National Airborne Field Experiments for Prediction in Ungauged Basins

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EXTENDED ABSTRACT

Environmental remote sensing has matured significantly over the past two decades as a result of new satellites and intensive airborne campaigns. As such, current remote sensing technology has a huge potential for hydrologic prediction in ungauged basins, through an ability to measure many land surface states, fluxes and parameters that impact on basin prediction. For instance, it is now possible to measure evapotranspiration rates that impact on soil moisture and baseflow, near-surface soil moisture content that controls rainfall partitioning into infiltration and runoff, snow water equivalent of the snow pack that impacts spring-time runoff, vegetation parameters such as leaf area index and greenness that impact on evapotranspiration, land surface elevation and canopy height that impact on runoff routing and evapotranspiration, and so on. However, there are still many unanswered questions that need to be addressed, such as validation of these data products from new sensors, maturing retrieval algorithms, developing techniques for downscaling, and merging remote sensing data with model predictions through the process of data assimilation. To answer these questions and more it is essential that modelling be undertaken in conjunction with field experimentation in well instrumented basins together with intensive ground-based and airborne measurements of the appropriate type and spatial/temporal resolution.

This paper describes the National Airborne Field Experiments (NAFE) planned for 2005 and 2006 (see www.nafe.unimelb.edu.au) in several well instrumented catchments in south-eastern Australia with a range of climatic, land use, land cover and topographic conditions. While these experiments have a particular emphasis on the remote sensing of soil moisture, they are open for collaboration from interested scientists from all disciplines of environmental remote sensing and its application. Moreover, scientists will additionally be addressing questions on carbon budgets, ecohydrology and flood forecasting in 2005, and bushfire prediction, evapotranspiration and precipitation in 2006.

The catchments to be studied in these experiments are i) the Goulburn River experimental catchment in the Upper Hunter during November 2005 and ii) the Yanco/Colleambally and Kyeamba creek experimental areas of the Murrumbidgee catchment during November 2006 (see www.oznet.unimelb.edu.au). Approximately 100 hours of airborne data will be collected across each of the 4-week field campaigns, together with an extensive amount of ground truth data.

The airborne measurements will consist of vertical and horizontal polarisation passive microwave data together with thermal infrared, near infrared, visible and lidar data. Passive microwave data will be collected in both mapping and multi-incidence angle line modes. The mapping data will be collected at a range of spatial resolutions (62.5m to 1km for passive microwave, 1m to 20m for thermal to visible, and 1m for lidar) across spatial extents ranging from individual farms to 50km regions. The high resolution farm data will be collected twice a week at each of 8 farms while low resolution data will be collected once a week for the entire region. Additionally, the CoSMOS-2 experiment initially planned for Europe has been moved to Australia as part of NAFE ’05 and it is anticipated that flux measurements will be made as part of NAFE ’06 if there is sufficient interest.

A trial campaign to evaluate the airborne and ground measurements planned for both NAFE campaigns has recently been conducted in the Waikerie region of South Australia. This is the first airborne data set with such high resolution passive microwave data. Moreover, it is unique in that there is such a complete suite of airborne measurements made from the same low-cost platform. This paper presents preliminary data obtained from that trial campaign, showing a clear soil moisture signal in the passive microwave data.

1. INTRODUCTION

Internationally there has been a significant decline in the number of gauged basins over recent years, yet the demand for hydrologic prediction is greater than ever, particularly as we enter an era of uncertainty due to global climate change. The potential for reliable hydrologic prediction in ungauged basins exists only through an increasing ability to remotely sense land surface states, fluxes, and parameters that impact on basin prediction. For instance, it is now possible to measure evapotranspiration rates that determine soil moisture and baseflow, near-surface soil moisture content that controls rainfall partitioning into infiltration and runoff, snow water equivalent of the snow pack that determines spring-time runoff, vegetation parameters such as leaf area index and greenness that control evapotranspiration, land surface elevation and canopy height that impact on runoff routing and evapotranspiration, and so on. However, there are still many unanswered questions that need to be addressed, including validation of data products from new sensors, maturing of retrieval algorithms, developing techniques for downscaling, and merging remote sensing data with model predictions through the process of data assimilation.

