Land Surface Model Data Assimilation for Atmospheric Prediction

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Introduction

Accurate latent and sensible heat flux prediction in response to land surface soil moisture at mid-latitudes has been shown to be as important as sea surface temperature in making accurate precipitation prediction at mid-latitudes over land (Koster et al., 2000). Unfortunately, land surface models typically give a poor prediction of soil moisture and atmospheric feedback, with large differences between predictions from different models even when using the same parameters, inputs, and initial conditions (Houser et al., 2001). To overcome this limitation, assimilation of observed quantities has been pursued. One of the earliest approaches has been the assimilation of screen level air temperature and relative humidity (eg. Mahfouf, 1991), which are only weakly related to soil moisture and not widely observed in remote areas. More recently, a wide range of alternate assimilation approaches have been explored for accurate land surface model prediction of soil moisture. Such approaches include the assimilation of i) remotely sensed near-surface soil moisture, ii) streamflow, iii) changes in terrestrial gravity, and iv) remotely sensed latent and sensible heat flux. This paper briefly describes progress from these approaches.

Soil Moisture Remote Sensing

Over the past two decades there have been numerous near-surface soil moisture remote sensing studies, using visible, thermal infrared (surface temperature) and microwave (passive and active) electromagnetic radiation. Of these, passive microwave soil moisture measurement has been the most promising technique, due to its all-weather capability, its direct relationship with soil moisture through the soil's dielectric constant, and a reduced sensitivity to land surface roughness and vegetation cover (Njoku et al., 2002). Due to the long wavelengths required for soil moisture remote sensing, space-borne passive microwave radiometers (both current and planned) have a coarse spatial resolution, being on the order of 50km, but have a frequent temporal resolution of 1 to 2 days.

May 2002 saw the launch of NASA's Advanced Microwave Scanning Radiometer for the Earth observing system (AMSR-E) on the Aqua satellite, the first passive microwave sensor in space with appropriate frequencies for measuring near-surface soil moisture content since the Scanning Multi-channel Microwave Radiometer (SMMR) ceased operations in 1987. During the SMMR mission, soil moisture remote sensing was in its infancy, and so there were no dedicated field campaigns for verification of remotely sensed and derived root zone soil moisture. This lack of concurrent data has made evaluation of SMMR-based studies effectively impossible (Walker et al., 2003). In addition to AMSR-E, there are two dedicated soil moisture missions planned with optimal frequencies for soil moisture measurement. These are the ESA Soil Moisture and Ocean Salinity (SMOS) and NASA HYDROspheric States (HYDROS) satellites to be launched in 2007 and 2009 respectively.

While these remote sensing satellites may be used to give measurements of soil moisture in the top few centimetres for areas with low to moderate vegetation cover, they do not provide any direct information on root zone soil moisture. However, there are a number of studies over the past decade that have shown the potential for improving near-surface and root zone soil moisture, and the resultant latent and sensible heat flux predictions, through the assimilation of this data into a land surface model. Moreover, a number of operational forecast centres are actively expanding their capacity in this direction in anticipation of data that will soon be available from SMOS and HYDROS. An example of how such data may be used to constrain root zone soil moisture predictions is given in Fig. 1.

