ISEM-6:
INFRARED SURFACE EMISSIVITY MODEL FOR RTTOV-6

V. Sherlock and R. Saunders

The Met. Office, Bracknell, United Kingdom

Abstract

The Version 6 release of the NWP fast radiative transfer operator RTTOV-6 includes a revised default infrared surface emissivity model, ISEM-6. ISEM-6 emissivities depend on surface type classification (sea/land/snow and sea-ice). A critical survey of models and studies appearing in the literature has been undertaken to select model parameterisations for each surface type. This paper summarises the current emissivity model parameterisation and model error characteristics for the three surface type classifications.

1 INTRODUCTION

Accurate models of surface emissivity are required to interpret satellite radiance observations and to retrieve surface temperature. In general, emissivity will depend on satellite zenith angle and the roughness and refractive index characteristics of the surface itself. The radiative properties of the sea surface are approximately isotropic but surface roughness due to the wind generated surface wave field must be taken into account. The land surface exhibits much greater spatial and temporal variability (e.g. soil water content, snow cover, type and senescent state of vegetation) and surface emissivity is more difficult to model as a consequence. Despite the complexity of surface emissivity specification, a very simple default infrared emissivity (unit emissivity for all satellite zenith angles and infrared wavelengths) has been used up until now in the RTTOV forward radiative transfer operator for Numerical Weather Prediction (NWP).

The Version 6 release[1] of the NWP fast radiative transfer operator RTTOV-6 includes a revised default infrared surface emissivity model, ISEM-6. In ISEM-6 the infrared surface emissivity is based on surface type classification (sea/land/snow and sea-ice). A critical survey of models and studies appearing in the literature has been undertaken to select model parameterisations for each surface type. The major improvement in ISEM-6 is the introduction of a wavelength and satellite zenith angle dependent model of the emissivity of the rough sea surface. Minor improvements have been made to the default surface emissivities over land, snow and sea-ice.

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[1] RTTOV-6 documentation can be viewed at `http://www.met-office.gov.uk/sec5/NWP/NWPSAF/rtm`

2 SEA SURFACE INFRARED EMISSIVITY

The Masuda sea surface emissivity model at zero windspeed has been adopted as the default surface emissivity model over sea, based on the modelling studies of Masuda et al. (1988), Watts et al. (1996) and Xu and Smith (1997) and the results from measurement campaigns (Smith et al., 1996, Xu and Smith, 1997).

Channel average emissivity is predicted as a function of satelite zenith angle:

$$\overline{\epsilon} = \epsilon_0 + \epsilon_1.\hat{\chi}^{\mathrm{N}_1} + \epsilon_2.\hat{\chi}^{\mathrm{N}_2}, \tag{1}$$

where $\overline{\epsilon}$ is the convolution of the spectral emissivity $\epsilon(\nu)$ with the instrument spectral response function $I(\nu)$:

$$\overline{\epsilon} = \frac{\int I(\nu)\epsilon(\nu)d\nu}{\int I(\nu)d\nu}, \tag{2}$$

and $\hat{\chi}$ is the normalised satellite zenith angle $\chi/60$ (χ in degrees). Calculations of the sea surface emissivity at high spectral resolution (0.25 cm^{-1}) were performed using the Masuda model as coded for RTIASI by M. Matricardi (Matricardi and Saunders, 1999). Two sets of polynomial basis functions were required to fit the zenith angle dependence for wavenumbers greater than and less than $\sim$ 750 cm^{-1}.

To date regression coefficients have been generated for the following infrared satellite instruments:

- VTPR on NOAA 2-5,
- AVHRR and HIRS on TIROS-N and NOAA 6-16,
- MVIRI on METEOSAT 5-7 and SEVIRI on MSG-1,
- GOES 8-12 IMAGER,
- GOES 8,10 and 11 SOUNDER.

NOAA-15 HIRS channel average spectral emissivities are plotted as a function of channel average wavenumber for satellite zenith angles between 0 and 60 degrees in Figure 1. The high resolution spectral emissivity data used to evaluate the channel average emissivities are also plotted for reference. Fitting residuals for parameterisation of the satellite zenith angle dependence are illustrated in the lower panel.