To answer these important questions it is essential that field campaigns with coordinated satellite, airborne and ground-based data collection be undertaken, giving careful consideration to the diverse data requirements for the range of questions to be addressed. Moreover, it must be recognised that such invaluable data sets do not come without considerable effort and cost. Thus it is increasingly important that scientists collaborate nationally and internationally on the collection and subsequent analysis of such data to share in the burden and reap the benefits of more extensive data sets than are possible on an individual basis. To this end two month-long National Airborne Field Experiments (NAFE; see www.nafe.unimelb.edu.au) have been planned in consultation with scientists from diverse backgrounds (soil moisture, runoff, evapotranspiration, carbon, forestry, bushfires, water quality, irrigation and salinity) and organisations (several divisions of CSIRO, State Agencies, CRC's, national and international universities, NASA and ESA).

While there is a clear emphasis on soil moisture remote sensing in the two planned NAFE experiments (a primary objective of the research project which provides core funding), the nature of the airborne and supporting data to be collected makes these campaigns applicable to a wide range of environmental remote sensing disciplines and applications.

These coordinated field experiments are open to collaboration from all interested parties. In November 2005 (NAFE '05) there will be participants from the University of Melbourne, University of Newcastle, Airborne Research Australia, and several European universities and organisations including the European Space Agency (ESA), undertaking research on soil moisture, flood forecasting, carbon budgets and ecohydrology. In November 2006 (NAFE '06) it is anticipated that participants will undertake research on soil moisture, evapotranspiration, bushfire prediction and precipitation measurement. This is the first campaign to collect such a wide range of high resolution remote sensing data This paper describes in detail the core soil moisture component to these two field campaigns.

2. SCIENCE QUESTIONS

Information on soil moisture may be obtained from three sources. First, ground-based soil moisture profile measurements may be made continuously at individual points. Unfortunately, these are rarely representative of the spatial distribution (Grayson and Western, 1998), and so are unsuitable for mapping of large areas. Second, remote sensing may be used to give measurements of soil moisture in the top few centimetres for areas with low to moderate vegetation cover but do not provide any direct information on root zone soil moisture (Engman and Chauhan, 1995). Third, land surface models may be used to predict the spatial and temporal variation of soil moisture (near-surface and root zone) but those estimates suffer from inadequate model physics, parameter estimates, and atmospheric forcing data (Lin *et al.*, 1994). Clearly these different approaches are complementary, and so one approach has been to utilise all three sources of data, by assimilation of the remotely sensed near-surface soil moisture measurements into a land surface model, and relying on the point measurements for verification (Walker and Houser, 2001). While current progress on this approach has been good, application has been confined to large scale estimates with little appropriate data available for assimilation and/or field verification. **Therefore appropriate observation and verification data needs to be collected to mature this technology.**

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 25 to 50km, but have a frequent temporal resolution of 1 to 2 days. While this spatial resolution is appropriate for some broad scale applications, it is not useful for small scale applications such as on-farm water management, flood prediction or meso-scale climate and weather prediction. Thus methods need to be developed for reducing these large scale measurements to a smaller scale. This may ultimately be possible using information from other types of higher resolution sensors (eg. thermal and visible imagery from the MODerate resolution Imaging Spectrometer (MODIS) or LANDSAT Thematic Mapper), but any **downscaling approaches must first be developed and validated with direct high resolution passive microwave measurements and such data must be collected**.

