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An evaluation of AMSR–E derived soil moisture over Australia

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ABSTRACT

This paper assesses remotely sensed near-surface soil moisture over Australia, derived from the passive microwave Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR–E) instrument. Soil moisture fields generated by the AMSR–E soil moisture retrieval algorithm developed at the Vrije Universiteit Amsterdam (VUA) in collaboration with NASA have been used in this study, following a preliminary investigation of several other retrieval algorithms. The VUA–NASA AMSR–E near-surface soil moisture product has been compared to in-situ soil moisture data from 12 locations in the Murrumbidgee and Goulburn Monitoring Networks, both in southeast Australia. Temporally, the AMSR–E soil moisture has a strong association to ground-based soil moisture data, with typical correlations of greater than 0.8 and typical RMSD less than 0.03 vol/vol (for a normalized and filtered AMSR–E timeseries). Continental-scale spatial patterns in the VUA–NASA AMSR–E soil moisture have also been visually examined by comparison to spatial rainfall data. The AMSR–E soil moisture has a strong correspondence to precipitation data across Australia: in the short term, maps of the daily soil moisture anomaly show a clear response to precipitation events, and in the longer term, maps of the annual average soil moisture show the expected strong correspondence to annual average precipitation.

1. Introduction

This paper demonstrates the utility of passive microwave remote sensing for observing near-surface soil moisture over Australia. The passive microwave signal offers several advantages over other methods for remote sensing soil moisture; it can penetrate cloud, it has a direct relationship with soil moisture through the soil dielectric constant, and it has a reduced sensitivity to land surface roughness and vegetation cover. Within the microwave spectrum, lower frequencies respond to a deeper soil layer and are less attenuated by vegetation, and so are best suited for soil moisture remote sensing. Currently, the lowest frequency radiometer in orbit is the Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR–E), which observes passive microwave brightness temperatures at six dual polarized frequencies, centered at 6.9, 10.6, 18.7, 23.8, 36.5, and 89.0 GHz (the radiometer on-board the Coriolis/WINDSAT Weather Satellite also observes at frequencies similar to the lowest five AMSR–E bands). AMSR–E has been orbiting Earth on NASA's Aqua satellite since May 2002, and with the exception of regions of dense vegetation, snow, ice, or frozen soils, it provides global soil moisture coverage every 2 days, from both the ascending (day) and descending (night) overpasses (Njoku et al., 2003). AMSR–E brightness temperatures are reported on a 25×25 km^2 grid, which for the 6.9 GHz band (C-band), is re-sampled from overlapping 45×75 km^2 swath data. The C-band observations are sensitive to soil moisture in the uppermost ~1 cm of the Earth's surface (Njoku et al., 2003).

Studies evaluating near-surface soil moisture fields derived from AMSR–E have shown promising results over both Europe (e.g., Rüdiger et al., in press; Wagner et al., 2007) and the United States (e.g., Crow and Zhan, 2007; McCabe et al., 2005). However, validation efforts have in general been hampered by the limited availability of ground truth data, and by radio frequency interference (RFI) from surface communication networks. The widespread occurrence of RFI prevents the use of C-band (and in some cases X-band) AMSR–E data for soil moisture retrieval in much of North America and Europe, and parts of East Asia (Njoku et al., 2005). In contrast to many other regions, AMSR–E soil moisture retrievals are well suited for observation over Australia, due to the unusually complete coverage of high-quality satellite data: Australia has only a small corridor of dense vegetation and/or frozen cover, and no apparent RFI (Njoku et al., 2005). AMSR–E has the potential then to be particularly useful for observing near-surface soil moisture over Australia, and initial evaluation of AMSR–E derived soil moisture is encouraging. For example, Liu et al. (submitted for publication) have demonstrated that soil moisture and vegetation derived from AMSR–E (and its passive microwave predecessors) contain a statistical signal of regional climate indices. The present study builds on this work, by providing an in-depth assessment of AMSR–E soil moisture retrievals

