PASSIVE MICROWAVE REMOTE SENSING OF SOIL MOISTURE – FROM OBSERVATIONS TO APPLICATIONS

Lester P. SIMMONDS
The Department of Soil Science - The University of Reading

1. INTRODUCTION

It is well known that the thermal emission of microwave radiation from the land surface is influenced strongly by the water content of the upper few centimetres of the soil profile. Over the past few decades there has been substantial progress in the development of passive microwave radiometry to gain information about soil surface wetness, much of which has been directed towards the future use of satellite-borne radiometers to provide a global soil moisture observing system. In the report from the NASA Post 2002 Land Surface Hydrology Planning Workshop it was stated that *"The lack of a global soil moisture observing systems is one of the most glaring and pressing deficiencies in satellite remote sensing and climate research", and that the need for such systems is because "Precise in situ measurements of soil moisture are sparse and each value is representative of a small area. Remote sensing... would provide truly meaningful wide-area soil wetness for hydrological studies".*

This paper picks up these themes, and is structured around the following topics:

- Potential applications of near-surface soil moisture observations in large scale models
- An overview of the theory of the observations
- Retrieval of information about land surface properties and processes from passive microwave observations
- Implications for end users and for the requirements of a future space-borne passive microwave mission

It is particularly important at this time to fully engage the potential end user community in this discussion. One motivation is that the European Space Agency (ESA) is planning a satellite borne passive L band (1.41 GHz) synthetic aperture radiometer as an Earth Explorer Opportunity Mission (currently in phase B of development), described by Kerr *et al.* (2001). The objective is to test the possibility for a global observing system for the dual purposes of monitoring soil moisture and ocean salinity (the Soil Moisture and Ocean Salinity [SMOS] mission). The proposed baseline for the mission is that the satellite will be in heliosynchronous orbit providing global coverage every three days, passing over the equator at 0600. The instrument is to be a 2-D interferometer providing multi-angular observations at horizontal and vertical polarisations. The provisional objective of the soil moisture component of the mission is to enable estimates of near surface soil moisture content to 4% by volume accuracy with a spatial resolution of around 50km.

The principle underlying the remote sensing of soil moisture is that the thermal emission of radiation in the microwave part of the spectrum from the soil surface is influenced strongly by soil wetness. The emissivity (the ratio of the observed radiometric brightness temperature, T_B, and the physical temperature of the emitting body, T_{eff}) varies from >0.9 for dry soils to around 0.6 for wet surfaces

(Schmugge *et al.*, 1986). However, as will be discussed later, other factors (particularly soil temperature, vegetation canopies and surface roughness) influence the observed brightness temperature, and need to be accounted for in the retrieval of sóil moisture information. Much effort has been directed towards the development of algorithms to retrieve near-surface soil water content from measurements of microwave brightness temperature (i.e. the emittance expressed in terms of the temperature that a perfect emitter would have in order produce the measured emission) (Njoku and Entekhabi, 1996). Most work to date has been motivated by possibilities for airborne (and, ultimately, satellite-borne) instruments. A major limitation of high altitude sensors is the low spatial resolution. Typical pixel sizes are several hundred metres and >20 km for airborne and proposed satellite platforms respectively. However, there has been much work done with ground-based radiometers (typical resolution of 1 m^2) to assist in the development of retrieval algorithms and to understand the relations between land surface properties and microwave emission, but this has usually been in the context of research to support the development of airborne and satellite-borne systems.

2. POTENTIAL APPLICATIONS OF NEAR-SURFACE SOIL MOISTURE OBSERVATIONS IN LARGE SCALE MODELS

2.1. Atmospheric models

Atmospheric models differ widely in their application. In climate research, they are generally run with relatively coarse resolution (typically 2.5^0) and used to simulate very long periods (>100s years). It is crucial in such applications that the critical processes are well simulated, and there is very strong impact of land surface schemes on model predictions (Garrat, 1993).

Rapid progress is being made in the incorporation of soil carbon turnover and interactive vegetation into climate change models in order to examine the feedbacks between climate change and the magnitude of terrestrial sources/sinks of CO_2. Studies using the UK Hadley Centre HadCM3LC model show that the model successfully predicts the evolution of atmospheric CO_2 from pre-industrial times to date, when the oceans and land surfaces have acted as net sinks that sequestered about 1.5-2 Gt CO_2 per annum (Jones and Cox, 2001). By the end of the 21^{st} century it is predicted that after an initial period of enhanced sequestration through CO_2 fertilisation effects, the terrestrial biosphere will switch from being a sink of CO_2 to being a source. This is attributable to increased soil temperature accelerating the decomposition of soil organic matter, and a decrease in photosynthesis in the Amazon rain forest caused by water stress induced dieback of the forest. Globally, the Hadley Centre model predicts a dramatic surge in terrestrial CO_2 production (reaching 7 Gt per annum by 2100) that will result in atmospheric CO_2 enrichment greater than the increase caused by anthropogenic sources. In effect, this is a "one-off" enrichment resulting from the oxidation of global soil reserves of carbon that have been accumulating over 1000s of years. An important conclusion of such studies is the central importance to climate change of changes in soil moisture regimes caused by shifting rainfall patterns.

At the other end of the spectrum is the application of atmospheric models in numerical weather prediction (NWP). Models will be run for a few days through to several months in the case of long-term forecasts. Spatial scales of operation vary from > 1° for global forecasting, with the current minimum resolution being 10 km (becoming the standard for meso-scale forecasting over Europe). The success of NWP models depends crucially on model initialisation (van den Hurk *et al.*, 1997). Hence NWP models are run operationally a few times each day so that initialisation can be updated. Initialisation is done using a blend of observations and model predictions. The quality of the observations and the data-assimilation techniques used to blend the observations with model predictions are major factors determining the skill of the NWP.

The main impact of soil water on weather forecasts is indirectly through the effect of soil water on latent/sensible heat partitioning. Initialisation of the water content of the soil profile is usually based to some degree on model predictions that are driven by modelled rainfall, which can have very large errors. For this reason, top of the 'wish list' of numerical weather forecasters for soil water-related observations are either rainfall or root-zone soil moisture, so that evaporation and sensible heat fluxes under water-limited conditions can be predicted correctly. A potential additional benefit of passive microwave observations is the possibility of detecting frozen soil, which is discussed further in section 4.4.

