Manju Hemakumara, Jetse Kalma, Jeffrey Walker, and Garry Willgoose (2004), **Downscaling of low resolution passive microwave soil moisture observations**, in *Proceedings of the 2nd international CAHMDA workshop on: The Terrestrial Water Cycle: Modelling and Data Assimilation Across Catchment Scales*, edited by A.J. Teuling, H. Leijnse, P.A. Troch, J. Sheffield and E.F. Wood, pp. 51–55, Princeton, NJ, October 25–27

Downscaling of low resolution passive microwave soil moisture observations

Manju Hemakumara[1], **Jetse Kalma**[1], **Jeffrey Walker**[2], **and Garry Willgoose**[3]

[1] *School of Engineering, University of Newcastle, Australia*
[2] *Department of Civil and Environmental Engineering, University of Melbourne, Australia*
[3] *School of Geography, University of Leeds, Leeds UK*

This paper addresses the validation and subsequent downscaling of low resolution (25 km × 25 km) passive microwave near-surface soil moisture data from the Advanced Microwave Scanning Radiometer for the Earth observing system (AMSR-E) on board the Aqua satellite. The paper first reports on large-scale validation experiments which have been undertaken in south eastern Australia, under a range of soil moisture conditions and in different seasons. On each occasion approximately 220 sites were monitored for soil and vegetation properties and soil moisture across a 40 km × 50 km area, with a range of vegetation, soil and topographic attributes. Second, the paper reports on downscaling of the low resolution AMSR-E near-surface soil moisture product to 1 km using two recent surface wetness index approaches which employ thermal and visible AVHRR and MODIS imagery.

Introduction Knowledge of spatial and temporal distribution of soil moisture is required for a variety of environmental studies. The Scaling and Assimilation of Soil Moisture And Streamflow (SASMAS) project aims to develop new methodologies for meaningful estimation of spatial distribution and temporal variations of soil moisture content through a combination of modeling, observations and data assimilation (see *Rüdiger et al.*, 2003). The recent development in microwave remote sensing techniques for near surface soil moisture monitoring (e.g., *Schmugge*, 1998; *Western et al.*, 2002) has been one of the triggers for the formation of the SASMAS project.

This paper addresses two SASMAS research objectives: (1) field validation of the Advanced Microwave Scanning Radiometer for the Earth observing systems (AMSR-E) soil moisture product; and (2) development of new methods for disaggregation of large area soil moisture estimates. Its broad aim is to assist in assessing the calibration reliability of AMSR-E and to increase its hydrological applicability by disaggregating the low resolution (25 km × 25 km) AMSR-E soil moisture data into moderate resolution (1 km × 1 km) soil moisture values. The paper describes preliminary results from recent intensive field validation campaigns and presents a soil moisture disaggregation methodology for AMSR-E footprints based on AVHRR and MODIS satellite data.

Theory Measurements in the microwave region of the electromagnetic spectrum can provide all-weather quantitative estimates of near-surface soil moisture under low-to-moderate vegetation cover. AMSR-E is a passive microwave sensor with a 6.9 GHz (C band) channel and footprint size of more than 25 km. Based on published results and supporting theory, AMSR-E holds great promise for estimating soil water content in the top 1 cm layer of soil for relatively low vegetation cover (*Choudhury and Golus*, 1988; *Ahmed*, 1995; *Njoku and Li*, 1999; *Schmugge et al.*, 2002).

Over the last two decades, substantial research has been dedicated to the development of new methods of using visible and thermal infrared observations for evaluating land surface wetness conditions (*Carlson et al.*, 1994; *Gillies et al.*, 1997; *Czajkowski et al.*, 2002; *Goward et al.*, 2002; *Weidong et al.*, 2002). These studies have shown that surface temperature and the Normalised Difference Vegetation Index (NDVI) can together provide information on vegetation and surface moisture conditions. Furthermore, these studies have introduced a range of moisture indices to better understand the regional distribution of soil moisture (e.g., *Moran et al.*, 1994; *Sandholt et al.*, 2002; *Wan et al.*, 2004).

