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Assimilation of gravity data into a soil moisture and groundwater column model

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Gravity has the potential to become a new source of important remote sensing data for catchment-scale hydrological modelling. Monitoring of changes in the earths gravity field through time is expected to yield information on the change in terrestrial water storage (soil moisture, groundwater, etc) over that time period. However, the usefulness of this data has not yet been demonstrated. Specifically, the ability to accurately disaggregate the vertical (and spatial) distribution of terrestrial water storage change information contained in gravity measurements has not been explored. Through a series of synthetic twin studies, we seek to demonstrate the potential for gravity data to constrain a land surface model through data assimilation, and thus yield more accurate predictions of soil moisture profile distribution and groundwater storage. This pilot study uses a simple soil column model to describe the temporal variation of soil moisture and groundwater for a point in the landscape; we do not address the spatial disaggregation problem in this paper, which presents a methodology but no results.

Introduction Soil moisture is important for a number of applications, including global climate modelling, numerical weather prediction, rainfall-runoff modelling, and agriculture (*Western et al.*, 2002). For meteorological applications it influences the energy balance by determining the partitioning of available energy at the land surface between latent and sensible heat fluxes. For hydrological applications it influences the water balance by partitioning precipitation between infiltration and runoff. For agriculture the amount and distribution of soil moisture heavily influences crop yield. However, the distribution of soil moisture is not well understood as it is highly variable in both space and time and there is a poor history of systematic monitoring. Hence there is a demonstrated need for improved prediction and monitoring of soil moisture. One potential way to improve predictions is from remotely sensed data assimilation.

With the recent launch of GRACE satellites in 2002, routinely collected gravity data has become a potential new source of remote sensing information for catchment-scale hydrological modelling. Monitoring changes in the earth's gravity field through time is expected to give information on the change in terrestrial water storage, which includes changes in soil moisture, groundwater, snow, lake and reservoir storage, etc, over that time period (*Wahr et al.*, 1998; *Rodell and Famiglietti*, 1999, 2001). However, temporal gravity observations provide only a lumped measure of total terrestrial water storage change over large areas. For these data to be useful, methods need to be developed to (1) relate changes in terrestrial water storage to actual storage levels, (2) vertically disaggregate the terrestrial water storage signal into at least surface, root zone and groundwater components, and (3) spatially downscale from large basin averages to small sub-catchments.

We seek to demonstrate through a series of synthetic twin studies the potential to use gravity data to improve hydrologic prediction of the surface, root zone and groundwater stores; we do not address the spatial downscaling in the context of this paper. Our approach uses the gravity data to constrain a land surface model through data assimilation. This pilot study uses a simple soil column model that describes the temporal variation of soil moisture (in three layers: near-surface, root zone and vadose zone) and groundwater. We present the methodology in this paper, but no results.

Model A simple column bucket model is used to predict the one-dimensional profile water storage in four different moisture stores. The first storage represents a shallow near-surface layer of 1 cm thickness (equivalent to the depth measured by passive microwave remote sensing satellites such as AMSR-E). The second storage represents the root zone, which we take to be approximately the top 1 m of soil. This is followed by vadose zone storage to approximately 4 m depth. Finally there is groundwater storage with an impermeable boundary assumed at 10 m depth.

The physics of the model are summarised as follows. Precipitation recharges the near-surface storage only. Bare soil evaporation (assumed to be 10% of the potential evapotranspiration multiplied by a moisture index for the near-surface store; the moisture index is the storage amount divided by storage capacity) is taken from the near-surface storage, and transpiration (assumed to be 90% of the potential evapotranspiration multiplied by the moisture index for the root zone store) is taken from the root zone storage. Water percolates down through the soil column to the underlying layer under gravity drainage. The gravity drainage is approximated as the saturated hydraulic conductivity multiplied by the moisture index of the origin store, constrained by the capacity of the receiving store. There is no possibility for water to move upward through the soil column or to be redistributed horizontally. Water is released from the groundwater store as baseflow, estimated as saturated hydraulic conductivity multiplied by the moisture index for the groundwater store. The model is run on a daily time step.