There has been limited progress in terms of systematic studies of the impact of assimilation of soil water observations into NWP models (due mainly to lack of appropriate observations). Instead, efforts have concentrated on assimilating screen-height observations of air temperature and humidity to 'nudge' the soil water component of the land surface scheme (e.g. Mahfouf, 1991; Bouttier *et al.,* 1993a,b; Douville *et al.*, 2000). However, these near surface quantities are only weakly related to soil moisture, particularly at times of strong advection, low fluxes or snow cover. Also, direct observations of these quantities are relatively sparse relative to the spatial variability in soil moisture. Opportunities for exploiting soil moisture observations derived from satellite observations are limited, hence the reliance on surrogates for soil moisture as described above. The Global Land Data Assimilation System (GLDAS: Houser, 2001) uses soil moisture retrievals from the Special Sensor Microwave Imager (SSM/I) and plans to use observations from the Advanced Microwave Sounding Unit (AMSU), though these are limited by being relatively high frequencies with limited penetration for good soil moisture retrievals.

2.2. Global vegetation modellers

There has been considerable activity in the development of Dynamic Global Vegetation Models (DGVMs), whose principal interest is in quantifying the distribution of the net primary productivity of vegetation (with implications for the terrestrial component of the current global CO_2 budget), and how global vegetation productivity might respond to future climate change. All these models are linked to atmospheric circulation models, and incorporate procedures to link vegetation water uptake and growth to the water content of the root zone.

The impact of soil moisture on the net primary productivity of vegetation is well illustrated in the results of the Potsdam 1995 model intercomparison study (Cramer *et al.* 1999) which brought together a wide selection of global dynamic vegetation models in a workshop to compare model predictions using a common atmospheric forcing data set. Some of the main conclusions emerging from this study (discussed by Churkina *et al.*, 1999) that are relevant to discussions of passive microwave applications are that:

- Soil water is a major factor limiting global net primary productivity (NPP);
- Differences between models in the prediction of soil water effects on NPP were the main reason for discrepancies between models in global NPP;
- Models with daily timesteps showed much stronger impacts of soil water on NPP than models with longer timesteps;
- Soil water was an important factor contributing to interannual variation in NPP, though this effect was secondary to interannual variations in dust content of the atmosphere.

Hence:

- Interannual variations in NPP and global atmospheric CO_2 content provide an opportunity for limited testing of models globally;
- Atmospheric "flask" experiments measuring fluctuations of both CO_2 and water vapour in the boundary layer coupled with remotely sensed near surface soil moisture provide opportunities for verifying land surface schemes within single grid squares ;

• In the long term, indirect monitoring of root zone soil moisture from near-surface soil moisture offers an opportunity to detect impacts of year to year variations in rainfall (and ultimately the impact of changing rainfall patterns) on NPP.
Also, there is potential interest in the possibilities for deriving semi-quantitative information about relatively dense canopies from estimates of the attenuation of microwave radiation by canopies (which might be a by-product of the retrieval of near-surface soil moisture - see section 4.1). The attraction of using the optical depth at L-band is that is saturates at much higher biomass values than any indices derived from remote sensing in the visible/IR part of the spectrum.

2.3. Hydrological modellers

The primary objective of hydrological modellers is to predict the surface water balance components of infiltration, surface run-off, evaporation, deep percolation of water through the vadose zone and the changes in the water content of the vadose zone. A key element is consideration of the routing of lateral flows, and so involves 3-dimensional modelling of the land surface that requires coupling vadose zone processes with overland surface water flow and groundwater flow models.
Hydrological models are necessarily applied over a wider range of scales than atmospheric models, because of the scale at which key processes (such as surface run-off) operate. Hence hydrological models might be run at resolutions anywhere between 50 km and the size of a farmers field, depending on the application.
In hydrological applications the focus is generally on surface run-off and deep percolation, as these provide the sources of water for surface and groundwater flows. Over much of the globe, the annual precipitation is less than (or little more than) the potential evaporation, so most precipitation is lost as evaporation. Consequently, deep percolation and, to some extent surface run-off (except where surface run-off is generated by rainfall intensity exceeding the infiltration capacity), is largely controlled by the difference between precipitation and evaporation, so accurate prediction of evaporation is essential. Hence hydrological models, as with atmospheric models, can potentially benefit from using observations of near-surface soil moisture for either data assimilation or model initialisation to improve the estimation of root-zone soil moisture.
Surface runoff and deep percolation are both highly non-linear functions of soil, vegetation and rainfall, as both occur only when some threshold is exceeded. This gives rise to scaling problems that are much more acute than is the case with evaporation. A number of large scale modelling studies have demonstrated the sensitivity of runoff predictions to the spatial scale at which models are operated. For example, Verant *et al.* [2001] showed strong effects of spatial resolution on modelling runoff over northern Spain, which was attributable to spatial variation in rainfall. Mesoscale modelling studies support the hypothesis that there can be feedbacks between rainfall and soil moisture heterogeneity. For example, Barros and Hwu (2002) used a coupled mesoscale model (MM5 version 3) to show how heterogeneity in soil moisture influenced summer rainstorms within the Southern Great Plains Experiment (SGP97).
So what are the implications of the above for the potential of near-surface soil moisture information derived from passive microwave to improve the prediction of surface runoff? First, we need to distinguish between surface runoff triggered by saturation excess to that triggered by intense rainfall that exceeds the short-term infiltration capacity of the soil. In the case of the latter, it is doubtful whether there is a role of passive microwave observations. Although, in principle, surface runoff can be diagnosed by temporary saturation of the soil surface, direct detection of this state is beyond the likely accuracy resolution of soil moisture retrievals, and the likely temporal and spatial resolutions of any future space-borne passive microwave observing system.
On the other hand, there may well be a role for passive microwave observations being applied to improve the prediction of surface runoff generated by the soil profile recharging to excess over large areas, as this depends on longer term history of water storage in the root zone. However, lack of adequate spatial resolution is likely to be a major issue. By comparison with evaporation, surface

runoff triggered by saturation excess is a very much more non-linear function of soil properties, vegetation and rainfall, and so models which average over large areas are likely to underestimate surface runoff because of the inability to predict the runoff generated in localised areas within the grid.
A number of lines of research are being followed to develop disaggregation techniques that may help overcome this problem. The analysis of spatial and temporal patterns of soil moisture retrievals over the 250x40km area of the SGP97 experiment revealed that topography dominates the spatial structure of soil moisture during and immediately after rainfall (Kim and Barros, 2002), whereas soil hydraulic properties control spatial patterns during inter-storm periods when the soil was close to field capacity. Not surprisingly, spatial variation in soil moisture was dominated by vegetation patterns during prolonged drydown periods. In complex terrain, orography might provide the key for dissaggregation of rainfall (Bindlish and Barros, 2000). There might also be possibilities for the synergistic interpretation of passive microwave observations with contemporary observations with finer spatial resolution (e.g. combining active and passive microwave radiometry, as demonstrated by Bindlish and Barros, 2002, in an analysis of SAR and ESTAR observations). Finally, there is the possibility for simultaneous multi-patch retrievals of soil moisture, temperature and canopy optical depth using multi-angular L-band observations that were demonstrated in principle by inverting multi-patch forward models (Burke *et al.*, 2002).