Even for the nadir view there are significant differences between the modelled emissivity and the previous unit emissivity default, and these differences increase with increasing satellite zenith angle. Associated changes in simulated brightness temperatures are plotted as a function of satellite zenith angle for three HIRS window channels in Figure 2. The results of radiative transfer calculations for two atmospheric states – tropical and sub-arctic – are illustrated. The impact of the change in modelled surface emissivity depends on the opacity of the overlying atmosphere:

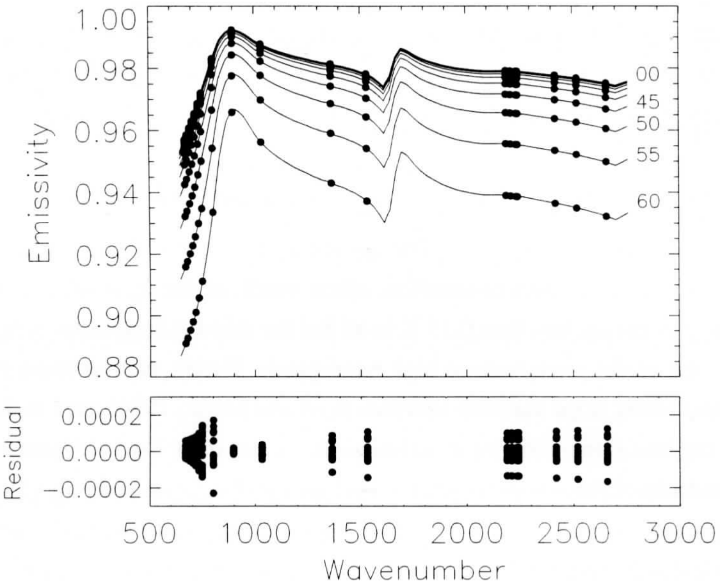

Figure 1: Channel average emissivities for the HIRS instrument on NOAA-15, traced as a function of channel average wavenumber and satellite zenith angle (dots). The high resolution spectral emissivity data used to calculate the channel average emissivities are illustrated for reference (solid lines).

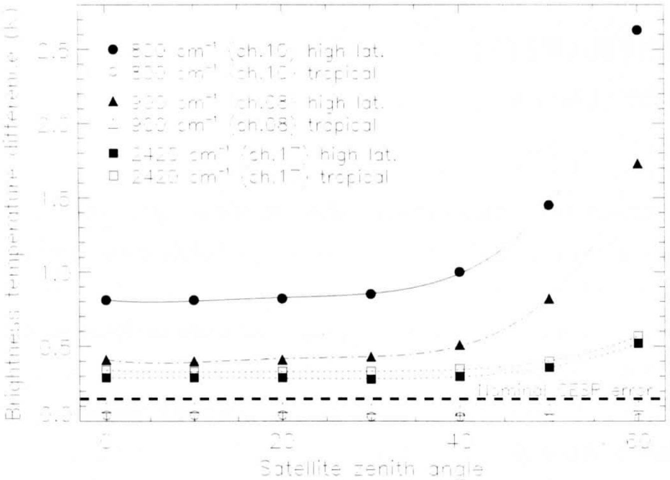

Figure 2: Brightness temperature differences $\Delta T_B = T_B\,|_{\epsilon=1.0} - T_B\,|_{\epsilon(\nu,\chi)}$ associated with the modification of the surface emissivity default, traced as a function of satellite zenith angle for selected channels of the NOAA-15 HIRS instrument. The nominal upper bound for errors due to windspeed independent emissivity and specular reflection approximations (CESR) is illustrated for reference.

the greatest changes are found for window channels at high satellite zenith angles in optically thin (dry) atmospheres. Thus, the introduction of the sea surface infrared emissivity model is expected to reduce latitudinal and satellite scan angle dependent biases in instrument channels where surface emission makes a significant contribution to the observed radiances. Forecast impact studies using ISEM-6 in the 3D-Var data assimilation system are planned in upcoming months.