Soil moisture (or wetness) index methods generally provide only a poor indication of *absolute* soil moisture content because they are based on measurements of the reflected shortwave and emitted thermal radiation, which are influenced by a wide range of other factors including organic matter, soil texture, surface roughness, angle of incidence, plant cover and colour. However, despite these limitations, such methods are potentially capable of providing an indication of *relative* variations of land surface wetness conditions. They can therefore provide a methodology to downscale 25 km $\times$ 25 km scale near surface soil moisture measurements based on the relative variations within the larger AMSR-E footprint. In this study such downscaling approaches are evaluated with ground based soil moisture measurements obtained during intensive AMSR-E validation campaigns.

The first disaggregation method used here employs the Water Deficit Index (WDI) proposed by *Moran et al.* (1996) with AVHRR and MODIS data. This index is based on the relationship between land surface-air temperature difference ($T_s - T_a$) and the soil adjusted vegetation index (SAVI). The hypothetical trapezoidal shape that results from plotting these data allows the wet and dry edges for each biome class to be defined. Once the boundary values are known, WDI may be computed as the ratio between difference of maximum and observed temperatures and the range of temperature for the particular SAVI class. Theoretically, this temperature ratio is equal to the ratio of actual to potential evapotranspiration and should be valid for partially-vegetated surfaces. The computed WDI values are then used as weighing factors to downscale the AMSR-E pixel value to 1 km resolution.

The second downscaling method used is based on the Vegetation Temperature Condition Index (VTCI) proposed by *Wan et al.* (2004). The VTCI uses a relationship between land surface temperature (LST) and NDVI. The scatter plot shape between these data is normally triangular at a regional scale if the study area is large enough to provide a wide range of NDVI and surface moisture conditions. The VTCI gives an indication of LST changes of pixels with specific NDVI values and it can be physically explained as the ratio of temperature differences among pixels. The higher values of VTCI are associated with wetter areas and lower values are associated with dryer areas, thus giving weighing parameters for downscaling of large area near surface moisture measurements.

Data The SASMAS project area is located in the 7000 km^2 Goulburn River catchment in SE Australia. The northern part of the catchment is dominated by an undulating landscape with average elevation of approximately 400 m, and is mainly cleared for cropping and grazing purposes, making it an appropriate region for remote sensing studies. For the field validation of an AMSR-E footprint, a sampling area of 40 km $\times$ 50 km was selected to ensure that a full 25 km $\times$ 25 km satellite footprint lay within the sampling area. Due to the large footprint size, available resources, travel times and access issues, complete coverage was not possible within a single day. Therefore, the validation area was divided into four quarters and one quarter assigned to each of four groups. Each quarter was further subdivided into nine cells, three of which were sampled per day over the three-day campaign period. A three-day field campaign was justified on the basis that soil moisture content would not vary greatly during the course of a few days under typical drying conditions. This was confirmed by the actual field data. The campaigns were undertaken on 7–9 November 2003, 1–3 May 2004 and 7–9 July 2004. These capture seasonal variations in soil moisture and vegetation conditions, and were scheduled to coincide with AMSR-E overpasses so that there was at least 1 overpass each day with 2 overpasses (am and pm) on the central day.

Each campaign was aimed at collecting soil moisture measurements at approximately 220 GPS

Table 2.1: Comparison of AMSR-E near surface soil water content and field measurements.