3. AN OVERVIEW OF THE THEORY OF OBSERVATIONS

The land surface emits microwave radiation dependent on the physical temperature of the emitting body. Conventionally, this is expressed in terms of the radiometric brightness temperature (T_B), which is the product of the effective physical temperature of the surface (T_{eff}) and the apparent emissivity (ε), which is the ratio between the actual emission and that which would be expected if the surface was acting as a perfect emitter (i.e. a black body).

Equation 1 $$T_B = \varepsilon \, T_{eff}$$

The development of an observing system for near-surface soil moisture exploits the fact that at frequencies around 1 GHz, the emissivity of wet soil ($\varepsilon \cong 0.6$) is very much less than for dry soils ($\varepsilon \cong 0.9$), because of the large dielectric constant of soil water. The preferred wavelength for soil moisture observations is 1.4 GHz (21 cm wavelength) – the so-called L-band. The reason for this preference is that it is a protected frequency. Also, the longer wavelength of L-band is less strongly influenced by atmospheric composition or the presence of vegetation by comparison with the higher frequencies of microwave radiation that are used widely for other purposes, such as atmospheric sounding (e.g. see comparison sensitivities of brightness temperature to soil moisture at L- and C-band in table 1). In principle, wavelengths longer than L-band would have even better penetration of vegetation, but other problems (such as Faraday effects, and very poor spatial resolution) become an issue. To put the sensitivities listed in Table 1 into context, the radiometric accuracy of the proposed SMOS mission will have to be a fraction of a Kelvin if it is to meet the requirements necessary for the retrieval of sea salinity, so radiometric accuracy is unlikely to be a limitation for useful retrievals of soil moisture at L-band, even in the presence of quite dense vegetation.

Table 1: Sensitivity of brightness temperature to % volumetric soil water content at L-and C-bands, for different amounts of vegetation cover

	Vegetation water content (kg m^{-2})	Sensitivity (K $\%^{-1}$)	
		L-band (1.4 GHz)	C-band (5.5 GHz)
Bare soil	0	3.4	3.2
Vegetated soil	1	2.7	1.6
Vegetated soil	2	2.2	0.8
Vegetated soil	4	1.5	0.2

In the case of vegetated surfaces, the observed brightness temperature has 3 principal components, namely the direct emission from the canopy, the downwelling emission from the canopy that is reflected from the soil surface, and the direct emission from the soil surface that is transmitted through the overlying vegetation canopy. Other contributions are negligible (e.g. the reflected sky emission contributes a few Kelvin at most). Figure 1 illustrates a widely-used approach to partitioning these various contributions, based on the assumption that the vegetation acts as a diffuse cloud with a single scattering albedo (ω) that is very small at L band, and which transmits fraction γ of incident radiation. γ depends on the optical depth of the canopy (τ) and the incidence angle (θ). This will be referred to henceforth as the "τ–ω model", and has been used widely in both forward modelling of microwave emission from the land surface, and in the retrieval of canopy and soil properties from passive microwave observations (Mo *et al.*, 1982).

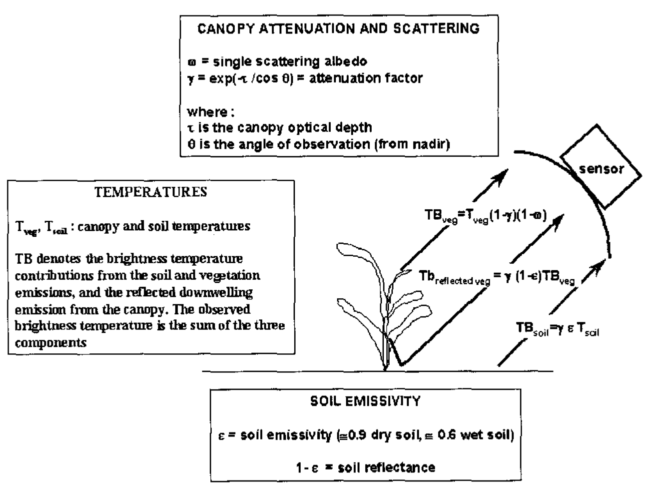

Fig. 1. The components of the τ–ω model for microwave emission from the land surface.

Soil water has strong influence on the apparent emissivity of the soil surface because of the large contrast between the dielectric constant of water at L-band (80) and that of the other soil constituents (c. 4 for soil particles). The dielectric constant for soils can be modelled using mixing models based on the fractional composition of air, solids and water (e.g. Wang and Schmugge, 1980). A complication is that some of the soil water is tightly bound, and has a dielectric constant similar to ice (c. 4), so the clay content of the soil can influence the relationship between soil water content and emissivity, but in a predictable way (Burke and Simmonds, 2000).

At one extreme, the relationship between e and the near surface soil moisture content of a soil profile implicit in the equations in Figure 1 can be described using a direct empirical or semi-empirical relationship (e.g. Simmonds and Burke, 1998). Alternatively, the Fresnel equations are implemented, based on knowledge of the dielectric constant for the soil. More complex still are models which combine a multilayer SVAT with a microwave emission model for stratified media (such as MICRO-SWEAT, Burke *et al.*, 1998), and so treat the soil as a layered medium in order to account for near-surface gradients in soil water content and temperature. A schematic outline of MICROSWEAT is given in Figure 2. A further complication in the emission from the soil surface is the effect of roughness. Though, in principle, roughness effects can be accounted for using relatively simple models (Wigneron *et al.*, 2001), a practical difficulty (particularly when inverting models to retrieve soil moisture) is that of knowing appropriate values for surface roughness to use. Hence it is often assumed that roughness effects at are negligible, which may be reasonable at L-band in many situations because of the 21 cm wavelength.