May 2002 saw the launch of NASA's Advanced Microwave Scanning Radiometer for the Earth observing system (AMSR-E) on the Aqua satellite. This is 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). It is therefore imperative that research programs are designed and undertaken now, in order to fully exploit the potential for retrieving important information on the spatial and temporal variation of soil moisture content from AMSR-E data. The Aqua satellite has an operational design life of 6 years, so there is only a narrow window of opportunity to undertake ground-based research. **Verification of space-borne observations at these coarse resolutions** can only be undertaken using airborne data with a ground resolution fine enough to allow its own accurate verification from ground-based measurements. All airborne soil moisture remote sensing campaigns to date have had spatial resolutions on the order of 1km – an order of magnitude greater than what will be achieved in the NAFE campaigns. Moreover, surface rock covers a large proportion of the Earth's surface and this is not currently considered in retrieval algorithms, leading to a potential underestimation in soil moisture.

In addition 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) sensors to be launched in 2007 and 2009 respectively. These new sensors each will have their own novel approach to soil moisture measurement, requiring algorithms to be developed and results verified using field data. The SMOS sensor will collect data at a range of incidence angles potentially alleviating some of the current assumptions and ancillary data requirements for soil moisture retrieval. HYDROS will collect both accurate low resolution passive microwave data together with noisy high resolution active microwave data to produce a 10km soil moisture product. However, both of these missions are planned for 6am/pm overpass times and it is likely that dew will impact on the 6am soil moisture retrievals, but this process is not well understood. Thus it is **important that we prepare now so as to obtain maximum benefit from these dedicated soil moisture sensors when they come online.**

3. DATA REQUIREMENTS

To answer the science questions outlined there are a number of ground and airborne data requirements to be considered (Fig. 1):

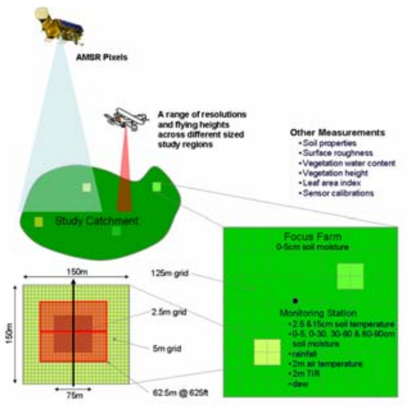

Figure 1. Schematic of the experimental design.

- long-term observation of soil moisture profiles and associated meteorological data for evaluation of derived root zone soil moisture
- extensive ground-based near-surface soil moisture and temperature data at a range of spatial scales during airborne campaigns for

scaling studies, aircraft and satellite verification and algorithm development

- continuous near-surface soil moisture, soil temperature, and thermal infrared point observation for relating air-to-ground measurements throughout the day
- vegetation biomass/water content and dew observation for determining vegetation and dew effects
- airborne passive microwave, thermal and NDVI data at a range of scales for algorithm development and satellite verification
- airborne lidar data for accurate topography and incidence angle information and vegetation height determination
- digital photography for land use and land cover information
- airborne observations coincident with ground observations and made as early in the morning as possible to ensure that soil and vegetation temperatures are more closely aligned, have a more uniform soil temperature profile, and to coincide more closely with AMSR-E (10am/pm) and SMOS/HYDROS (6am/pm) overpass times
- airborne observations at a range of altitudes (625ft to 10,000ft) to achieve a range of ground resolutions (62.5m to 1,000m for passive microwave and 1m to 20m for thermal and NDVI) for scaling, algorithm development and satellite verification

Figure 2. Location of Goulburn River, Kyeamba Creek and Yanco study areas with respect to the Murray Darling and Murrumbidgee catchments.

- airborne observations with passive microwave radiometer in mapping and multi-incidence angle configurations for SMOS and HYDROS algorithm development

4. THE STUDY REGIONS

The NAFEs will be undertaken in three intensive study areas (Fig. 2) located in diverse climatic, topographic and land use settings, set up under earlier funded projects. These are the Goulburn River (NAFE ’05), and Kyeamba Creek and Yanco study areas (NAFE ‘06). The existing network of monitoring sites and data management systems in each area provides an ideal basis for the soil moisture and meteorological measurements needed for these campaigns.

