Temporal and Spatial Resolution Requirements for a Soil Moisture Mission

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***Abstract* – The temporal and spatial resolution requirements for a soil moisture mission are addressed through a synthetic identical twin data assimilation study. Simulations were made for observations with various temporal resolutions (1, 2, 3, 5, 10, 15, 20 and 30 days), and spatial resolutions (0.5, 6, 12 18, 30, 60 and 120 minutes of arc). It was found that daily observations of surface soil moisture achieved the best predictions of soil moisture and evapotranspiration, with the greatest impact of temporal resolution being for 1 to 5 days. It was also found that observations with a spatial resolution less than the model resolution produced the best results, with spatial resolutions greater than the model resolution yielding only a slight degradation.**

I. INTRODUCTION

Defensible requirements of a remote sensing mission for the measurement of surface soil moisture are of vital importance to scientists planning such a mission. In particular, mission planners need: (i) justification for polarization, wavelength and look angle requirements of the sensor; and (ii) accuracy, temporal resolution and spatial resolution requirements of the measurement. The requirements of (i) have been fairly well defined, with horizontally polarized L-band radiometer measurements at a look angle of less than 50º yielding the greatest sensitivity to soil moisture. However, the requirements of (ii) have been less well defined. This paper seeks to address the last two of those three issues; temporal and spatial resolution requirements. The accuracy requirement has recently been addressed by [1].

II. MODELS

The temporal and spatial resolution requirements are addressed in this paper through a synthetic identical twin data assimilation study. First, a land surface model is used to generate a "truth" data set that provides both the surface soil moisture "observations" and the evaluation data. The land surface forcing data and initial conditions are then degraded to simulate the uncertainties in these data and a second simulation performed. Finally, simulations are made where the observations, with various temporal and spatial resolutions, are assimilated into the simulation with degraded atmospheric forcing data and initial conditions.

A. *Land Surface Model*

The land surface model used in this study is the catchment-based land surface model of [2], illustrated schematically in Fig. 1. It uses a non-traditional land surface model framework that includes an explicit treatment of sub-grid soil moisture variability and its effect on runoff and evaporation. A key innovation in this model is the shape of the land surface element, the hydrologic watershed as defined by the topography, rather than an arbitrary grid.

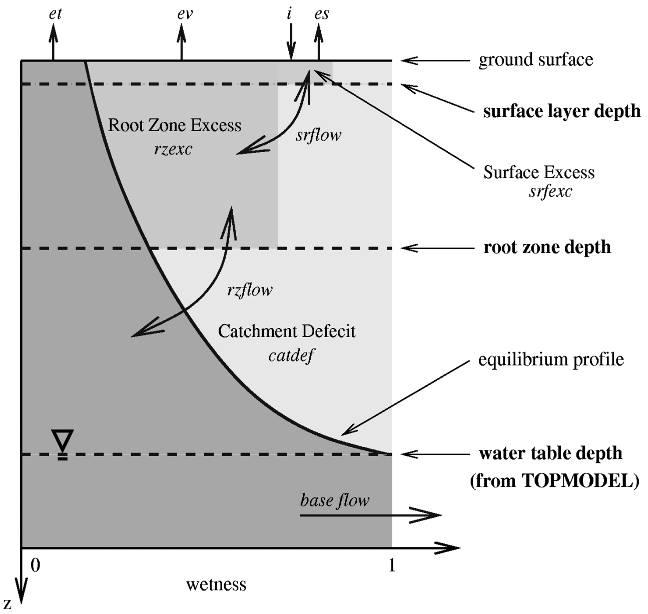

Fig. 1: Schematic of the catchment-based land surface model.

This land surface model uses TOPMODEL [3] concepts to relate the water table distribution to the topography. The consideration of both the water table distribution and non-equilibrium conditions in the root zone leads to the definition of three bulk moisture prognostic variables (catchment deficit, root zone excess and surface excess) and a special treatment of moisture transfer between them. Using these three prognostic variables, the catchment may be divided into regions of stressed, unstressed and saturated soil moisture regimes. A complete description of this model is given in [2].

B. *Kalman Filter*

The Kalman filter algorithm tracks the conditional mean of a statistically optimal estimate of a state vector and its covariance matrix, through a series of forecasting and update steps [4]. In this study, we have used a one-dimensional Kalman filter for updating the soil moisture prognostic variables of the land surface model. A one-dimensional Kalman filter was used because of its computational efficiency and the fact that at the scale of catchments used, correlation between the soil moisture prognostic variables of adjacent catchments is only through the large-scale correlation of atmospheric forcing. Moreover, all calculations for soil moisture in the land sur-

TABLE 1
UNIFORM SOIL PROPERTIES SPECIFIED FOR NORTH AMERICA

saturated surface hydraulic conductivity	2.2×10^{-3} m s^{-1}
transmittivity decay factor	3.26 m^{-1}
saturated soil matric potential	−0.281 m
Clapp and Hornberger *b*	4
root zone depth	1 m
wilting point	14.8 % v/v

face model are performed independent of the soil moisture in adjacent catchments.