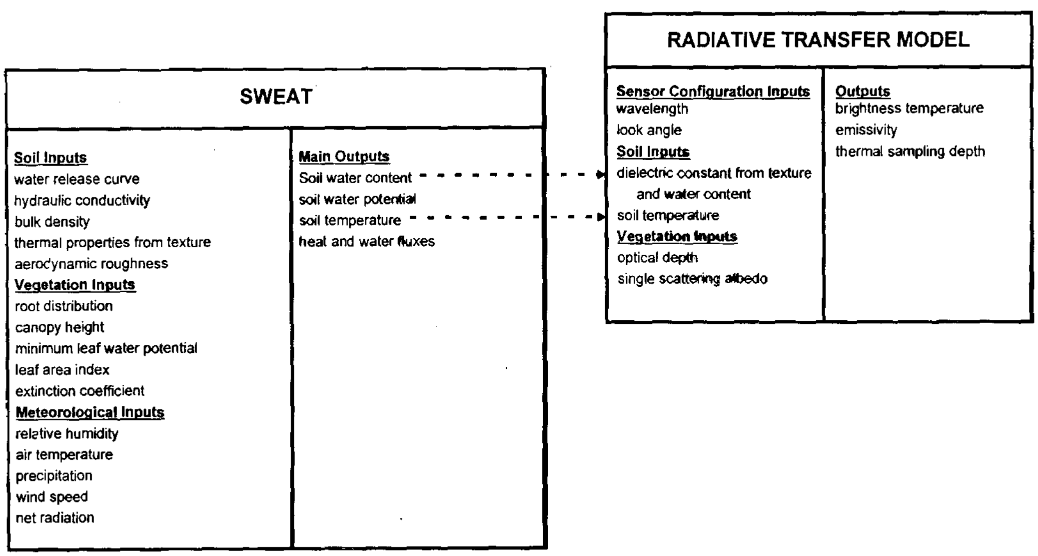

Fig. 2. The principal inputs and outputs of the MICRO-SWEAT model

The effects of vegetation are accounted for in the τ–ω model based on information about the single scattering albedo (ω) and the canopy optical depth. Fortunately, scattering effects are small, and ω is often assumed to be negligible. Parameterisation of optical depth is a more difficult problem. The optical depth depends primarily on the water content of the vegetation (but includes water intercepted by canopies – see Wigneron *et al.*, 1996). It is often assumed in both forward models and retrieval algorithms based on inversion of the τ–ω model that τ is proportional to the canopy water content (e.g. Jackson and Schmugge, 1991). However, the difficulties with such an approach are that :

• The coefficient of proportionality between canopy water content and optical depth is rather variable and difficult to know *a priori*

• The vegetation water content is rarely known *a priori*

• The canopy optical depth can vary with incidence angle, if the vegetation has structure that affects the emission of microwaves at the wavelength in question.

We shall return to some of these issues in the later discussion on soil moisture retrievals in section 4.1.

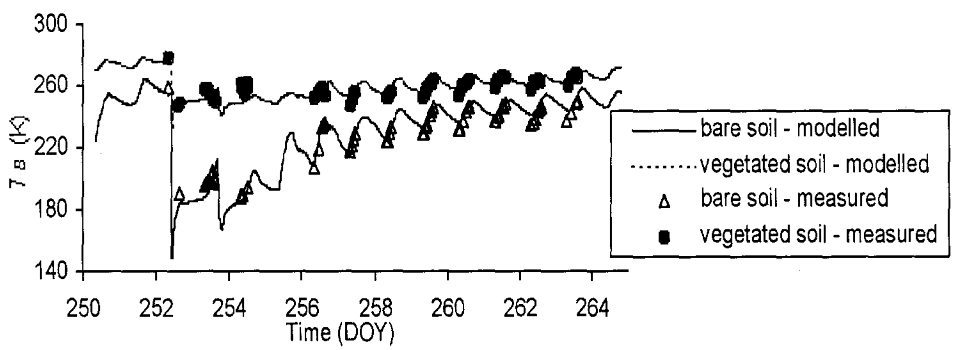

Fig. 3. Time courses of L-brightness temperatures measured (points) and simulated (lines) for a bare soil and a vegetated soil.

The dependence of microwave emission on land surface properties is well illustrated by Figure 3, which shows time courses of brightness temperature for a bare soil and an adjacent vegetated surface. The points show measurements made using the NASA-GSFC SLMR ground-based L-band radiometer, and the lines show the corresponding simulations made using the MICROSWEAT model. The time courses show the effects of irrigating a dry surface on day 252 of the year (with a small rain event also on the following day), and then the subsequent drydown. Note that:

• Irrigation dramatically decreased the brightness temperature because the near-surface soil was wetted. Modelling studies using MICROSWEAT based on drydowns following summer rain events in temperate environments suggest that the sampling depth varies depending on the water content of the soil, ranging from about 8 to 18 cm depth, though greater depths of sampling might occur under very arid conditions. Empirical relationships established between apparent emissivity and near-surface soil moisture content usually consider the upper 2 to 10 cm of the soil profile;

• The sensitivity of brightness temperature to soil moisture was very much reduced by the presence of vegetation;
• During the drydown period, there is a day-to-day increase in brightness temperature as the soil dries;
• There is a diurnal variation (more pronounced in the bare soil) due to fluctuations in surface temperature compounded by diurnal fluctuation in the soil water content very close to the surface;
• The good agreement between the measured and modelled brightness temperatures is encouraging if we are considering using statistical inversion of the t-w model as the basis of a soil moisture retrieval algorithm.