4.1. Goulburn Catchment

The 7,000km^2 Goulburn River catchment in the Upper Hunter region of New South Wales (Rüdiger *et al.*, 2003) is a joint experimental catchment between the Universities of Newcastle and Melbourne established in 2001. The catchment has a total of 26 continuous soil moisture profile monitoring sites, with 20 of these concentrated in two focus sub-catchments (the Krui and Merriwa Rivers) and 7 of those in a 728ha microcatchment. There are also a number of climate and streamflow recording stations (see www.sasmas.unimelb.edu.au). This experimental catchment has been designed specifically for remote sensing studies and has just been upgraded to include near-surface soil moisture and temperature measurements (Fig. 3). Field work undertaken in the Goulburn River catchment during NAFE ’05 will be limited to the northern cropping and grazing area (Fig. 4).

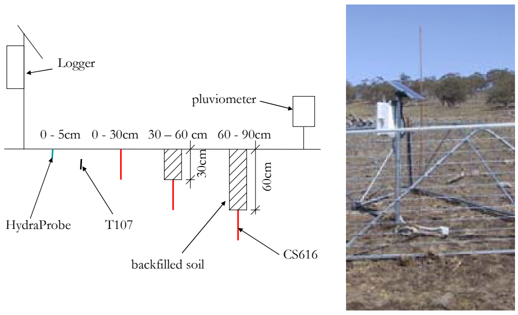

Figure 3. Long term soil moisture, temperature and precipitation measurements in the study catchments.

4.2. Murrumbidgee Catchment

The 100,000km^2 Murrumbidgee catchment ranges from semi-arid to alpine and covers a range of soil and vegetation types typical of much of Australia. It has been the focus of a joint project with the Bureau of Meteorology and the University of Melbourne for improving land surface

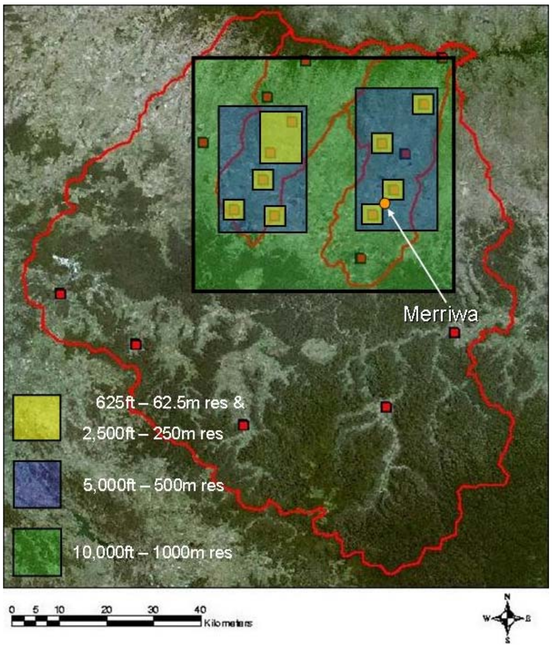

Figure 4. Location of monitoring sites (red squares), focus farms (yellow regions) and spatial resolution and extent of passive microwave (and other) airborne measurements to be made in the Goulburn study catchment (shaded regions).