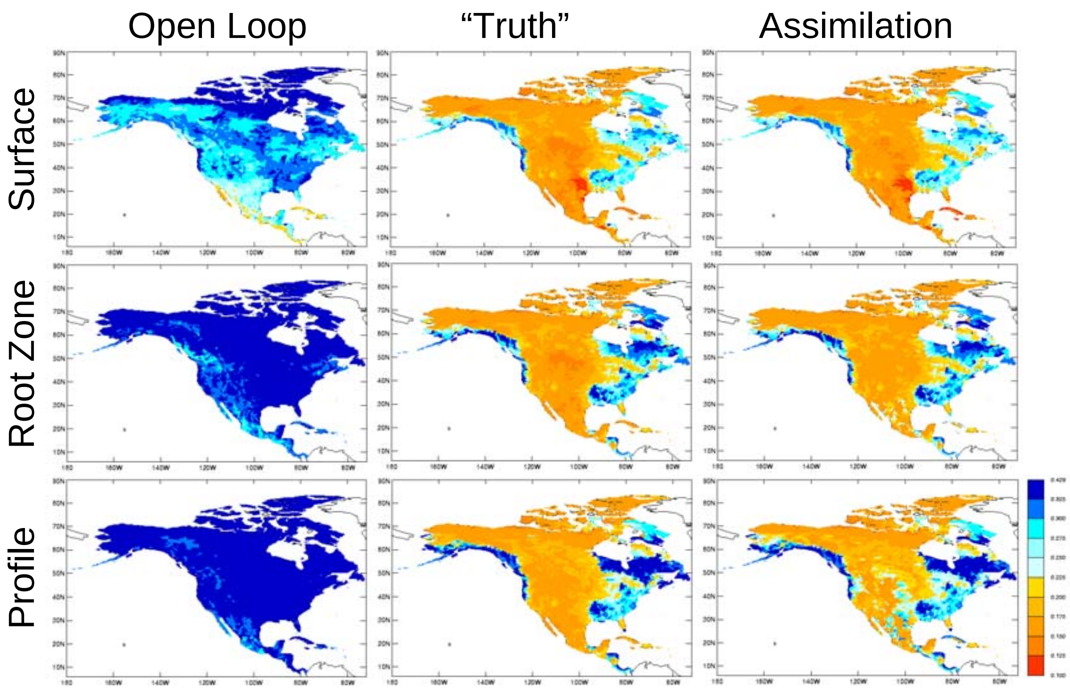

Fig. 1: Comparison of soil moisture (v/v) simulations in the near-surface layer (top row), root zone (middle row) and entire soil profile (bottom row) from degraded soil moisture initial conditions (left column), spin-up initial conditions (middle column), and degraded soil moisture initial conditions with assimilation of synthetic near-surface soil moisture observations from the true simulation once every 3 days (right column). Results are after 1 month of simulation (Walker and Houser, 2001).

Streamflow Observations

While there have been encouraging results from the assimilation of remotely sensed near-surface soil moisture data into land surface models, it is unlikely that this approach will satisfactorily address the predictability problem alone. The reasons for this are that i) current remote sensing of surface soil moisture is limited to regions of low-to-moderate vegetation (Jackson et al., 1982), ii) land surface models typically show the greatest uncertainty in regions of high vegetation (Houser et al., 2001), and iii) the regions where soil moisture knowledge is expected to have the greatest impact on precipitation prediction are also largely located in regions of high vegetation (Koster et al., 2000). This means that alternate approaches for soil moisture estimation must be sought if improvements in precipitation prediction are to be realised for these regions.

To overcome these limitations, the possibility of constraining land surface model soil moisture prediction through assimilation of widely available streamflow observations has been studied (Rüdiger et al., 2004; 2005). The basis of this approach is that streamflow is dependent upon the lumped soil moisture conditions in the upstream catchment(s) in response to rainfall events hours to weeks in the past. It has been shown that the assimilation of streamflow can have a significant improvement in the retrieval of profile and root zone soil moisture, but displays limitations in retrieving the surface soil moisture state (Fig. 2). In contrast, the assimilation of near-surface soil moisture in a single low-to-moderately vegetated catchment alone does not have any effect on the other catchments, as there is no feedback between the soil moisture predictions and respective runoff at the scale of catchments used in this simulation. However, the joint assimilation of both streamflow and surface soil moisture observations leads to a further improvement from the streamflow assimilation alone.

Gravity Remote Sensing

A new and novel remote sensing system is the Gravity Recovery And Climate Experiment (GRACE), which provides precise measurements of temporal changes in the Earth’s gravity field that are related to changes in terrestrial water storage (soil moisture, groundwater, river and reservoir storage, and

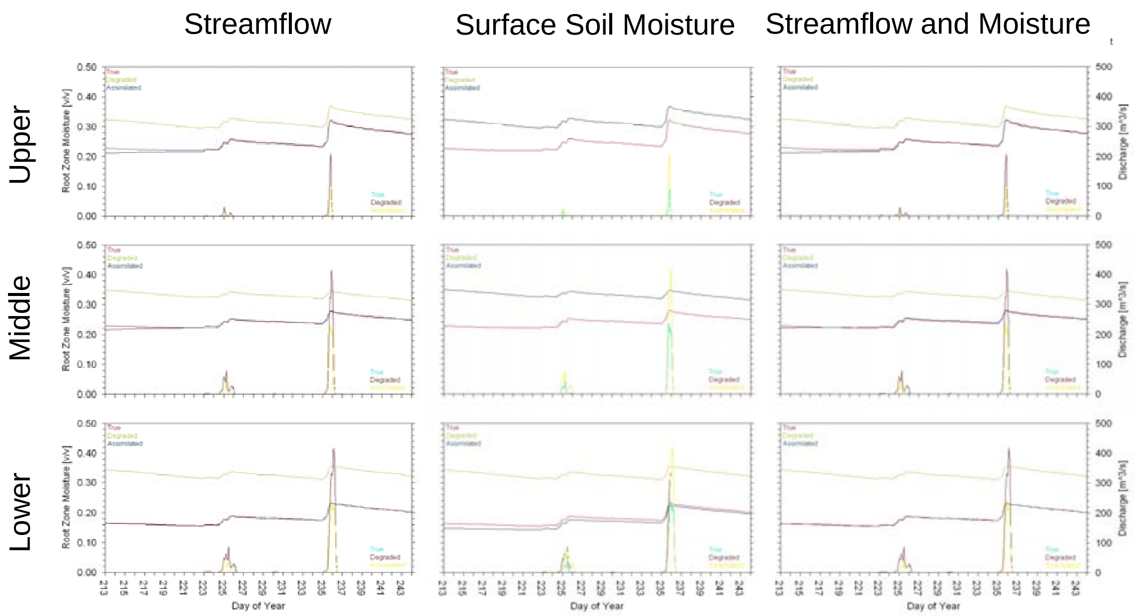

Fig. 2: Comparison of root zone soil moisture and runoff for an upper (top row), middle (middle row) and lower catchment (bottom row) with assimilation of streamflow at the outlet (left column), near-surface soil moisture in the lower catchment only (middle column), and both streamflow at the outlet and near-surface soil moisture in the middle catchment (right column). True observations are shown in red, open loop simulation in green, and assimilated results in blue for soil moisture, and turquoise, burgundy and yellow for runoff, respectively (Rüdiger et al., 2005).

