature from the satellite infrared outgoing radiation measurements in the 10.5-12.5 μm band". *Meteorology and Hydrology*, **10**, 19-27 (in Russian).

Valor, E. and V. Caselles, 1996: "Mapping land surface emissivity from NDVI: application to European, African, and South American areas". *Rem. Sens. Environ.* **57**, 167-184.

Van de Griend, A.A. and M.Owe., 1993: "On the relationship between thermal emissivity and normalized vegetation index for natural surfaces". *Int. J. Remote Sens.*,**14**, 6, 1119-1131.

Watson, K, 1992: "Two-temperature method for measuring emissivity". *Rem. Sens. Environ.* **42**, 117-121.