4. RETRIEVAL OF INFORMATION ABOUT LAND SURFACE PROPERTIES AND PROCESSES FROM PASSIVE MICROWAVE OBSERVATIONS

4.1. Retrieval of near-surface soil moisture

The discussion in section 3 above illustrates the success with which microwave emission from the land surface can be modelled, given knowledge of the soil water and temperature regime, and the attenuation properties of the vegetation. In this section we consider the possibilities for retrieving information about the near surface soil moisture content from passive microwave observations. Many approaches have been attempted, and it is beyond the scope of this paper to review them all. A comprehensive review is expected to available shortly in a technical report submitted to ESA as part of an ongoing study (J.P. Wigneron, INRA Bordeaux, personal communication).
It is evident from the earlier discussion that the brightness temperature recorded by a radiometer pointing at the land surface will be influenced by the temperature(s) of the emitting surface(s), the near-surface soil water content, and the optical thickness of the vegetation canopy. If we are considering a satellite-borne radiometer, then we should also consider possible atmospheric influences, though these are small and largely predictable, except when there are very intense rainstorms resulting in large atmospheric liquid water content. A number of approaches have been tested for the retrieval of near-surface soil moisture content from observed brightness temperatures. Many of these require *a priori* information from which canopy optical depth and the effective surface temperature can be estimated, enabling the τ–ω model to solved directly for the soil surface emissivity, and hence near-surface soil moisture content.
However, this paper will restrict the discussion to the approach that has been proposed for the SMOS mission, which avoids the need for such *a priori* information (Wigneron *et al.*, 2000). The proposed algorithm takes advantage of the ability of the SMOS mission to deliver multi-angular observations of brightness temperature at both horizontal and vertical polarisations. The useful range of incidence angles vary from nadir to approximately 50° for ground segments along the track, but are limited to approximately 25° through to 50° for ground segments towards the edge of the useable swath. Hence for the purposes of developing a retrieval algorithm appropriate for SMOS, it is assumed that the range of incidence angles available is approximately 25° to 50°. Multi-angular and dual polarity observations provide a number of independent measurements of brightness temperature over the same ground segment that enables, in principle, the simultaneous retrieval of several unknowns (e.g. surface temperature, soil water content and canopy optical depth), provided the physics of the relationship between look angle, polarisation and brightness temperature is known.

The dependence of brightness temperature on viewing angle is explicit in the τ–ω model. In it's simplest form (regarding the canopy as a turbid cloud), the partitioning between the soil and vegetation contributions to the brightness temperature depends on the cosine of the incidence angle, as shown in Figure 1 (i.e. the path length through the canopy to the soil surface). However, the reality is not quite so simple, as vegetation can have structure that affects the influence of view angle on the amount of attenuation by the canopy (i.e. the effective optical depth, τ, is not constant, but depends on look angle). Such structural effects can be very different at H and V polarisations, depending on the predominant orientation of canopy elements. Hence the success of the retrieval algorithm proposed for SMOS depends on *a priori* knowledge of the τ: lookangle relationships at H and V polarisations for the vegetation type in question. There is good information available on this from ground-based radiometry over arable crops, but rather less information over grassland and forests. One approach currently being adopted for forests is to attempt to generate optical depth: polarisation: look angle relationships parameterisations fro experiments using a discrete canopy emission model that takes account of the sizes and geometries of the canopy elements (Ferrazzoli *et al.*, 2002).

Implementation of the multi-parameter retrieval approach discussed above requires some simplifications to the τ–ω model. For example, as with most retrieval algorithms proposed, it is assumed that the emitting surface is at uniform temperature (i.e. soil and canopy temperatures are the same). This assumption is most valid in the first few hours after sunrise, which is one of the reasons why dawn is considered the optimum time for satellite observations. Second, a value for the single scattering albedo is assumed (which is reasonable because ω is very small). If ω is considered negligible and the soil and canopy is at temperature T, then the τ–ω model shown in figure 1 reduces to:

$$T_b = \gamma\varepsilon T + (1-\gamma)T + \gamma(1-\varepsilon)(1-\gamma)T$$

where

$$\gamma = \exp\left[\frac{-\tau}{\cos\theta}\right]$$

Wigneron *et al.* (1995) tested the possibilities for the simultaneous retrieval of canopy optical depth and near-surface soil moisture using the above equation using dual polarised, multi-angular data collected over wheat and soybean crops. In a subsequent study based on simulated data, Wigneron *et al.* (2000) showed that it was possible to retrieve simultaneously the surface temperature, near-surface soil moisture content and the canopy optical depth to acceptable accuracies (in particular, achieving the error target for soil moisture content of < 4% by volume) using H and V brightness temperatures between 25° and 50° look angles, provided that surface temperature was known *a priori* to within 2K. There was only slight improvement in retrieval accuracy using the full range of angles from nadir to 50°. This initial result is highly encouraging with respect to the proposed SMOS mission.

4.2. Retrieval of root zone soil moisture

The ability to retrieve information on the water content of the root zone is a recurring theme in the wish lists of potential end users of global observing systems for near-surface soil moisture observations. The root zone is the location of the "memory" of the land surface for past rain events. It controls the partitioning of the water balance between evaporation, surface runoff and deep percolation of water below the depth at which water is available in the short term for evaporation. Root zone soil moisture is also a major factor affecting the growth of vegetation, with implications for both agricultural productivity and the terrestrial carbon budget. However, in global and mesoscale models involving atmospheric processes, the water status of the profile is one of the most poorly modelled and sparsely measured components of the system (Dirmeyer, 1995).

Fortunately, there is a strong coupling between the near-surface soil moisture and the water content of the root zone. Recharge of the root zone during infiltration and subsequent redistribution occurs as water flows from surface to deeper layers via processes that depend on the vertical distribution of soil water. Similarly, during drying periods the near-surface water content depends on the balance between the upward flow from relatively wet soil in the root zone and the rate at which water evaporates directly from the soil surface. Hence there is an implicit coupling between surface and root zone soil moisture status within models of soil water dynamics. In principle, this coupling is most strong during periods when evaporation from the soil surface is slowest, suggesting that it is around dawn when surface soil moisture status is dominated by the water status of the underlying soil.

A number of studies have demonstrated the ability to retrieve information about the water status of the root-zone by assimilation of near-surface soil moisture observations into SVATS. The atmospheric modelling community has developed considerable experience in the use of data assimilation techniques, but these are only recently being applied to soil water related issues. It is beyond the scope of this document to discuss in detail the various approaches for data assimilation. Excellent articles appear elsewhere that describe the current state of the art with respect to assimilation of soil moisture observations into hydrological models and land surface schemes underlying atmospheric models (van Loon and Troch, 2001; Reichle, McLaughlin and Entekhabi, 2001a,b; Reichle, Entekhabi and McLaughlin, 2001; Walker and Houser, 2001).