For the initial covariance matrix, diagonal terms were specified to have a standard deviation of the maximum difference between the initial prognostic state value and the upper and lower limits, with off diagonal terms specified as zero. The diagonal terms of the forecast model error covariance matrix were taken to be the predefined values of 0.0025, 0.025 and 0.25 mm/min for *srfexc*, *rzexc* and *catdef* respectively, with the off diagonal terms taken to be zero.

III. SYNTHETIC EXPERIMENTS

To demonstrate the effect of temporal and spatial resolution of surface soil moisture measurements in retrieving the soil moisture profile by assimilation, a set of synthetic experiments have been undertaken for the entire North American continent.

A. *Model Input Data*

In this study, atmospheric forcing data and soil and vegetation properties from the first International Satellite Land Surface Climatology Project (ISLSCP) initiative [5] have been used as model input for the year 1987. Soil properties not defined by ISLSCP were assumed uniform with the values in Table 1. Total soil depth had a variation of 1 to 3.6 m. Initial model states were derived by driving the model to equilibrium at the beginning of 1987.

B. *Observation and Evaluation Data*

Using the catchment-based land surface model of [2], the initial conditions from spin-up and the model input data described above, the temporal and spatial variation of soil moisture across the North American continent was forecast for 1987. The forecasts of surface soil moisture were output once per day to represent the soil moisture that would be measured by a remote sensing satellite. This data was then sub-sampled to represent observations with a temporal resolution of 1, 2, 3, 5, 10, 20 and 30 days. The spatial resolution study was performed for a temporal resolution of 3 days, as this is the most likely temporal resolution of any near-future soil moisture missions. Using the stressed, unstressed and saturated soil moisture output from the catchment-based land surface model, and the spatial variation of compound topographic index within a catchment at 30 seconds of arc, the catchment-based model output of surface soil moisture was transformed to a gridded 30 seconds of arc observation data set. This data set was then aggregated up to resolutions of 0.5, 6, 12, 18, 30, 60 and 120 minutes of arc, and transformed back to the catchment space. In addition to surface soil moisture observation data, this simulation provided the data for evaluation of degraded simulations.

TABLE 2
STANDARD DEVIATIONS USED FOR APPLYING RANDOM PERTURBATION TO THE INITIAL CONDITIONS AND ATMOSPHERIC FORCING DATA

srfexc	1 mm
rzexc	10 mm
catdef	100 mm
convective precipitation	50% or 0.1 to 8 mm hr^{-1}
total precipitation	50% or 0.1 to 8 mm hr^{-1}
2 m air temperature	5 °C
2 m dewpoint temperature	5 °C
downward longwave radiation	25 w m^{-2}
downward shortwave radiation	50 w m^{-2}
surface pressure	1 kPa
10 m wind speed	1 m s^{-1}

C. *Degraded Simulation*

To represent the errors associated with forecast land surface states in a typical land surface model simulation as a result of poor initial conditions and errors in atmospheric forcing data, both the initial conditions and forcing data were degraded. The initial conditions were degraded by applying zero mean normally distributed random perturbations with the standard deviations given in Table 2, to each of the three soil moisture prognostic variables from the original spin-up data. The forcing data were similarly degraded using the standard deviations in Table 2 to represent the uncertainty associated with atmospheric forcing data, as a result of both measurement and interpolation error.

Applying perturbations to precipitation was more difficult than other forcing parameters, as the occurrence of precipitation is an intermittent process. Hence, precipitation was perturbed by a fraction of the precipitation rate to account for spatial variability. To account for the fact that precipitation could have occurred even when the data suggested there was none, a perturbation to precipitation was added whenever a randomly distributed zero mean number greater than three times its standard deviation was generated. Under this situation, the standard deviation for the perturbation was taken as 1 mm hr^{-1}, multiplied by the ratio of mean annual precipitation for the catchment (55 mm to 4595 mm) to the average mean annual precipitation (595 mm) for the North American continent. As wind speed, downward radiation and precipitation cannot be negative, negative values after perturbation were truncated to zero.

D. *Effect of Temporal and Spatial Resolution*

To demonstrate the effect of temporal and spatial resolution of surface soil moisture observations on soil moisture profile retrieval, individual simulations were made where the observations with various temporal and spatial resolutions were assimilated into the degraded simulation described above. The effects of temporal and spatial resolution on the rms and mean error of both soil moisture and evapotranspiration forecasts are shown in Figs. 2 and 3 respectively.

