

Thermal remote sensing of the land surface for numerical weather prediction models

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Abstract Soil–vegetation–atmosphere transfer (SVAT) models provide the lower boundary for numerical weather prediction (NWP) models and general circulation models (GCM). Typically, these models are not parameterized with reference to actual measured land surface behaviour, but have parameters specified according to approximate and simplified concepts of land surface type. Spatial variability of processes and fluxes coupled with uncertainty in input rainfall mean that significant uncertainty should be associated with land surface models used in NWP models. In this paper, an assimilation approach—thermal remote sensing—is advocated; whilst subject to some uncertainty, it may be usefully employed to update land surface models, addressing issues of both parameter and input rainfall uncertainty.

Key words SVAT modelling; NWP modelling; land surface fluxes; thermal remote sensing; assimilation; heating rates

INTRODUCTION

Soil–vegetation–atmosphere transfer (SVAT) models provide the lower boundary for numerical weather prediction (NWP) models and general circulation models (GCM). Typically, these models are not parameterized with reference to actual measured land surface behaviour, but have parameters specified according to approximate and simplified concepts of land surface type. Typically, application of SVAT models has been achieved through prescribed one-dimensional “biome-type” parameterizations. However, these biome-type parameterizations are applied over large heterogeneous areas. The constituent parameters of each biome-type must therefore be *effective* representations of areally-averaged land surface characteristics. Deriving such effective parameterizations requires aggregation through robust scaling laws, but also requires accurate detailed parameter distributions and their covariance. In the absence of scaling laws and detailed data, much uncertainty must be associated with such an approach.

In addition to the problem of deriving effective parameterizations of sub-grid variability, SVAT models are subject to significant uncertainty in the forcing data, especially input rainfall. Errors in rainfall persist due to storage in SVAT models. Acknowledging the role of rainfall errors input to SVAT models in combination with marked uncertainty in appropriate parameter values controlling available moisture, it is clear that the accurate representation of land surface fluxes through SVAT models cannot be guaranteed.

Large-scale thermal remote sensing offers the ability to improve land surface representations by providing measures of actual land surface behaviour. However, such measures are themselves subject to uncertainty—their utility in improving land surface models remains uncertain. To use remote sensing appropriately such uncertainties must be explicitly addressed.

In this study, the uncertainty of the atmospheric evolution of a NWP model to land surface fluxes is demonstrated. To address such uncertainties, an assimilation approach for improving land surface representations for NWP models is advocated. The approach is to use simple SVAT models conditioned with uncertain thermal measures of their gross functional behaviour (in terms of land surface fluxes). Results combining SVAT and NWP modelling with thermal remotely sensed data are then reviewed.

SENSITIVITY OF ATMOSPHERIC EVOLUTION TO LAND SURFACE FLUXES

To demonstrate the sensitivity of the atmosphere to land surface fluxes, and to assess the possibilities of exploiting thermal imagery to measure those fluxes, a simple analysis is presented. Two atmospheric simulations using a computational environmental modelling system, CEMSYS3, were performed representing extreme initial soil moisture conditions. A “wet” simulation was run with the initial water potential at field capacity and the “dry” simulation was run with the initial water potential at wilting point. Each simulation was run for 144 hours (6 days: 1–7 February 1996). This corresponds to a period in mid–late summer where rainfall was primarily convective. Forcing data are provided by the National Center for Environmental Prediction (NCEP).

Figure 1 shows the final state of the atmosphere at the end of the simulation for both the wet and dry runs. The top panels show the differences in the surface pressure field. As can be seen, differences in the regional pressure are apparent. The high pressure region has progressed further southeast during the wet run. Analysis of corresponding rainfall fields displays spatial differences, as would be expected. The middle panels show the surface aerodynamic temperature across Australia. Average differences between the initially dry and wet runs are of the order of 10°C. Also of note is the higher variability of surface temperature in the initially dry run. It is likely that this is a result of convective rainfall variability across certain areas providing moisture to the initially dry locations. Finally, the bottom panels show the near-surface air temperature for the dry and wet runs. As can be seen, an average difference of about 3°C is apparent across Australia. This would largely be the result of enhanced near-surface heating due to higher sensible heat fluxes in the initially-dry simulation.