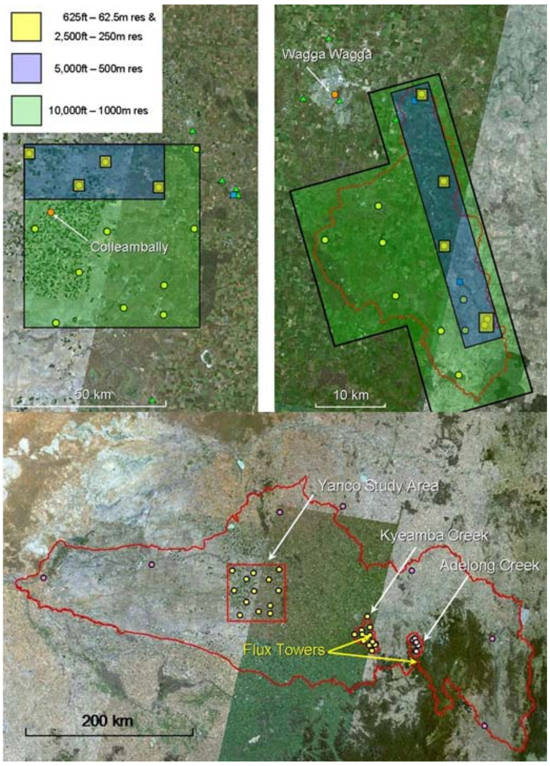

Figure 5. Location of monitoring sites (yellow circles), focus farms (yellow regions) and spatial resolution and extent of passive microwave (and other) airborne measurements to be made in the Yanco and Kyeamba Creek study areas within the Murrumbidgee Catchment.

representation in the Bureau of Meteorology numerical weather prediction model (Western *et al*., 2002). Monitoring in this catchment was upgraded in 2003 for validating terrestrial water storage retrieval from combined remote sensing measurement of surface soil moisture and temporal variation in the Earth's gravity field. There are now a total of 38 continuous soil moisture profile monitoring sites across the entire Murrumbidgee catchment, with 13 of these located in each of two focus study areas; the 2,500km^2 Yanco area and the 500km^2 Kyeamba Creek catchment (Fig. 5). There are also a number of climate and streamflow recording stations (see www.oznet.unimelb.edu.au). These study areas will be further upgraded in late 2005 to include a near-surface soil moisture and temperature measurement.

5. AIRBORNE MEASUREMENTS

Airborne measurements will be made using a small, low-cost, two-seater motor glider from the Airborne Research Australia national facility (Fig. 6) together with the recently acquired Polarimetric L-band Multibeam Radiometer (PLMR) and thermal imager. This new infrastructure will allow for the first time, very high resolution passive microwave (~50m) and land surface skin temperature (~1m) observations to be made across large areas. There is no other capacity world-wide to make such high resolution measurements together with a range of other supporting data including a first-last return lidar, NDVI scanner and 11MegaPixel digital camera.

The aircraft can carry a typical science payload of up to 120kg with cruising speed of 92-203km/h and range of 4-8hrs or 800-1500km. The PLMR measures both V and H polarisations using a single receiver with polarisation switch at incidence angles +/–7°, +/–21.5° and +/–38.5° in either across track (pushbroom) or along track configurations. The thermal imager is a FLIRTS ThermaCam S60 with spectral range 7.5 to 13µm, accuracy +/–2°C or +/–2% of reading, thermal sensitivity 0.08°C and 80° × 60° FOV lens with

Figure 6. The Diamond ECO-Dimona aircraft with PLMR mounted under the fuselage, and thermal imager, digital camera and NDVI scanner in an underwing pod.

1.3mrad IFOV. While the thermal measurements provide the near-surface soil temperature data for soil moisture retrieval, the dual polarisation microwave measurements enable simultaneous solution of soil and vegetation moisture content (Owe *et al*., 2001). The high resolution thermal and NDVI data will allow the development of soil moisture downscaling algorithms from spatially averaged data at a ground resolution that can be adequately monitored using ground-based techniques.

Airborne measurements will be made daily at a range of spatial resolutions – from 62.5m to 1km (for passive microwave; 1m to 20m for thermal imagery and NDVI) – and extents – from individual farms to entire AMSR-E foot prints. Approximately 100 mission hours will be flown during each of these month-long experiments. Additionally, in NAFE '05 there will be approximately 50 mission hours flown with an AeroCommander operated by Airborne Research Australia, carrying the European L-band passive microwave radiometer EMIRAD-2 designed specifically for SMOS algorithm development. In NAFE '06 it is possible that airborne flux measurements be made if sufficient interest is shown in obtaining that data.