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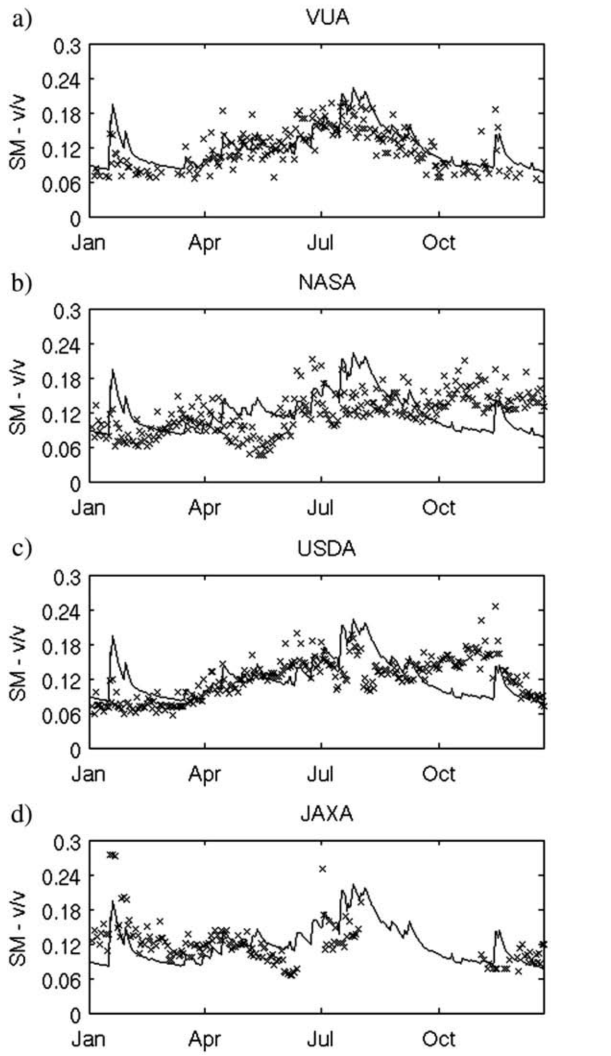

Fig. 1. Comparison of the AMSR–E near-surface soil moisture retrievals (crosses) to in-situ data (solid lines) at Adelong over 2006, based on the algorithms developed at a) VUA–NASA, b) NASA, c) USDA, and d) JAXA. All AMSR–E timeseries are based on X-band data, and have been normalized (as described in the Data section) to enable better visual comparison.

over Australia, through comparison to in-situ soil moisture from the Murrumbidgee and Goulburn monitoring networks, and to continental-scale precipitation data.

2. Data and methods

2.1. AMSR–E soil moisture data

Near-surface soil moisture can be derived from microwave brightness temperatures via a land-surface radiative transfer model that accounts for the contribution of soil moisture, soil temperature, and vegetation, to passive microwave emissions. Several algorithms are routinely applied to retrieve soil moisture from AMSR–E, the most prominent of which have been developed at;

- NASA, following Njoku et al. (2003);
- the Japanese Aerospace Exploration Agency (JAXA), following Koike et al. (2004);
- the United States Department of Agriculture (USDA), following Jackson (1993); and
- the Vrije Universiteit Amsterdam (VUA) in collaboration with NASA (referred to below as VUA–NASA), following Owe et al. (2001).

Each of these algorithms frames the radiative transfer equations differently, and perhaps more importantly, they approach the problem of under-determination of these equations differently. Consequently, the retrieval algorithms can generate quite different soil moisture fields, with different degrees of realism. In response to RFI in C-band AMSR–E data across much of North America and East Asia, the NASA, JAXA, and USDA soil moisture retrieval algorithms use only X-band and higher frequency AMSR–E data. The VUA–NASA retrieval algorithm is separately applied to C- and X-band AMSR–E observations.

Fig. 1 shows a comparison of the four AMSR–E soil moisture products listed above with ground-based soil moisture data at Adelong (M10 in Fig. 2 — the in-situ data is described in full in the following section). The VUA–NASA product has a good correspondence to the in-situ data, while the other three diverge from the in-situ data for extended periods, and do not capture the entire seasonal cycle well (note that this applies only for the versions of the algorithms presented here; all of the algorithms are under active development). The JAXA timeseries is also missing a substantial period of data. The superior match of the VUA–NASA timeseries to the in-situ data is consistent across all of the soil moisture monitoring stations that have been used in this study. It is also consistent with previous studies that have shown that the VUA–NASA soil moisture has a better match to in-situ observations in Spain (Wagner et al., 2007), and to modeled soil moisture in France (Rüdiger et al., in press), when compared with the NASA AMSR–E soil moisture.