The feasibility of using brightness temperature measurements (both microwave and infrared) to retrieve information about root-zone soil moisture by assimilation of these observations into coupled heat and water flow models through bare soils was demonstrated by Entekhabi *et al.* (1994). Most validated studies of the ability to retrieve root-zone soil moisture from surface observations have been point-scale studies, based on direct measurements of near-surface soil moisture (e.g. Calvet *et al.*, 1998; Galantowicz *et al.*, 1999; Wigneron *et al.*, 1999; Montaldo and Albertson, 2001). Relatively few (e.g. Wigneron *et al.*, 2002) have been based on passive microwave observations, thereby incorporating the uncertainties associated with the retrieval of near-surface soil moisture from measured microwave brightness temperatures. Synthetic experiments have been carried out at larger scales (e.g. the use of variational data assimilation using synthetic experiments based on the SGP97 experiments; Reichle, Entekhabi and McLaughlan, 2001).

A number of studies have been carried out to study the impact of frequency of observations (and lengths of assimilation periods) required for the accurate retrieval of root zone soil moisture. The various studies by Calvet and co-workers (e.g. Calvet *et al.*, 1998; Calvet and Noilhan, 2000; Wigneron *et al.*, 1999) suggest that variational assimilation of observations of near-surface soil moisture every 3-4 during (at least) a 15 day period was sufficient to obtain good estimates of the root zone moisture content. Other studies have tended to support this conclusion.

A major issue with future operational assimilation schemes based on satellite sensors is that there is likely to be a bias between the values of near-surface soil moisture retrieved from satellite observations and the values of near-surface soil moisture as they are predicted by land surface modelling schemes. There are a number of reasons for this, including:

- Radiometric biases (hopefully small!);
- Systematic biases in the retrieval of near-surface soil moisture, due to factors (such as topographic effects) not accounted for in the retrieval algorithm;
- Systematic biases in the retrieval of near-surface soil moisture, due to incorrect parameterisation (e.g. incorrect parameterisation of the canopy optical depth/look angle relationship);
- Near surface soil moisture contents predicted by land surface schemes being unrealistic – which is very likely;
- Assumptions made about the soil dielectric/water content relationship, that can have a small but significant influence on the apparent emissivity at a given soil water content (e.g. Burke and Simmonds, 2000).

In many of the point scale studies referred to above such biases are not an issue, because considerable work has gone into ensuring that the SVAT schemes used for the assimilation do a good job of predicting the observed soil moisture contents. However Calvet and Noilhan (2000) provide an interesting example of where biases did exist between the observations of near surface soil moisture and model predictions. They took the approach of including a bias term in the assimilation scheme, and found that the bias between observations and model predictions could be quantified, thereby enabling successful retrieval root zone soil moisture. Furthermore, they found that the magnitude of the bias term varied during the season.

For vegetated surfaces, a complication is that the dynamics of the root zone soil moisture is dominated by the uptake of water by vegetation, which depends strongly on the leaf area index of the crop and on the vertical distribution of roots. Hence in any operational system for the successful retrieval of root zone soil moisture, there is need for information about the extent of the canopy and the depth of rooting. In an analysis of the 1993 PORTOS experiment involving multi-angular, dual polarisation measurements of L-band brightness temperature over a wheat field, Wigneron *et al.*, (2002) have taken the first, promising, steps towards demonstrating how SVAT models coupled with interactive vegetation growth and microwave emission models can be used to assimilate microwave brightness temperatures for the simultaneous retrieval of canopy size, surface and root zone soil moisture and surface temperature. This was a preliminary study to develop new modelling schemes, with no attempt yet to optimise the assimilation process or to analyse the sensitivity of retrievals to the frequency of microwave observation. However, the problem of parameterising rooting depth (particularly in locations where rooting depth is limited by soil conditions) remains a very considerable problem in large scale applications. In summary, it is clear that there are strong possibilities for inferring root zone soil moisture through assimilation of near-surface soil moisture observations (or direct assimilation of brightness temperatures into SVATs. There are a wide range of assimilation techniques being investigated, some of which are more appropriate for operational use than others. It is evident from point scale studies that the temporal frequency of observations required for satisfactory root zone retrievals are of the order of every 3-5 days. The question of systematic biases between observations and predictions of near surface soil moisture is a major issue, though this may well solvable through the use of appropriate assimilation techniques.

4.3 Retrieval of soil hydraulic properties

The ability to retrieve information on soil hydraulic properties using earth observation techniques is high on the 'wish list' of hydrologists and atmospheric modellers seeking to improve the formulation and parameterisation of land surface schemes. In principle, the hydraulic properties of the soil will influence the near-surface soil water dynamics, and so be retrievable from time courses of near-surface soil moisture observations. Figure 4 (from Simmonds and Burke, 1998) illustrates how soils differ in the time course of microwave brightness temperature during a multi-day drying period following irrigation, expressed as differences in both the diurnal amplitude and the day-to-day changes in brightness temperature.

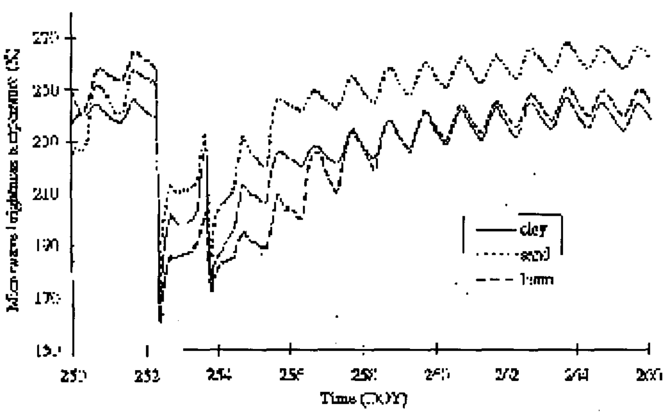

Fig. 4. Simulated time courses of L-band brightness temperature during a multi-day drydown over different soil types.

Retrieval of soil hydraulic properties from either passive microwave observations or more direct observations of near-surface soil moisture has been done effectively at the point scale. For example, Burke *et al.* (1998) showed that the 4 soil parameters describing the water retention and hydraulic conductivity functions within the MICRO-SWEAT model could be well retrieved from detailed time courses of observations during a multi-day dry-down, based on a few passive microwave observations each morning for a number of successive days (examples of results for soil 'b' value and bulk density are shown in Figure 5). This was done by 'tuning' MICRO-SWEAT to achieve the best fit between the observed and simulated time courses of brightness temperature.