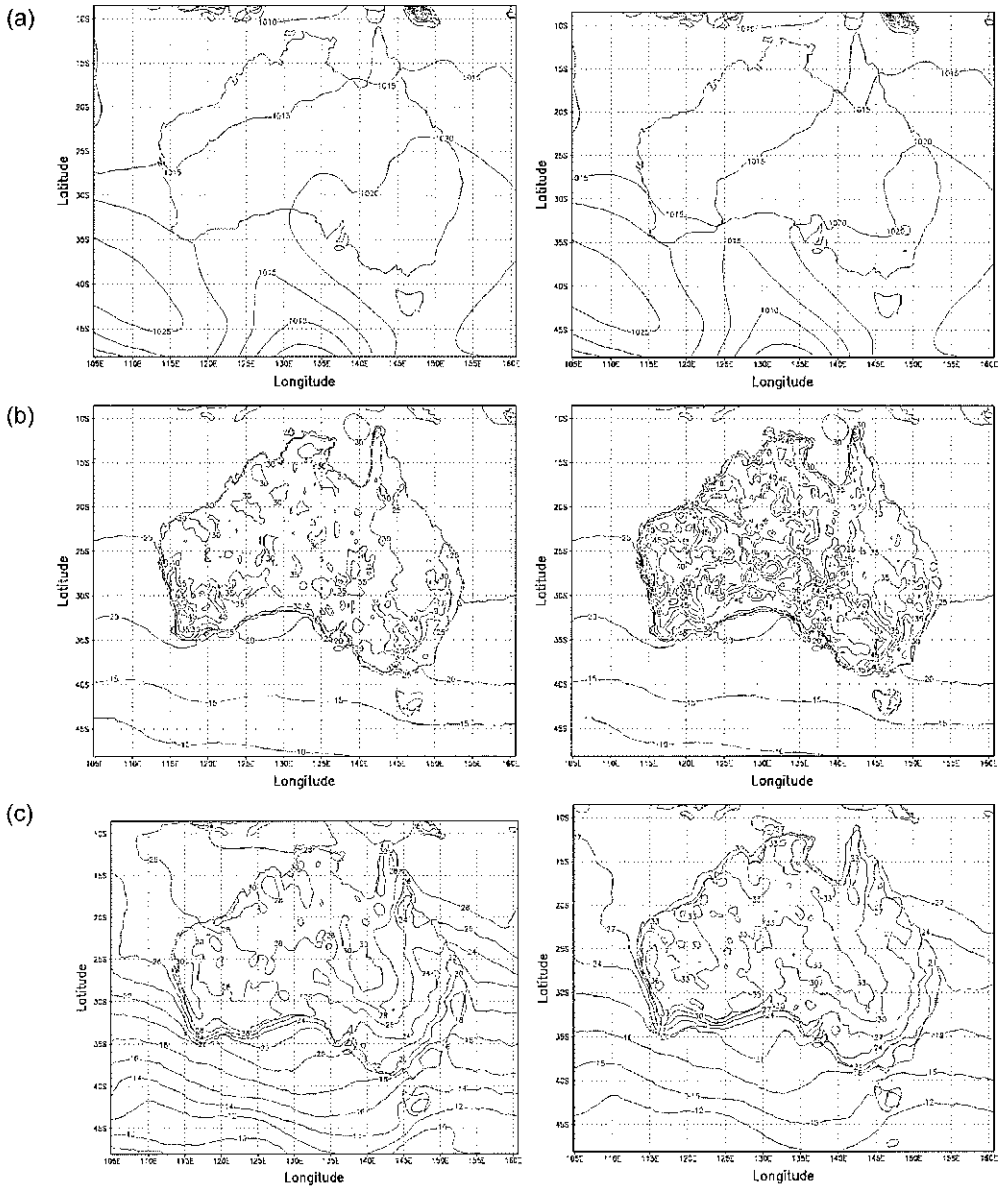


Fig. 1 (a) Surface pressure, (b) surface aerodynamic temperature, and (c) near-surface air temperature, for wet (left) and dry (right) runs, respectively.

In summary, the differences in the wet and dry initial land surface states, demonstrate the possibility of substantial atmospheric differences after 6 days. Importantly, under clear-sky conditions, surface temperatures reveal marked differences in wet and dry land surfaces indicating thermal remote sensing could be used to assess model latent heat flux estimates.

ASSIMILATION OF REMOTE SENSING DATA IN REGIONAL ATMOSPHERIC MODELS

Data assimilation is the incorporation of observations into a numerical model with the purpose of providing the model with the best estimate of the current state of a modelled system. The process of data assimilation was developed initially for use in meteorological forecasting. A wide range of assimilation techniques has been presented in the literature, with most techniques having been derived for meteorological and oceanographic applications. McLaughlin (1995) has noted that applications in hydrological modelling are more limited, which is largely due to the limited and widely scattered sources of traditional hydrological data. Several authors, including Otlé & Vidal-Madjar (1994), Njoku & Entekhabi (1996) and Houser *et al.* (1998), have used remotely sensed soil moisture data for assimilation in hydrological and soil physical models.