Since it showed the strongest agreement with the Australian in-situ data in the above comparison, only the VUA–NASA soil moisture will be assessed in detail here. The soil moisture generated at VUA–NASA follows the retrieval algorithm developed by Owe et al. (2001), using the subsequent refinements of de Jeu and Owe (2003). The defining feature of the retrieval is the expression of vegetation optical depth as a function of the dielectric constant and the passive microwave polarization ratio. This function is substituted into the radiative transfer equation for the H-polarized brightness temperature, together with ancillary soil temperature (derived from 36.5 GHz V-polarized data). The radiative transfer equation is then solved for the soil dielectric constant, and subsequently soil moisture content.

In a global RFI survey for June 2002–May 2003, Njoku et al. (2005) did not note any RFI in either C- or X-band AMSR–E data over Australia. This result is consistent with Australia's extremely low population density, since RFI is in general associated with densely populated urban areas (Li et al., 2004). To confirm that RFI is not problematic over Australia, the spectral difference method of Li et al. (2004) was applied to identify regions where RFI occurred in the AMSR–E data on more than 30 days in 2006. This measure did not identify any regions as having problematic C-band RFI, while for X-band only a small region in

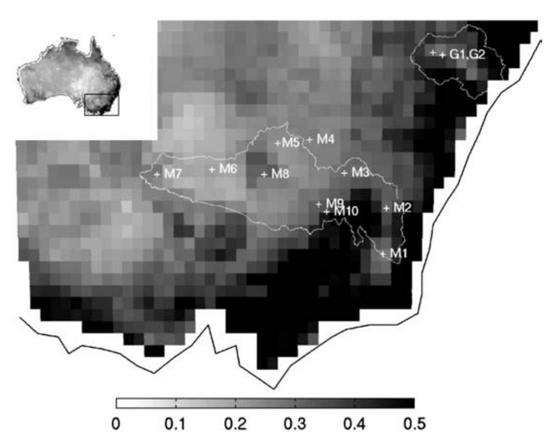

Fig. 2. Location of the Murrumbidgee and Goulburn Monitoring Network stations used in this study, overlaid on the mean 2006 NDVI. The NDVI has been aggregated to the (0.25°) AMSR–E grid. See Table 1 for explanation of station codes.

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northeast-Australia was identified. Since RFI is not then prevalent over Australia, the soil moisture retrievals from both the C- and X-band AMSR–E data will be considered below. The VUA–NASA AMSR–E soil moisture is reported on a regular 0.25° grid.

2.2. In-situ soil moisture data

Timeseries of the VUA–NASA AMSR–E soil moisture are compared to in-situ soil moisture data from the Murrumbidgee and Goulburn River Basins, both of which are located in eastern Australia (see Fig. 2). The Murrumbidgee monitoring network (Smith et al., submitted for publication), is maintained by the University of Melbourne, and consists of 38 monitoring stations at which surface hydrologic and thermodynamic variables are observed every 20 to 30 min. The Goulburn River Basin (Rüdiger et al., 2007) is located approximately 200 km north of the Murrumbidgee and has 26 monitoring stations, which are operated by the University of Newcastle. Soil moisture is observed across both networks with a mixture of Hydraprobes and Campbell Scientific CS615s (and CS616s), for which the average RMSE have been estimated at 0.03 vol/vol (Merlin et al., 2007) and 0.02 vol/vol (Western et al., 2001), respectively.