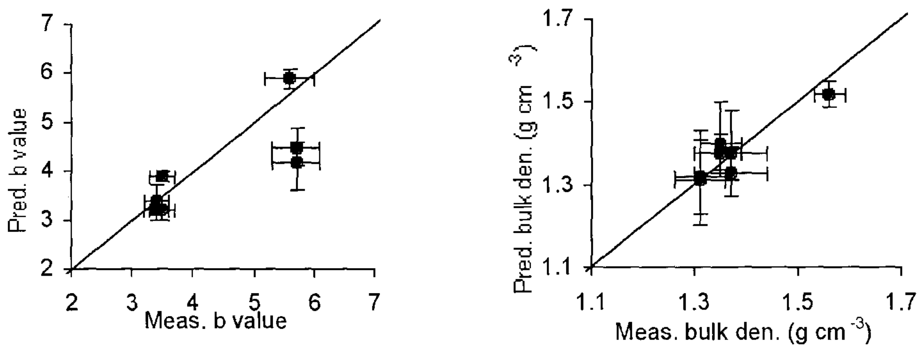

Fig. 5. Examples of the agreement between measured values of the soil "b" value (the exponent in the water release curve function) and bulk density and the values obtained by "tuning" MICRO-SWEAT to best simulate observed time course of microwave brightness temperature. From Burke et al., 1998

Other studies at the point scale have demonstrated similar abilities to retrieve soil hydrulic properties (e.g. Calvet *et al.*, 1998; Montaldo and Albertson, 2001). Studies have also been carried out at using mesoscale models. For example, Hollenbeck *et al.* (1995) and Mattikali *et al.* (1998) showed that near-surface soil moisture estimates retrieved from time series of microwave radiometry during a continous drying sequence enabled effective parameterisation of saturated hydraulic conductivity of the soil as it was used in the model.

There are a number of issues that arise, which require systematic studies to answer. Successful retrieval of some soil hydraulic properties probably requires accurate absolute estimates of soil moisture, whereas other applications of near-surface soil moisture observations (e.g. retrievals of root zone soil moisture) depend more on the detection of temporal changes in soil moisture, and so can be driven by relative soil moisture contents. Retrieval of soil hydraulic properties (e.g. using the techniques used by Burke *et al*, 1998 and Montaldo and Albertson, 2001) probably relies on accurate information on atmospheric forcing. Rainfall is undoubtedly a major issue in this context, but techniques based on observations during known drydowns will avoid problems of uncertainties in rainfall, provided it is known that no rain has fallen.

Studies of the effects of random errors in near surface soil observations on the retrievals of soil hydraulic properties (e.g. Pearson and Simmonds, University of Reading, unpublished) or evaporation (e.g. Chanzy *et al*, 1995) resulted in the very similar conclusions that random errors of about 4% volumetric water content or 8K brightness temperature were acceptable.

This is not a surprising result. The range of volumetric water content between field capacity and the permanent wilting point is typically between 10 and 20%, so a random error of 4% by volume would allow discrimination of 3-6 classes of soil wetness within the available water range. The upper few centimetres of the soil will have a rather wider range of observable water contents, as there will be times when the soil water content either exceeds field capacity or is drier than the permanent wilting point. Hence the ability to estimate volumetric soil water content to 4% by volume enables even more classes of soil wetness to be distinguished.

However, distinction should be made between the impacts of random and systematic errors in the retrievals of near surface soil moisture status. Systematic errors might be tolerable in the retrieval of root-zone soil moisture, provided that the possibility of such biases is recognised and accounted for in the assimilation procedure (as demonstrated by Calvet and Noilhan, 2000). The same is not necessarily true in the case of the retrieval of soil hydraulic properties. However, there is insufficient evidence to be more quantitative statements at this stage about the absolute accuracy requirements for the retrieval of soil hydraulic properties.

No clear picture has yet emerged as to the temporal requirements for the retrieval of soil hydraulic properties. A number of studies have used either daily or sub-daily observations of near-surface soil moisture for the retrieval of dynamic soil hydraulic properties (e.g. Burke *et al.*, 1998; Montaldo and Albertson, 2001) – but these studies did not consider how effective less frequent observations might have been. Calvet *et al.* (1998) showed that soil hydraulic properties that do not rely on rates of change of water content for their estimation (in their case, the field capacity water content) could be retrieved as part of the retrieval of root zone soil moisture (i.e. requiring observations every 3-5 days). Probably the most that can be concluded at this stage is the retrieval of dynamic soil hydraulic properties requires several observations during a dry-down, and so the frequency of observations required probably depends on the temporal rainfall distribution, but will typically require a revisit time of 1-2 days (e.g. Ahuja *et al.*, 1993).

4.4. Soil Freezing

Soil freezing can be a serious complication to the retrieval of soil moisture information from passive microwave observations, because of the large impact of freezing on the dielectric constant. On the other hand, the detection of soil freezing, if possible, could be a significant benefit to end users. The impact of soil freezing is illustrated in Figure 6, which shows a time course of L-band brightness temperatures measured using the University of Reading SWAMP radiometer over a a few m^2 of bare soil during a winter period. On mornings where there was transient freezing there were evident spikes in the time course of brightness temperature with magnitudes ranging from over 60K when the soil was at its wettest to less than 20K, the peaks of which occurred about 0600 GMT. There is a suggestion in Figure 5 that the magnitude of the peaks are smaller towards the end of the period shown when the soil was drier, which might be a combination of the smaller contrast between unfrozen and frozen soil when soils are relatively dry, and the likely shallower depth of freezing that is expected when soils are relatively dry.

The potential for detecting soil freezing may have useful applications. Freezing/thawing can have major impact on the heat balance, accounting for half the annual heat balance in Arctic areas (Wismann, 2000). In such areas, the duration of freezing can have important implications for the annual bioproductivity, with implications for evaporation and the carbon budget. For example, interannual variations in bioproductivity of the forests in boreal regions can account for 30% of the annual variability in the CO_2 concentration at Mauna Loa (referred to by Wismann, 2000). In this context, relatively coarse resolution information about freeze/thaw status would be extremely valuable if available at temporal resolutions of the order of a few days.