Campaign		Surface soil water content ($cm^3\,cm^{-3}$)		
Number (dates)	Sample size	AMSR-E	0–6 cm	0–1 cm
1 (7–9 Nov, 2003)	230	15.0	14.1	10.9
2 (1–3 May, 2004)	216	17.0	16.6	18.9

located sites spread across the validation area. It was expected that this number of point measurements and their coverage should provide a sufficient basis for the validation of the satellite soil moisture product and for the development of a procedure for downscaling large area-average moisture measurements. Five 0–1 cm soil moisture samples were obtained at each site with a steel sampling ring of 82 mm diameter and 10 mm thickness. The five samples were combined and used to obtain volumetric soil moisture contents. In addition, five observations were made at each site with a Theta® probe which yielded volumetric soil moisture content values integrated over a 0–6 cm layer. Apart from soil moisture, soil and air temperatures, soil type, and surface conditions were also recorded, and vegetation samples collected for determining vegetation water content and dry biomass.

In addition to AMSR-E data, NOAA and MODIS satellite images were also obtained. In order to use the best images for analysis, all available day and night images from NOAA 15, 16 and 17 were obtained and after careful consideration final images selected for the derivation of moisture index values.

Results Results from the first two validation campaigns are shown in table 2.1 where AMSR-E near surface soil moisture values are compared with footprint averages of the volumetric soil moisture content in the top 1 cm and top 6 cm. The table indicates that AMSR-E is capable of providing reasonable estimates of near soil moisture content when compared with point observation averages. It should be noted that on theoretical grounds the 6.9 Hz channel of AMSR-E is expected to yield integrated soil moisture values for the top 1 cm. The AMSR-E values have been obtained with the old algorithm and will be modified once the new algorithm is implemented by the NASA DAAC.

An important task in the validation was to determine the minimum number of sampling sites reasonably required to obtain a representative areal average for the 25 km $\times$ 25 km AMSR-E footprint area. Figure 2.2 shows the effect of the number of sampling sites on the computed area average soil moisture content for 0–1 and 0–6 cm as compared with the averages based on all available sites (i.e., 230 sites during campaign 1 and 216 sites during campaign 2). It is shown that for the 0–1 cm observations the regional average stabilizes at about 100 sites, whilst for the 0–6 cm observations at least 150 sites are required.

Figure 2.3(a) shows a map of volumetric soil moisture content for the top 6 cm layer for the second campaign. The grid cells in this map is 1.21 km^2 in area and has been chosen to enable comparisons with wetness index distribution patterns obtained from AVHRR data as discussed below. Reasonably coherent patterns emerge, with strong similarities between the maps particularly for the 6 cm observation depth. It is also noticeable that the southern half of the study area appears to be drier than the northern half. This is partly due to differences between the clayey soils in the north and the sandy soils in the south.

The WDI and VTCI methods have been used with AVHRR and MODIS data for the first two campaigns. In order to ensure that a significant range of vegetation and surface soil moisture

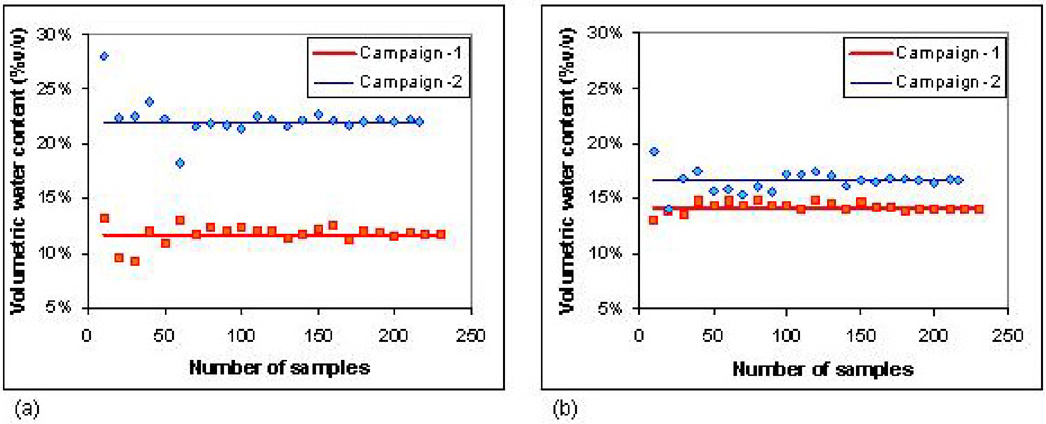

Figure 2.2: Spatial variation in field measured soil moisture for a) top 1 cm and b) top 6 cm soil layer in the first two intensive field campaigns (%).

