MoistureMap: A soil moisture monitoring, prediction and reporting system for sustainable land and water management

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Introduction

Accurate knowledge of current and future spatial variation in surface and root zone soil moisture at high resolution is critical for achieving sustainable land and water management. The fundamental limitation is that spatial and temporal variation in soil moisture is not well known, nor easy to measure or predict. Consequently, the recently funded project described here seeks to develop a prototype soil moisture monitoring, prediction and reporting system (MoistureMap) for Australia, with the Murrumbidgee as the demonstration catchment. The system will provide current and future soil moisture information and its uncertainty at 1km resolution, by combining weather, climate and land surface model predictions with soil moisture data from the European Space Agency's Soil Moisture and Ocean Salinity (SMOS) satellite scheduled for launch in October 2008; the first-ever dedicated microwave soil moisture mission.

The unique feature of this project as compared to existing projects, such as the "Australian Water Availability Project" of the Australian Bureau of Rural Sciences and the "Short Term Climate Outlooks" of the Centre for Ocean, Land and Atmospheres in the USA, is that microwave observations offer a direct measure of surface soil moisture, rather than the indirect measure that thermal observations and energy balance algorithms or rainfall forecasts provide. It is widely recognised that passive microwave is the most promising remote sensing method for soil moisture measurement [*Njoku et al.*, 2002].

While passive microwave remote sensing holds the most promise for cost-effective surface soil moisture mapping, it will not directly provide high resolution observations or information about the deeper soil moisture. Such information can be gleaned from models, but it is limited by the fidelity of model physics, parameter estimates, and atmospheric forcing data. Consequently, remotely sensed observations and model predictions must be combined by data assimilation [*Walker and Houser*, 2005], with point measurements used for verification. MoistureMap will provide near-real-time monitoring and prediction of soil moisture and its uncertainty at 1km resolution, by assimilating (i) low-resolution passive microwave-derived surface soil moisture (SMOS) and (ii) high-resolution thermal infrared skin temperature (MODIS) observations into a land surface model using weather and climate model ensemble forecasts from the Bureau of Meteorology

Approach

The key elements of this project are outlined in Fig. 1. Specifically, it will develop and test innovative techniques for monitoring, prediction and reporting of 1km resolution soil moisture content from extensive ground-, air- and space-based measurements for Australian conditions. Data collected in the field program will consist of: (i) long-term monitoring of soil moisture profiles and supporting data; (ii) air-borne radiobrightness, thermal infrared, shortwave infrared and visible data; and (iii) satellite radiobrightness, thermal infrared, shortwave infrared and visible data from the SMOS and MODIS sensors. While this proposal will rely heavily upon the comprehensive NAFE data sets collected from recent air-borne field experiments in the Murrumbidgee (and Goulburn) Catchments [*Walker et al.*, 2007], additional air-borne and ground-based data collection coincident with SMOS overpasses will be needed to verify the results obtained from real SMOS data. Consequently, MoistureMap and the five projects which underpin its development all leverage off the same air-borne and ground-based monitoring data to be collected.

Study Regions and Data Sets

The field work required by this project will be undertaken in three study areas with distinctly different characteristics. These are the Simpson Desert and Wet Tropics World Heritage Area for SMOS calibration studies, and the Murrumbidgee Catchment for SMOS verification, and demonstration and verification of MoistureMap and the projects that underpin it.