At lower latitudes, the ability to detect very transient (i.e. early morning) freezing events could have useful application. Implicit in such transient freezing events is the knowledge of the surface temperature, which can be used as verification/initialisation of NWP models. The potential value of such information is implicit in the study described by Viterbo *et al.* (1999) which was motivated by the realisation that the 1993-96 version of the ECMWF model had a pronounced near-surface cold bias, which was exacerbated by an over-strong positive feedback that exists in the land surface boundary-layer coupling. The purpose of the Viterbo et al. paper was to present improvements to

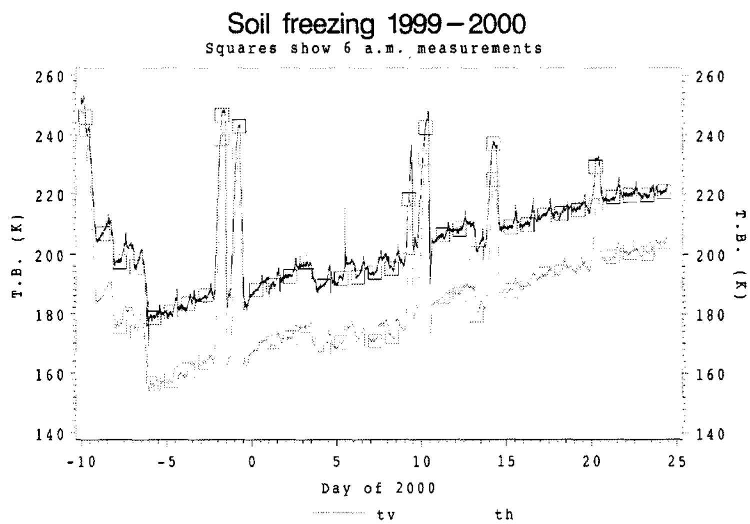

Fig. 6. The time course of brightness temperature measured over fallow soil using the University of Reading SWMAP L band radiometer during a winter period. The squares indicate 0600 readings. The early morning "spikes" evident on some days were due to transient soil freezing.

the model to reduce such bias problems through better formulation of the soil freezing process. The implication from this study was that the strength of the land surface-atmosphere feedbacks via soil freezing can have major impact on forecasting, implying considerable potential benefits of having observations of transient freezing in near real time.

Key issues arising are:

i. How large do freezing "spikes" have to be in order to be identified unequivocally against a background of fluctuating brightness temperature in response to changes in soil temperature, soil moisture and vegetation?

ii. What are the implications of i) for the accuracy of brightness temperature observations required to detect soil freezing?

iii. What temporal frequency do NWP modellers require?

5. IMPLICATIONS FOR MISSION REQUIREMENTS

It is useful to conclude by summarising the implications of the discussions above for the technical requirements of a future L-band passive microwave mission, that take account of both the requirements of the various groups of potential end users, and any requirements that there might be for optimising the mission with respect to retrieval algorithms. The table below is a tentative attempt at this, though in some cases (indicated by question marks) it is difficult to specify appropriate values.

	Spatial resolution	Temporal resolution	Accuracy of observations	Time of day	Comments
OPERATIONAL NWP MODELS					
Root zone soil moisture retrieval	50 km	3d	4% soil moisture (1)	Sunrise	Global forecasting. Retrieved by assimilation of near-surface soil moisture (often in combination with near-surface observations of other types), to improve estimations of rainfall and latent/sensible heat partitioning.
	10 km	3d	4% soil moisture	Sunrise	Meso-scale forecasting. Retrieved by assimilation of near-surface soil moisture (often in combination with near-surface observations of other types), to improve estimations of rainfall and latent/sensible heat partitioning.
Freezing	50 km	5d	5K Tb (2)	Any	Detection of duration of winter freezing in Arctic regions which can vary by 30 days from year to year. Other instruments may be more appropriate (e.g. scatterometry).
	10-50 km	1d	5K Tb	Sunrise	Identification of areas with transient freezing in significant proportion of grid element within NWP models. Used either for model verification or initialisation.
DEVELOPMENT/VALIDATION/PARAMETERISATION OF GCM LAND SURFACE SCHEMES					
Soil hydraulic properties	10-50 km	1d? Sampling should extent over sufficiently long time window including multiple wetting/dry ing phases	4% soil moisture	?	Calibration of soil model forced by observed precipitation (and evaporation) using surface moisture time series. Need good rain data and evaporation estimate (but retrospective analysis possible).

Development, validation and parameterisation of models relating soil moisture to CO_2 and latent heat fluxes	10 km	3d	4% soil moisture	Sunrise	Comparison with "flask" experiments in which CO_2 and water vapour balances of boundary layer (P-E) are measured over grid elements.
	50 km	3d	4% soil moisture	Sunrise	Comparison with temporal fluctuations of global atmospheric CO_2.
HYDROLOGICAL MODELS					
Surface run-off due to infiltration excess	1-10 km	1d	???	Any	Doubtful whether spatial resolution and accuracy of passive microwave is appropriate
Evaporation, via retrieval of root zone soil moisture	50 km	3d	4% soil moisture	Sunrise	Seasonal water balances at global scale Onset of surface run-off due to saturation excess at high latitudes
	10 km	3d	4% soil moisture	Sunrise	Seasonal water balances at global scale Onset of surface run-off due to saturation excess at high latitudes
	1 km	3d	4% soil moisture	Sunrise	Seasonal water balances at catchment scale
Soil hydraulic properties	1-50 km	1d? Sampling should extent over sufficiently	4% soil moisture	?	Calibration of soil model forced by observed precipitation (and evaporation) using surface moisture time series. Need good rain data
		long time window including multiple wetting/dry ing phases			and evaporation estimate (but retrospective analysis possible)

VEGETATION MODELLERS					
Qualitative changes or variation in biomass inferred from microwave optical depth	10-50 km	>5d	?	Any	Advantage over visible/IR observations because saturates at much higher canopy biomass. Potentially useful for diagnosing spatial and interannual variation in biomass.
Crop/natural vegetation stress monitoring	10-50 km	3d	2K Tb	Any	Anomalously high Tb indicating unusually hot/dry surface
	1-10 km	3d	4% soil moisture	Sunrise	Stress detections through estimation of root zone soil moisture.
OTHER					
Fire risk	1-10 km	3d	2K Tb	Any	Detected as anomalously high Tb, due to combination of hot/dry soil

Footnotes:
• 4% soil moisture in effect allows the available water range to be divided into about 5 classes.
• On bare wet soil, freezing can change the brightness temperature by 60-80 K. The value of 5 K shown in the table allows for the presence of vegetation reducing the sensitivity of brightness temperature to soil water, and also to allow detection of partial freezing of the soil surface within the pixel.
• The spatial resolution requirements are based on the assumption that the current generation of global and mesoscale models are being operated at typical spatial resolutions of 50 and 10 km respectively.

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