As shown in Fig. 1, surface temperatures display marked changes with soil moisture. This may immediately suggest the direct use (or insertion) of remotely sensed thermal measurements. However, complicating factors prevent this. Variable atmospheric moisture affects the optical transmission of the atmosphere, whilst spatially variable surface emissivity means that the received radiative thermal signal is not the required aerodynamic temperature. Furthermore, absolute values of model surface temperatures may be more sensitive to the uncertainty in the aerodynamic roughness parameters than to the latent heat flux.

However, many of the problems can be reduced through the estimation of heating rates between two points in time. The use of temporal temperature changes is preferable to using single thermal images in that it reduces the need for (a) absolute accuracy in satellite measurements, (b) atmospheric corrections and (c) precise land surface parameterizations.

As noted by Huband & Monteith (1986), whilst the effect of real-body emissivities ($\epsilon < 1.0$) is to induce inherent differences between the measured radiative temperature and the required aerodynamic temperature, the effect is essentially constant. Additionally, the sensitivity of absolute values of surface temperature to incorrectly specified area-effective aerodynamic parameters can be reduced, as temperature differences in time are less sensitive to these parameters. In a similar manner, the effect of atmospheric transmission, if assumed constant in time between the two remotely sensed scenes, would cancel. The comparison of temporal temperature differences in time should therefore represent a good approximation (e.g. Franks *et al.*, 1999). Indeed, McCabe *et al.* (1999) have investigated this useful approximation with a patch scale TOPUP-SVAT model and flux/thermal data from the FIFE campaign. Their results indicate that the approach can be used to calibrate the model and to reproduce the corresponding measured fluxes, at least at the local patch scale.

LARGE-SCALE USE OF HEATING RATES

The surface energy balance at sites with strong diurnal surface temperature changes can be assumed to be governed by sensible heat exchange, while low heating rates indicate areas with strong evaporative cooling. Hence significant heating rates are

usually associated with drier sites. This association between surface temperature changes and surface wetness has led to variety of remote sensing methods, including satellite infrared heating rate methods (e.g. McNider *et al.*, 1994), satellite infrared diurnal methods (e.g. Diak, 1990; Diak & Whipple, 1995), and combined infrared diurnal methods (e.g. Gillies & Carlson, 1995). Anderson *et al.* (1997) developed a two-source surface energy balance model requiring measurements of the time rate change of surface temperature and an early morning sounding of the atmospheric boundary layer.

Jones *et al.* (1998a) used GOES derived surface temperature changes in time to update the soil moisture condition in a regional atmospheric model. They adjusted the soil moisture content in the model forcing the model to exhibit a surface heating rate comparable to the satellite observations. Jones *et al.* (1998b) described a case study which showed that the method was able to pick up a soil moisture distribution which is compatible with a record of antecedent rainfall in the Great Plains area of the United States, independently confirmed by a SSM/I microwave image.

A technique has recently been described by Suggs *et al.* (1999) for assimilating GOES-IR skin temperature tendencies into the surface budget equation of the MM5 mesoscale climate model developed by Penn State University and the National Center for Atmospheric Research. The MM5 model is an advanced numerical weather prediction model used for real-time weather forecasts. Its model configuration employs a 36 km domain that covers the continental United States and a 12 km nest over the South East Region. The assimilation of GOES data aims at minimizing the difference between the simulated rate of temperature change and GOES satellite observations of skin temperature through adjusting the soil moisture availability and hence the latent heat flux.

Some preliminary work on remotely sensed data assimilation into a regional atmospheric model has recently been carried out at the Royal Netherlands Meteorological Institute (KNMI). Diurnal surface temperature changes derived from METEOSAT images of the area encompassing The Netherlands, Belgium and a small portion of the UK in various periods in 1995 have been compared to estimates of the surface temperature change made with the regional climate model, RACMO (Christensen & Van Meijgaard, 1992). In this work heating rates are computed as $(T_{\max} - T_{\min}) / (t_{\max} - t_{\min})$ where T is temperature and t is time, with $06:00 \text{ UTC} < t_{\min} < 11:00 \text{ UTC}$ and $12:00 \text{ UTC} < t_{\max} < 16:00 \text{ UTC}$.

Figure 2 summarizes some early results obtained in this work. The figure shows the differences between RACMO and METEOSAT heating rates for 25 June 1995 for six major synoptic meteorological stations (SYNOPS) in the region. These regularly reporting SYNOPS stations were selected on the basis of the absence of clouds during most of that day, enabling a more straightforward interpretation of satellite derived heating rates. The RACMO heating rates were calculated for two separate RACMO runs: one with a relatively dry soil moisture content, and one with a 5% wetter soil. Results of these two runs are interconnected with lines for each individual SYNOPS station. The difference between the RACMO and METEOSAT heating rates are plotted *vs* the error in relative humidity calculated by RACMO, compared to the SYNOPS observations.