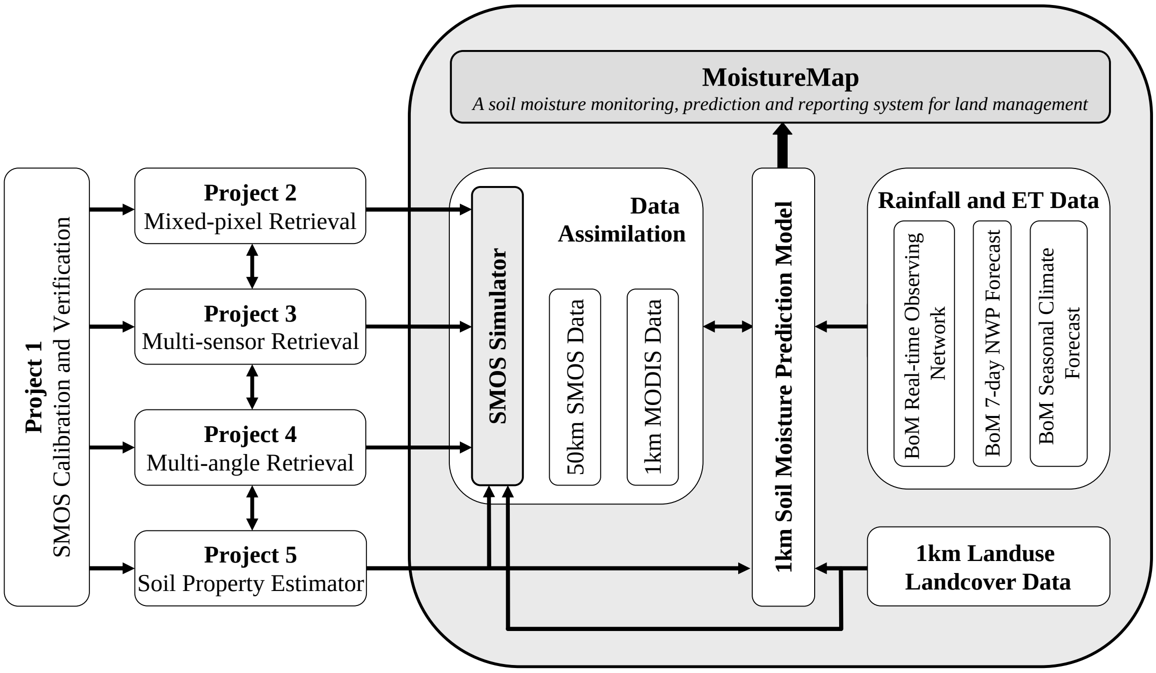

Fig. 1: MoistureMap and its underpinning projects. Project 1 provides calibrated and verified SMOS data for the Australian environment, Projects 2 to 4 develop components of an advanced soil moisture retrieval algorithm (SMOS Simulator) for Australian conditions, and Project 5 derives Australian soil hydraulic properties for soil moisture retrieval and modelling. MoistureMap delivers the current soil moisture information by fusion of model predictions and observations, and future soil moisture information from ensemble weather and climate forecast propagation.

SMOS Radiobrightness and Supporting Measurements: The SMOS satellite will have a spatial resolution of about 50km, with a 6:00am/pm overpass once every 2 to 3 days [*Kerr et al*, 2001]. A unique feature of SMOS is its vertical and horizontal polarisation measurements of radiobrightness at a range of incidence angles for each pixel. Thermal infrared, shortwave infrared and visible data will be provided by the MODIS satellite, which has daily 1km resolution and a 10:30am/pm overpass time. Landuse classification and landcover (vegetation) information will also be provided from MODIS. Thermal data at 4km resolution coincident with SMOS overpasses will be obtained from the hourly MTSAT-1R satellite.

Air-borne Radiobrightness and Supporting Measurements: Air-borne measurements will be made using the Polarimetric L-band Multibeam Radiometer (PLMR) and a thermal infrared imager, together with visible and shortwave infrared measurements, coincident with SMOS overpasses. An integral part of this proposal are calibration campaigns in the Simpson Desert and Wet Tropics, and verification campaigns for a 100km wide transect along the length of the Murrumbidgee Catchment (Fig. 2) under different seasonal and climatic conditions. This 1km resolution air-borne data is a critical component for verification of the 1km MoistureMap predictions of near-surface soil moisture.

Simpson Desert and Wet Tropics World Heritage Area: Deserts, tropical forests and the Antarctic are purported to have spatially and temporally consistent microwave emission characteristics, making them suitable ground-based targets for passive microwave calibration [*Ferrazzoli et al.,* 2002; *Macelloni et al.,* 2006]; a hypothesis that Project 1 will test. Consequently, a 100km area of the Simpson Desert and a 30km area of the Wet Tropics World Heritage Area just north of Port Douglas (the largest expanse of tropical forest that still exists in Australia) have been chosen for the SMOS calibration study; funding to test the Antarctic site is still being sought. Additional to the air-borne data described above, there will be coincident ground and high resolution air-borne characterisation across a small area of these sites. Such data will include soil moisture and temperature, and vegetation biomass, temperature, structure and roughness using ground measurements and a full wave-transform LIDAR.