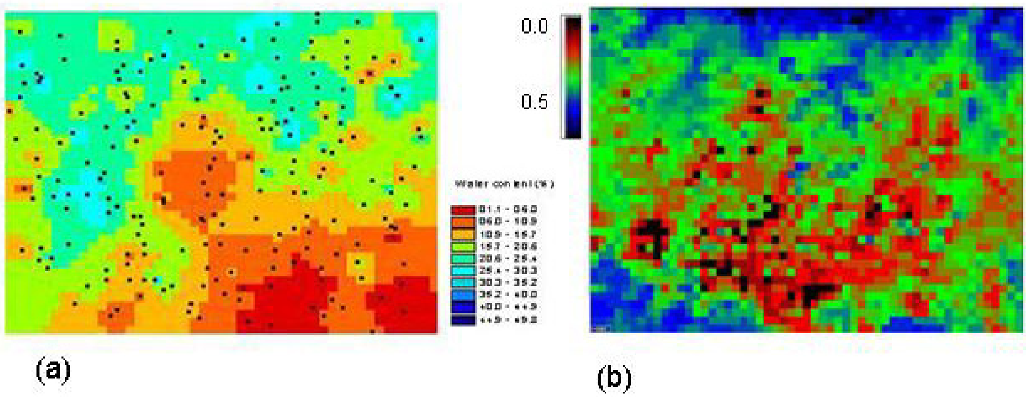

Figure 2.3: (a) Top 6 cm volumetric soil water content ($cm^3\ cm^{-3}$) distribution within the validation area for Campaign-2 (b) Disaggregated near surface water content ($cm^{-3}\ cm^{-3}$) for the validation area on 2 May 2004.

conditions were included in the computations, the entire Goulburn catchment (104 km $\times$ 124 km) was used in both methods.

A range of algorithms has been explored for using the index data in downscaling the AMSR-E near-surface soil moisture product and further work is continuing in this area. Preliminary results of one such downscaling approach using the WDI method with AVHRR data are shown for the 2 May 2004 campaign in figure 2.3(b). This downscaling approach involved calculating a weighting factor for each grid cell as the ratio between the index value for that cell and the sum of all index values across the AMSR-E footprint. Multiplying the AMSR-E value with this weighting factor yielded soil moisture content values across the study region. Reasonable agreement may be observed between the computed and observed near-surface soil moisture values. Particularly good agreement was found for areas with low to moderate vegetation.

Conclusions This paper has presented encouraging preliminary results for the validation and subsequent downscaling of low resolution AMSR-E passive microwave near-surface soil moisture data using soil moisture observations obtained in several large-scale field campaigns in south eastern Australia, and thermal and visible remote sensing imagery obtained with NOAA-AVHRR and

MODIS. The approach described here is part of an ongoing research project, which addresses various practical issues associated with the use of remote sensing for operational measurement of soil moisture. These include the role of vegetation and the relationship between near-surface soil moisture and total profile soil moisture. The soil moisture observations obtained in the field campaigns described here, as well as soil moisture data obtained at 26 monitoring sites with continuous soil moisture profile measurements, will also be analysed in greater detail to identify relationships with topography, soil properties and vegetation (e.g., *Western et al.*, 2002). This involves the use of regionalisation techniques such as those outlined by *Sulebak et al.* (2000).

Acknowledgements This project is funded by Australian Research Council Discovery Project Grant DP0209724. MH is supported by a University of Newcastle Research Scholarship. The authors acknowledge the assistance of Barry Jacobs, Greg Hancock, Patricia Saco, Christina Martinez, Emily Barbour, Christoph Rüdiger, Ian Jeans and Makeena Kiugu for their assistance during the three field campaigns.