The errors in modelled brightness temperatures due to the assumptions of a windspeed independent emissivity and specular reflection have been quantified (Watts et al., 1996) for the ATSR forward view. These estimates[2] are reproduced in Figure 3. The assumptions of a windspeed independent emissivity and specular reflection lead to an underestimation, albeit small, of the upwelling longwave radiation: brightness temperature errors are less than 0.15 K in all but the driest atmospheres at high windspeeds.

Caveats apply to the model predictions at high windspeeds. Firstly, there is some suggestion (Apel, 1994) that the Cox and Munk slope variance statistics (Cox and Munk, 1954) used in the Masuda model may underestimate the true slope variance at windspeeds greater than 7 m/s. Alternative scenarios for the windspeed dependence of slope variance give rise to the non-linear contraction of the velocity scales illustrated on the upper x-axes of Figure 3 (for more details see Sherlock (1999)). Secondly, at windspeeds greater than 7 m/s whitecaps begin to form. The ISEM-6 sea surface infrared emissivity model makes no prediction of foam fraction or foam emissivity, mainly beacause the emissivity of foam in the infrared is not well known. In an extreme worst case scenario, assuming unit emissivity for foam, foam fractions of 12 and 30% (windspeeds of 20 and 25 m/s) and a satellite zenith angle of 60 degrees, modelled brightness temperatures may be in error by 0.5 to 1.5 K. Validation of model predictions at high windspeeds will be required.

3 REVISED INFRARED EMISSIVITY DEFAULTS OVER LAND, SNOW AND SEA-ICE

The radiative characteristics of the land surface depend on soil water content, on the chemical composition, roughness and structure of the land surface and on vegetation type, fractional cover and senescent state. These parameters all exhibit high spatial and temporal variability: modelling land surface emissivity is a difficult problem.

No attempt has been made to treat the land surface emissivity in detail in RTTOV-6, but we have sought a more realistic default emissivity value, based on the work of Snyder et al. (1998) and references therein. The revised land surface emissivity default is a fixed emissivity of 0.98 independent of wavenumber or satellite zenith angle.

The results illustrated in Snyder et al. (1998) give a clear illustration of the gross errors inherent in a wavenumber dependent emissivity approximation in general. Focussing on the longwave window regions, emissivity errors are of the order of 0.01 to 0.02, however larger errors occur in the 1050 – 1250

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[2] Note these esitmates provide an upper bound for errors at lower satellite zenith angles. Because the errors are evaluated for optically thin regions of the infrared spectrum, these estimates also provide upper bounds for errors at other wavenumbers (errors decrease with increasing atmospheric opacity).