snow). These observations of subtle changes in the Earth's gravity field through time are made by precisely monitoring the separation between two satellites in response to mass variations below as they orbit the Earth. While this type of observation is not constrained by vegetation, these estimates are for very large areas, on order 1000km (Rodell and Famiglietti, 1999). However, through assimilation of observed changes in terrestrial water storage at monthly timescales, the ability to improve soil moisture estimates for smaller areas has been demonstrated (Fig. 3).

Latent and Sensible Heat Flux Remote Sensing

A key assumption of the foregoing approaches is that a correct physical soil moisture content estimate for the land surface model will result in an improved flux estimate. As most land surface models used by atmospheric models have historically used soil moisture as simply a tuning parameter rather than a physical quantity, improved flux prediction is not guaranteed when a soil moisture (particularly a physical soil moisture) observation is assimilated. Since land surface fluxes can be estimated from thermal remote sensing (Savige et al., 2005), it is also possible to constrain model soil moisture and temperature predictions using these observations under cloud free conditions. Research is underway to explore the impact from assimilating observed sensible and latent heat flux data into a land surface model, to correct the model's prediction of latent and sensible heat flux by modifying the model's prediction of soil moisture and temperature (Pipunic et al., 2004). The impact of assimilation on these states can then be compared with observations. This is an approach that has received little attention to date, with Schuurmans et al. (2003) representing one of the few published examples of this approach, which suffered from lack of an appropriate validation.

Discussion

Progress on land surface initialisation is being made on a number of fronts, each with their own inherent strengths and weaknesses. Hence a combination of these approaches is required to yield the accurate flux and soil moisture predictions required for atmospheric prediction. Additionally, the next major advances in land surface initialization for atmospheric prediction will not be realised until lessons learned from these off-line model simulations are actually incorporated with an atmospheric prediction model.

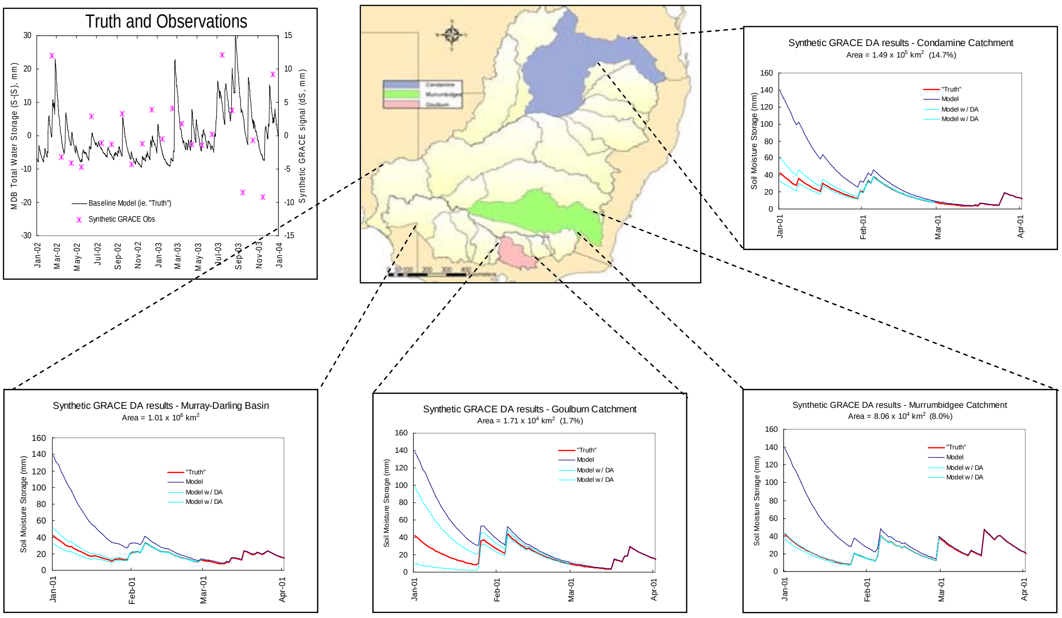

Fig. 3: Comparison of retrieved and true soil moisture estimates for catchments of the Murray Darling Basin from assimilation of monthly total terrestrial water storage for the entire Murray Darling Basin (Ellett et al., 2004).

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