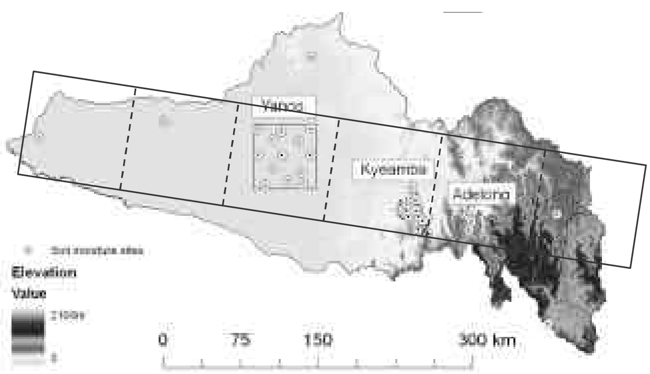

Fig. 2: The Murrumbidgee Catchment showing location of soil moisture monitoring sites, variation in topography, and transect (100km pixels) to be used for verification purposes.

Murrumbidgee Catchment: The Murrumbidgee Catchment has been instrumented and monitored for soil moisture and supporting data for more than 5 years. The existing network of monitoring sites (Fig. 2), data sets, and detailed knowledge of the catchment provide an ideal basis for the field work and data requirements of this research. Moreover, the diverse climatic, topographic and land cover characteristics make it an excellent demonstration test-bed for SMOS Simulator and MoistureMap developments. No intensive ground data collection is planned during the air-borne transect campaigns, as they will be underpinned by the monitoring network.

National Air-borne Field Experiment (NAFE) Dataset: NAFE'06 was undertaken in the Murrumbidgee Catchment during November 2006 [*Walker et al.*, 2007], providing an ideal data set for SMOS soil moisture retrieval and data assimilation developments. The study area included the Yanco area (which contains the Coleambally Irrigation Area) and a 40km x 50km area containing the Kyeamba Catchment (and the city of Wagga Wagga). PLMR and the thermal infrared imager were flown to provide 1km resolution passive microwave data across the Yanco area every 2 to 3 days (and Kyeamba catchment weekly) for a period of 3 weeks, together with extensive ground monitoring. This both simulated a SMOS pixel and provided 1km soil moisture data for surface soil moisture assimilation and downscaling techniques to be tested with remote sensing data which is consistent with that from MODIS and SMOS. Additionally, multi-angular passive microwave data were collected for SMOS algorithm development. Consequently, this data set provides an ideal test-bed for initial development of MoistureMap and Projects 2 to 5, with final testing to be conducted using SMOS, Murrumbidgee Monitoring Network and air-borne transect data.

SMOS Calibration and Verification, the SMOS Simulator, and MoistureMap

The campaigns described above provide the necessary ground-, air- and space-borne data for SMOS calibration and verification studies (Project 1), and verification data of both the SMOS Simulator (Projects 2 to 5) and MoistureMap.

Project 1 – SMOS Calibration and Evaluation: This project will test the hypothesis that desert, rainforest and Antarctic sites are suitable for ground-based SMOS calibration. Aircraft and supporting ground data, together with radiobrightness modelling, will be used to understand spatial and temporal variability in microwave emission from these targets. The campaign observations for the desert (and Antarctic if funded) sites will be compared to SMOS overpass data; as the rainforest site is not suitable for direct comparison with SMOS, knowledge gleaned from the Wet Tropics site will be explored for its transferability to the larger Amazon rainforest. A timeseries of SMOS data will also be analysed for the Simpson, Amazon and Antarctic sites. Finally, SMOS radiances and official SMOS soil moisture products will be compared with coincident PLMR radiances and derived soil moisture content for the Murrumbidgee transect.

Project 2 – Mixed-Pixel Retrieval: This project will test the hypothesis that high resolution optical data can be used to account for the mixed-pixel response that will confound passive microwave retrieval of soil moisture throughout much of Australia. In addition to agricultural and natural variations in land cover, most agriculturally significant parts of Australia contain urban areas and/or standing water across 50km scales; it has been shown that as little as 3% standing water coverage leads to more than 4%v/v error in derived soil moisture [*Walker et al.*, 2006] – the target accuracy for SMOS soil moisture retrieval. Consequently, methods will be developed to account for crop, pasture, urban and water (farm dams, rice paddies, etc) emission contributions to the overall SMOS microwave response. The wide range of landcover characteristics in the Murrumbidgee will provide a thorough test of SMOS retrieval algorithms. The retrieval algorithms will be developed using NAFE'06 data and verified across the Murrumbidgee Catchment using Murrumbidgee transect flight data.