Bibliography

Ahmed, N., Estimating soil moisture from 6.6 GHz dual polarization, and/or satellite derived vegetation index, *Int. J. Remote Sens.*, *16*, 687–708, 1995.

Carlson, T., R. Gillies, and E. Perry, A method to make use of thermal infrared temperature and ndvi measurements to infer surface soil water content and fractional vegetation cover, *Remote Sensing Reviews*, *9*, 161–173, 1994.

Choudhury, B., and R. Golus, Estimating soil wetness using satellite data, *Int. J. Remote Sens.*, *9*, 1251–1257, 1988.

Czajkowski, K., S. Goward, D. Shirey, and A. Walz, Thermal remote sensing of near-surface water vapor, *Remote Sens. Environ.*, *79*(2–3), 253–265, 2002.

Gillies, R., T. Carlson, J. Gui, W. Kustas, and K. Humes, A verification of the "triangle" method for obtaining surface soil water content and energy fluxes from remote measurements of the Normalized Difference Vegetation Index (NDVI) and surface radiant temperature, *Int. J. Remote Sens.*, *18*(15), 3145–3166, 1997.

Goward, S., Y. Xue, and K. Czajkowski, Evaluating land surface moisture conditions from the remotely sensed temperature/vegetation index measurements, *Remote Sens. Environ.*, *79*(2–3), 225–242, 2002.

Moran, M., T. Clarke, Y. Inoue, and A. Vidal, Estimating crop water deficit using the relation between surface-air temperature and spectral vegetation index, *Remote Sens. Environ.*, *49*, 246–263, 1994.

Moran, M., A. Rahman, J. Washburne, D. Goodrich, M. Weltz, and W. Kustas, Combining the Penman-Monteith equation with measurements of surface temperature and reflectance to estimate evaporation rates of semiarid grassland, *Agr. Forest Meteorol.*, *80*, 87–109, 1996.

Njoku, E., and L. Li, Retrieval of land surface parameters using passive microwave measurements at 6 to 18 GHz, *IEEE T. Geosci. Remote Sens.*, *37*, 79–93, 1999.

Rüdiger, C., R. Davidson, H. Hemakumara, J. Walker, J. Kalma, G. Willgoose, and P. Houser, Catchment monitoring for scaling and assimilation of soil moisture and streamflow, in *Proceedings of the international congress on modelling and simulation (MODSIM), 14–17 July, 2003*, pp. 386–391, Modellin and simulation society of Australia and New Zealand, Townsville, Australia, 2003.

Sandholt, I., K. Rasmussen, and J. Andersen, A simple interpretation of the surface temperature / vegetation index space for assessment of surface moisture status, *Remote Sens. Environ.*, *79*(2–3), 213–224, 2002.

Schmugge, T., Applications of passive microwave observations of surface soil moisture, *J. Hydrol.*, *212-213*, 188–197, 1998.

Schmugge, T., W. Kustas, J. Ritchie, T. Jackson, and A. Rango, Remote sensing in hydrology, *Adv. Water Resour.*, *25*(8-12), 1367–1385, 2002.

Sulebak, J., L. Tallaksen, and B. Erichsen, Estimation of areal soil moisture by use of terrain data, *Geografiska Annaler*, *82A*, 89–105, 2000.

Wan, Z., P. Wang, and X. Li, Using MODIS land surface temperature and normalized difference vegetation index products for monitoring drought in the southern Great Plains USA, *Int. J. Remote Sens.*, *25*(1), 61–72, 2004.

Weidong, L., F. Baret, G. Xingfa, T. Qingxi, Z. Lanfen, and Z. Bing, Relating soil surface moisture to reflectance, *Remote Sens. Environ.*, *81*(2–3), 238–246, 2002.

Western, A., R. Grayson, and G. Blöschl, Scaling of soil moisture: A hydrologic perspective, *Annu. Rev. Earth Planet. Sci.*, *30*, 149–180, doi:10.1146/annurev.earth.30.091201.140434, 2002.