The results from this spatial resolution study do not take into account the additional information, such as fraction of catchment in stressed, unstressed and saturated soil moisture

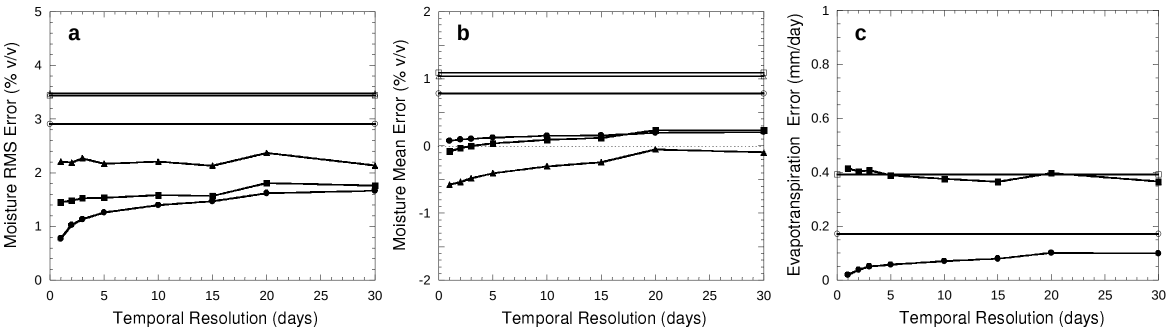

Fig. 2: Effect of surface soil moisture data temporal resolution on: a) surface (circle), root zone (square) and profile (triangle) soil moisture rms error; b) surface (circle), root zone (square) and profile (triangle) soil moisture mean error; and c) evapotranspiration rms (square) and mean (circle) error. Simulations with assimilation (solid symbols) are compared with the simulation without assimilation (open symbols). Spatial resolution of observation data is 0 minutes of arc.

regimes, which can be obtained from the higher spatial resolution observations. Moreover, these results are applicable to a land surface model with spatial resolution of approximately 30 minutes of arc, land surface models with a finer spatial resolution may show a stronger dependence on spatial resolution. While not shown here, the rms error in soil moisture observations as a result of spatial resolution rose quickly from zero at the finest resolution to approximately 1.5%v/v at 30 minutes of arc (the land surface model resolution), and then increased only marginally for coarser resolutions.

IV. CONCLUSIONS

It was found that daily observations of near-surface soil moisture were required to achieve the best results for soil moisture and evapotranspiration prediction using a land surface model with average spatial resolution of 30 minutes of arc, particularly for surface soil moisture and evapotranspiration. Longer times between observations had only a minor impact on the root zone and total soil moisture profile assimilation capability. The greatest impact of temporal resolution was from 1 to 5 days, with longer times between observations having a marginal degradation from 5 days. Moreover, surface soil moisture observations with a spatial resolution less than the model resolution were found to produce the best prediction of soil moisture and evapotranspiration. Observations with a spatial resolution greater than the model resolution produced only slightly poorer results than observations at the model resolution. Assimilation of observations at half the spatial resolution of the land surface model was found to be a good compromise. The results also indicate that spatial resolution is more important than temporal resolution.

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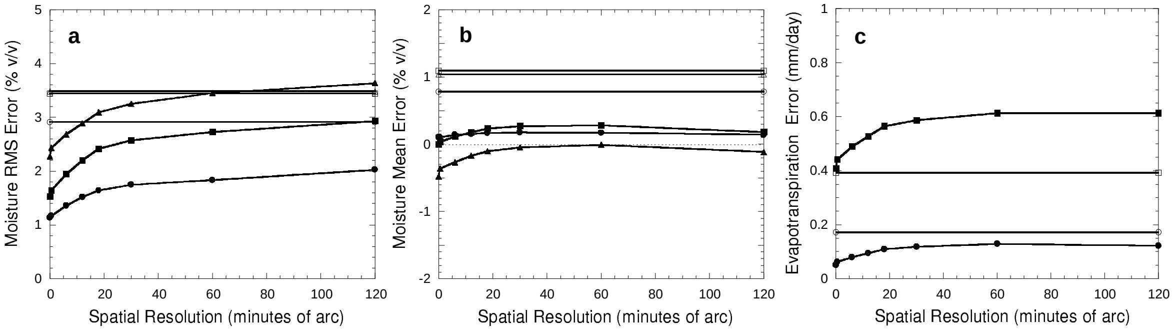

Fig. 3: Effect of surface soil moisture data spatial resolution on: a) surface (circle), root zone (square) and profile (triangle) soil moisture rms error; b) surface (circle), root zone (square) and profile (triangle) soil moisture mean error; and c) evapotranspiration rms (square) and mean (circle) error. Simulations with assimilation (solid symbols) are compared with the simulation without assimilation (open symbols). Surface soil moisture data are assimilated every 3 days.