Project 3 – Multi-Sensor Retrieval: This project will test the hypothesis that more accurate soil moisture information can be derived from SMOS if vegetation and soil temperature information are derived from other coincident remote sensing observations at higher resolution. Current state-of-the-art retrieval algorithms require ancillary information on soil properties, surface soil temperature and vegetation water content in order to estimate soil moisture from horizontally polarised passive microwave data. The current approach has been to estimate the vegetation water content using vertically polarised passive microwave data, and soil temperature from 37GHz microwave data [*Owe et al.*, 2001] or model predictions, but there will be no 37GHz observations coincident with SMOS and model estimates are inaccurate [*Betts et al.*, 2003]. However, preliminary analysis of the NAFE'05 dataset has shown that vegetation and temperature data can be estimated with sufficient accuracy from independent visible, shortwave infrared and thermal infrared data, with an overall absolute soil moisture retrieval error better than 6% v/v [*Maggioni et al.*, 2006]. This project will further develop and test algorithms for estimating vegetation water content and soil temperature using NAFE data, apply them to SMOS using visible and shortwave infrared data from MODIS and coincident thermal infrared data from MTSAT1R, and verify the retrieved moisture with Murrumbidgee transect flight data.

Project 4 – Multi-Angle Retrieval: This project will test the hypothesis that more accurate soil moisture information can be derived from SMOS if we take advantage of its unique multi-incidence angle capability.

Microwave emission from the land surface varies as a function of viewing angle. Consequently, there is great potential for retrieving more accurate ancillary data (soil properties, vegetation water content, surface temperature etc.) required by current state-of-the-art retrieval algorithms, and/or reducing the error in derived soil moisture content by simultaneously using all the information that exists in multi-angle observations. A retrieval algorithm will be developed using the multi-angle data collected during the NAFE campaigns, applied to SMOS data, and tested using Murrumbidgee transect flight data.

Project 5 – Soil Property Estimator: This project will test the hypothesis that more accurate soil hydraulic properties can be derived from remotely sensed passive microwave and/or time series soil moisture observations, leading to more accurate soil moisture monitoring and prediction. Specifically, this project will develop techniques to estimate soil wilting point, porosity, hydraulic conductivity and characteristic curve parameters. Methods for soil property estimation will include (i) temporal analysis of timeseries surface soil moisture remote sensing information, (ii) model calibration using, and model assimilation of, timeseries surface soil moisture observations, and (iii) multi-incidence angle and multi-sensor retrieval approaches leveraging developments in Projects 3 and 4.

MoistureMap: This is the framework through which the basic research of Projects 1 to 5 is transferred to a specific application. MoistureMap's development consists of three key components: (i) the soil moisture prediction model, (ii) observed and forecast meteorological data, and (iii) the data assimilation component which contains the SMOS Simulator.

The soil moisture prediction model to be used is CSIRO Atmosphere Biosphere Land Exchange (CABLE), a column model based on Richards' equation that simulates water and energy fluxes between a vertical profile of six soil layers, land surface, vegetation and the atmosphere [*Kowalczyk et al.*, 2006]. This model is ideally suited to the assimilation requirements of this project due to its prediction of surface and root zone soil moisture together with surface soil and vegetation temperature, which are necessary for radiance and thermal data assimilation. Moreover, its grid-based structure makes the 1km application relatively straight forward.

Near-real-time observational data will be provided by WRON and the BoM's existing observational grid-based data streams, and forecast data will be derived from ACCESS. ACCESS will also be run retrospectively from 2005 to enable testing and development with NAFE data, and will provide the meteorological ensemble forecast data out to 7-days and 3-months [*Kamal Puri, pers. comm.*].

The SMOS Simulator will be based on algorithm developments from Projects 2 to 4, together with soils data from Project 5. This will simulate radiobrightness data for comparison with SMOS observations and ultimate assimilation in CABLE. We will use a Bayesian framework to combine the SMOS and MODIS observations with the soil moisture knowledge embodied in an ensemble of CABLE simulations. Initial MoistureMap development will be based on NAFE data followed by extensive verification using Murrumbidgee Monitoring Network and Murrumbidgee transect data.

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