6. GROUND MEASUREMENTS

Ground-based monitoring of near-surface soil moisture and temperature will be undertaken at focus farms (having different characteristics) in each study area. These farms are shown in Figs. 4 and 5. Near-surface soil moisture and temperature measurements will be made using HydraProbes® with electronic fieldbooks (iPAQs®) running ArcPAD® and bluetooth connection to GPS for real-time position and data logging. These roving measurements will be made on grids on each farm (Fig. 1), in order to collect data across a range of soil, vegetation and terrain conditions. Continuous logging of near-surface soil moisture and temperature, and thermal infrared will be made for a single point at focus farms to verify that soil moisture is not changing significantly across the day and to derive relationships between near-surface soil temperature and thermal infrared observations. Observations of dew, vegetation water content, fractional coverage of surface rock, soil properties and surface roughness will also be made to account for those factors in soil moisture retrieval from the airborne and satellite measurements.

7. DISCUSSION

In preparation for these two intensive airborne field experiments, a trial campaign was conducted near Waikerie, South Australia in May 2005. This campaign simulated at small scale (approximately 5km by 15km) the airborne and ground measurements to be made during NAFE '05 and '06. In addition to developing optimal operating procedures for the new airborne infrastructure, it provided an ideal test-bed for planned ground measurements. Fig. 7 shows an example of the airborne data collected during this short campaign (thermal infrared data are not shown). There are

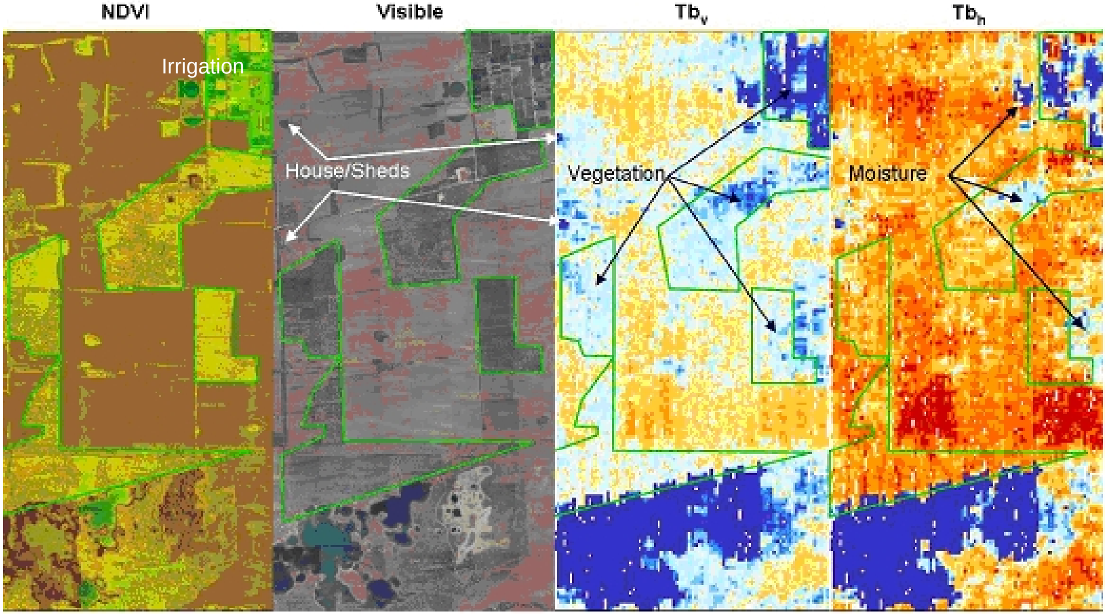

Figure 7. Example of airborne data collected from a trial campaign near Waikerie in South Australia. Note that the vertically (Tb_v) and horizontally (Tb_h) polarized passive microwave data are shown with a different colour scale.

two particularly unique features to this data. First, these are the first passive microwave maps at such high resolution, with all previous mapping done at approximately 1km resolution. Second, this is the most comprehensive set of airborne measurements made from the same low-cost platform, including passive microwave, thermal infrared, near infrared, visible green and red bands, and high resolution digital photography (lidar is also possible but was not implemented at the time of this trial campaign).