Data The observation and evaluation data to be used for this investigation are synthetically generated from the column bucket model described above. The only input data required by the model are saturated hydraulic conductivity (assumed as 5 $\mathrm{mm\,h^{-1}}$), soil porosity (assumed as 50% v/v), initial moisture storage levels, precipitation, and potential evapotranspiration. Precipitation and evapotranspiration data are taken from 2-years of the Nerrigundah catchment data set (*Walker et al.*, 2001). The catchment is located in temperate south eastern Australia.

Initial conditions for the moisture stores are obtained through repeated simulation of the model for 10 years using a single year of forcing data. The model is then run for the two years of forcing data to provide the "truth" evaluation data for vertical distribution of soil moisture and groundwater. The monthly synthetic gravity data "observations" are generated from the model output of soil moisture and groundwater at the start of each month.

Data Assimilation Two assimilation approaches are explored for the retrieval of soil moisture and groundwater from the monthly observations of gravity. These are the Kalman filter and variational approaches.

The Kalman filter is used to sequentially assimilate gravity observations as they become available (*Kalman*, 1960). As temporal gravity data is only useful in terms of the change in gravity from one observation time to the next, rather than the absolute amount (the absolute gravity signal contains information on mass of the earth etc which is not part of a typical land surface model), the assimilation scheme either needs to include an additional state (change in total terrestrial water storage) or be used to estimate an additional parameter (the time invariant component of the gravity signal). In this way either changes in observed gravity, or the absolute gravity observation itself, may be sequentially assimilated. We have chosen the latter approach, with an added assumption that we actually know the time invariant component of the gravity signal. Further refinements to the algorithm will explore ways to determine this through the assimilation procedure.

The variational approach is used to assimilate the gravity data by considering the match between model predictions and observations over some time window. In this way the models predictions of change in gravity (by difference between the two observation times) are optimised against the observed changes in gravity directly, by "calibrating" the model initial conditions. As such this is a conceptually more simple approach. Rather than derive an adjoint to perform the optimisation, we use a "brute-force" approach with standard optimisation software. We explore assimilation window lengths ranging from 1 month to 2 years.

Gravity Observations The Bouger slab approximation is obtained by calculating the gravitational attraction of a subterranean right vertical cylinder, and extending the radius of the cylinder to infinity (*Telford et al.*, 1990). In this way the density of the slab multiplied by its thickness is directly proportional to the gravity. However, there is a change in gravity if the density is held constant but there is a change in height (useful for representing water table fluctuations), or if the height of the slab is maintained and its density is varied (useful for modelling gravity changes due to volumetric soil moisture variation). It should be noted however that the Bouger slab approximation is independent of depth to the source, so that large magnitude hydrological changes result in large magnitude modelled gravity even if the changes take place far underground (e.g., deep water table fluctuations).

Discussion Starting from poor initial conditions a number of simulations will be made for the 2 year time period. Both assimilation and non-assimilation predictions of soil moisture, groundwater and gravity will be compared with the truth and observation data. It is expected that the largest magnitude changes will be most accurately retrieved (usually groundwater table fluctuations) and that the assimilation will be ineffective for the smallest magnitude changes (near-surface soil moisture). This is particularly so if the Bouger slab model is used as it assumes independence of depth to source, contrary to the inverse distance square law of gravity. It is also hypothesised that maximum sensitivity will be obtained by having the water storages in terms of dimensionless volumetric water content rather than storage amounts. The longer assimilation windows are expected to give best results in the case of perfect model, forcing and observation data, but shorter assimilation windows are expected to give best results in the case of significant model and/or forcing error. This is because the initial conditions can be changed more often to account for mass imbalances. Finally, assimilation of daily near-surface soil moisture data (as available from the AMSR-E satellite) together with the monthly gravity data is expected to yield the greatest soil moisture retrieval accuracy. The accuracy requirements of temporal gravity will also be explored through the addition of white noise to gravity observations.

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