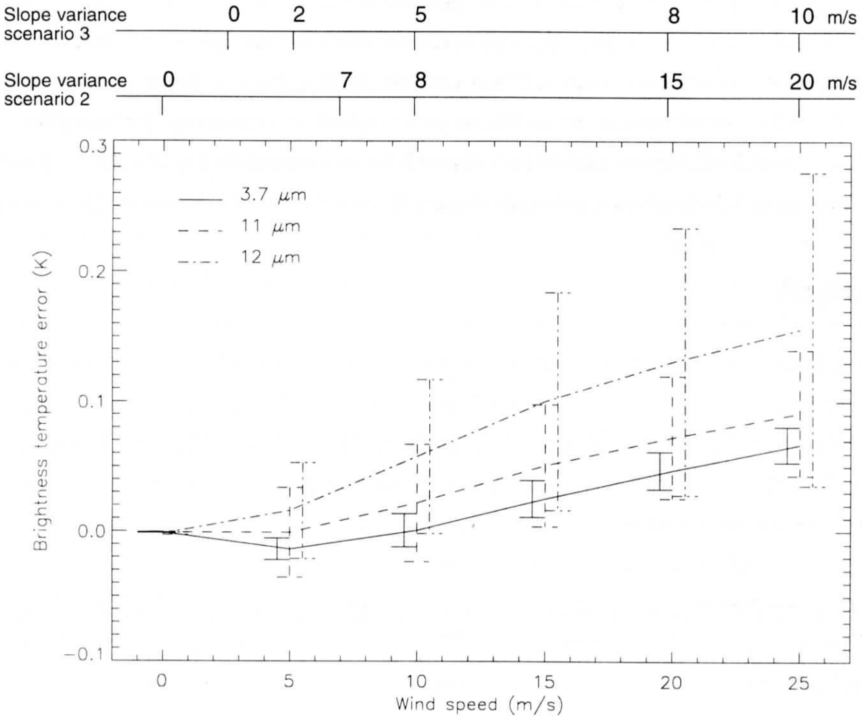

Figure 3: Mean and standard deviation of brightness temperature errors due to windspeed independent emissivity and specular reflection approximations (CESR), traced as a function of windspeed for a satellite zenith angle of 55 degrees and wavelengths of 3.7, 11 and 12 μm, reproduced from Watts et al. (1996). Uncertainties in modelled slope variance at moderate to high windspeeds modifiy the windspeed dependence of the brightness temperature errors. Velocity scales for alternative slope variance scenarios are traced on the upper x-axes.

cm^{-1} interval for bare and sparsely vegetated soils. A satellite zenith angle independent emissivity will be inappropriate for certain land surface classes (bare and sparsely vegetated terrain). For these classes a rough surface specular reflection model, as used for modelling the sea surface emissivity, would be more appropriate. Development of an infrared land surface emissivity model based on an emissivity atlas is planned in the near future.

Similarly, no attempt has been made to treat snow and sea-ice emissivities in detail in RTTOV-6, but we have sought a more realistic default emissivity value, based on the work of Snyder et al. (1998). The revised snow and ice emissivity default is a fixed emissivity of 0.99 independent of wavenumber or satellite zenith angle. Although the spectral variation and climatological variability of emissivity is lower for the snow and ice class than for many of the land surface classes, a fixed, wavenumber independent emissivity still introduces errors of the order of 0.01 in emissivity. Furthermore, a satellite zenith angle independent emissivity approximation will be inappropriate for sea-ice: a rough surface specular reflection model, as used for modelling the sea surface emissivity, would be more appropriate.

4 SUMMARY

A survey of rough sea surface emissivity models appearing in the literature has been undertaken. Based on published results the Masuda sea surface emissivity model at zero windspeed has been adopted to replace the previous infrared surface emissivity default (unit emissivity) over sea. The assumptions of a windspeed independent emissivity and specular reflection lead to an underestimation, albeit small, of the upwelling longwave radiation; brightness temperature errors are less than 0.15 K in all but the driest atmospheres at high windspeeds. The satellite zenith angle dependence of the rough sea surface channel average emissivity has been parameterised for infrared channels on the VTPR, HIRS, AVHRR, GOES IMAGER and SOUNDER and METEOSAT MVIRI and SEVIRI radiometers. Pre-operational trial results indicate that the new sea surface emissivity parameterisation should significantly reduce latitudinal and scan angle dependent bias corrections. Uncertainties still remain regarding the validity of the Cox and Munk slope variance statistics at high windspeeds and the emissivity of foam in the infrared (and microwave). Further intercomparisons with observational data will be necessary to determine the validity of the sea surface emissivity model at high windspeeds and high satellite zenith angles.

The values of the default infrared emissivity over land and over snow and sea ice have also been revised based on studies appearing in the literature (from $\epsilon = 1.0$ to 0.98 and 0.99 respectively). While no attempt is made to model the real spatial and temporal variability of the land surface emissivity, these revised default values should reduce the magnitude of bias corrections in cases where infrared satellite observations are used over land, snow and sea-ice. A more accurate model of land surface, snow and sea-ice emissivities at infrared wavelengths will be pursued in the future, in conjunction with recent developments in modelling land surface emissivity at microwave wavelengths (English and Poulsen, 2000).

Acknowledgements
We would like to thank P. Watts, S. English and A. Harris for useful comments and discussions during the

course of this work. Thanks too to P. Watts and W. Snyder for providing electronic versions of published figures for this presentation.

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TECHNICAL PROCEEDINGS OF THE ELEVENTH INTERNATIONAL ATOVS STUDY CONFERENCE

Budapest Hungary

20-26 September, 2000

Edited by

J.F. Le Marshall and J.D. Jasper

Bureau of Meteorology Research Centre, Melbourne, Australia

Published by

Bureau of Meteorology Research Centre

PO BOX 1289K, GPO Melbourne, Vic., 3001, Australia

June 2001