The study area is predominately dryland farming with some irrigation in the north east corner and a highly saline evaporation basin in the south. The irrigation area includes two centre pivots and a large amount of intensive agriculture, consisting of a mix of citrus and grape vines. There are a number of features in these data worthy of note. First, the water body to the south is clearly visible in all the data, appearing as a cold (blue) region in the passive microwave data. Second, the NDVI data (combination of red and near infrared) shows clearly the areas of more dense and/or active vegetation as corroborated by the visible data. This vegetation signal is also apparent in the vertically polarised passive microwave data to be used for determination of vegetation biomass in the soil moisture retrieval algorithm. Third, the soil moisture signal (cooler regions) expected in the irrigation region is clearly seen in the horizontally polarised passive microwave data. Finally, there is “radio frequency interference” (RFI) in both the vertical and horizontal polarisation data as a result of tin roofs in the study region. No other sources of RFI were observed in the data, nor is it expected to be a problem in the NAFE study sites. However, intensive ground monitoring areas have been chosen to specifically avoid areas with tin roofs.

8. CONCLUSIONS

Interested parties are invited to participate in these planned field experiments and reap the benefits of collaboration. In particular, people with an interest in remote sensing of evapotranspiration and precipitation, or other under represented areas of environmental remote sensing that can utilse the high resolution passive microwave, thermal infrared, near infrared, visible and/or lidar data to be collected, are especially welcome.

9. ACKNOWLEDGMENTS

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10. REFERENCES

Engman, ET and N Chauhan (1995). Status of microwave soil moisture measurements with remote sensing. *Rem. Sens. of Env.*, **51**(1), 189-198.

Grayson, RB and AW Western (1998). Towards areal estimation of soil water content from point measurements: time and space stability of mean response. *J. Hydrol.*, **207**, 68-82.

Lin, DS, EF Wood, PA Troch, M Mancini and TJ Jackson (1994). Comparisons of remotely sensed and model-simulated soil moisture over a heterogenous watershed. *Rem. Sens. of Env.*, **48**, 159-171.

Njoku, EG, WJ Wilson, SH Yueh, SJ Dinardo, FK Li, TJ Jackson, V Lakshmi and J Bolten (2002). Observations of soil moisture using a passive and active low-frequency microwave airborne sensor during SGP99. *IEEE Trans. Geosci. Rem. Sens.*, **40**(12): 2659-2673.

Owe, M, R de Jeu, and JP Walker (2001). A methodology for surface soil moisture and vegetation optical depth retrieval using the microwave polarization difference index. *IEEE Trans. Geosci. and Rem. Sens.*, **39**(8), 1643-1654.Rüdiger et al., 2003

Walker, JP and PR Houser (2001). A methodology for initializing soil moisture in a global climate model: Assimilation of near-surface soil moisture observations. *J. Geophys. Res.*, **106**(D11), 11761-11774.

Walker, JP, N Ursino, RB Grayson and PR Houser (2003). Australian Root Zone Soil Moisture: Assimilation of Remote Sensing Observations. *Proc. Int. Cong. Modelling and Sim.*, July, 2003.

Western, AW, H Richter, FHS Chiew, RI Young, G Mills, RB Grayson, M Manton and TA McMahon (2002). Testing the Australian Bureau of Meteorology’s land surface scheme using soil moisture observations from the Murrumbidgee catchment. *Hydrology and Water Resources Symposium*, July, 2002.