From Fig. 2, it can be seen that (a) wetter soil moisture initialization reduces the error in relative humidity (RH) and reduces the surface temperature diurnal cycle, and

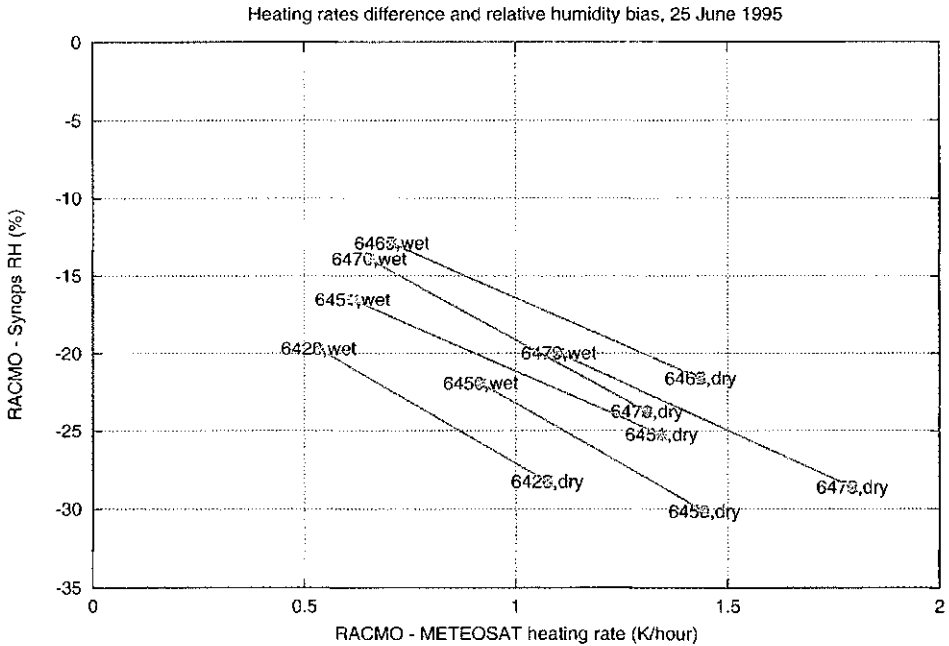


Fig. 2 Difference between RACMO and METEOSAT surface temperature heating rates for six cloud-free SYNOP stations on 25 June 1995, plotted against RACMO forecast error in relative humidity. Shown are results for two runs, with different moisture content (wet and dry).

(b) the slope of this sensitivity points at a minimum error in RH for heating rates which are very similar to the heating rate derived from METEOSAT observations. The important message from this simple graph is that the information content in the METEOSAT surface temperature change is compatible with the information in the SYNOPSIS data. These results indicate that assimilation of heating rates as estimated from thermal data may be successfully employed to improve the model simulations.

DISCUSSION

This paper has sought to assess the potential for updating soil moisture estimates in coupled atmosphere–land surface models. Significant progress has been made in recent years in estimating surface fluxes from the temporal variation in thermal imagery. The use of temporal temperature changes is preferable to use single thermal images in that it reduces the need for (a) absolute accuracy in satellite measurements, (b) atmospheric corrections and (c) precise land surface parameterizations. It is therefore argued that coupled atmosphere–land surface models can benefit substantially from the estimation of surface heat fluxes from thermal remote sensing.

Without an integrated measure of land surface behaviour, land surface models will be inherently uncertain due to (a) the inability to measure all key land surface parameters at a location, (b) the inability to identify specific area-effective parameterizations due to spatial variability of land surface properties, and (c) the effect

of error and uncertainty in the rainfall input to the land surface model. By using a measure of actual behaviour, the land surface component of the coupled system can be periodically updated to address propagating errors in the soil moisture.

Although previous research and the results shown here indicate that such an approach would be useful, several issues remain to be addressed. Previous studies have typically been at short temporal scales. The techniques for deriving appropriate heating rates assume fixed aerodynamic parameters. As noted earlier, these must be area-effective and yet there is no clear method for measuring and scaling the spatial variability of land surface parameters at sub-grid scales. It should also be noted that temporal variability of area-effective parameters may require a dynamic vegetation description in many areas. To make thermal assimilation methods routinely useful over periods of significant change in the vegetation structure requires an ability to independently measure those vegetation changes. Approaches based on remote sensing of vegetation indices may be of some use.

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