The monitoring stations from the Murrumbidgee and Goulburn monitoring networks that were used in this study are shown in Fig. 2. Initially, the shallowest soil moisture sensors in the Goulburn network observed a 0–30 cm soil layer, although shallow sensors observing the 0–5 cm layer were installed in late 2005. Only 0–5 cm soil moisture data have been used here, to better approximate the very thin surface layer observed by AMSR–E, limiting this study to 2006. Soil moisture data from thirteen Goulburn stations have been used; three of these stations are within a single AMSR–E pixel at Merriwa (G1), and ten are within a nearly adjacent pixel at Krui (G2), with seven of these being further clustered into a 1 km^2 focus area. For the Murrumbidgee monitoring network, there are 17 stations for which shallow (0–8 cm) moisture data are available for 2006; four of these are in one AMSR–E pixel at Adelong (M10), five are in one pixel at Kyeamba (M9), and the remaining eight stations are spread throughout the Murrumbidgee Catchment (20 more shallow (0–5 cm) sensors were installed at the remaining sites in late 2006). The mean 2006 Normalized Difference Vegetation Index (NDVI; from the Advanced Very High Resolution Radiometer (AVHRR)) has been included in Fig. 2 to provide a measure of vegetation attenuation across the monitoring networks. All of the monitoring stations are in grassland, and the mean 2006 NDVI ranges from 0.19 at Hay (M6) in the west, to 0.42 at Adelong (M10) in the east, with a mean across all of the stations of 0.29. However, there are areas of much denser vegetation very close to some of the stations, which may fall within the AMSR–E swath (in particular pixels adjacent to Adelong are forested). The vegetation at the Goulburn and Murrumbidgee monitoring sites is relatively dense within the Australian context; a 2006 mean NDVI of 0.29 (the mean across the stations) or 0.42 (the maximum across the stations) represents the 80th and 93rd percentile of the mean 2006 NDVI across Australia.

The in-situ timeseries have been sub-sampled each day at the approximate time of each Aqua overpass (1:30 am/pm local time) for comparison to data from the co-located AMSR–E pixel. Where there are multiple monitoring stations in a pixel, their average has been used. To prevent local conditions in the focus area dominating the pixel average at Krui, the average of the seven stations within this area was treated as a single observation.

2.3. Precipitation data

In the absence of ground-based soil moisture observations for the rest of Australia, maps of AMSR–E derived soil moisture differences have been compared to maps of precipitation to examine the continental-scale spatial patterns in the AMSR–E data. Since precipitation is the dominant forcing of soil moisture at atmospheric timescales, a strong spatial correlation is expected between near-surface soil moisture and precipitation. Precipitation maps are based on the Australian Bureau of Meteorology's daily rain-gauge analysis (Weymouth et al., 1999), which analyses daily precipitation observations (to 9 am) from approximately 6000 rain-gauges across Australia onto a 0.25° grid.

3. Results

3.1. Normalisation and filtering of the AMSR–E data

There are systematic differences between remotely sensed and in-situ data observations of soil moisture which prevent absolute agreement between the two, however their temporal dynamics should be similar, and inter-comparisons are best based on measures of association (Reichle et al., 2004). Consequently, comparison of remotely sensed and in-situ timeseries is often aided by re-scaling the remotely sensed data to better match the distribution of in-situ data (e.g., Rüdiger et al., in press; Wagner et al., 2007). The AMSR–E soil moisture data is directly compared to the in-situ data in this section to highlight these systematic differences, before the AMSR–E data is re-scaled and a more in-depth comparison is made in the following section.

Compared to the in-situ data, the AMSR–E timeseries have more noise and a bias (seasonal and annual). For example, Fig. 3 shows the AMSR–E and in-situ data at Kyeamba. In addition to noise generated by the usual sampling uncertainties of remotely sensed data, the method used to map the swath data onto the 0.25° grid generates noise. The AMSR–E value for each grid-cell is the mean of all (level 2a) swath data for which the foot-print is centered on that grid (Owe et al., 2008), and due to the progression of the Aqua orbit the land area (and hence the soil moisture) contributing to each grid-cell varies from day to day, with a 16-day cycle. The bias between the remotely sensed and ground-based soil moisture, given in Table 1, varies across the sites (within a range of −0.01 to 0.19 vol/vol). These biases have several main causes. First, the retrieval algorithms require soil parameters (e.g., wilting and saturation points) that are not accurately known across much of the globe, and the use of incorrect values will inevitably lead to biased soil moisture retrievals. Second, the horizontal and vertical resolutions of the in-situ data and the remotely sensed data are different. The AMSR–E data is the area-average soil moisture on a 0.25° grid, with a depth of ~1 cm, while the monitoring stations observe moisture at a single point (or at the most, a modest number of points within the pixel), with a depth of 8 cm. While the monitoring stations have been located with the intention of capturing the large-scale hydrology (Smith et al., submitted for publication), it is unlikely that the in-situ data is truly representative of the absolute

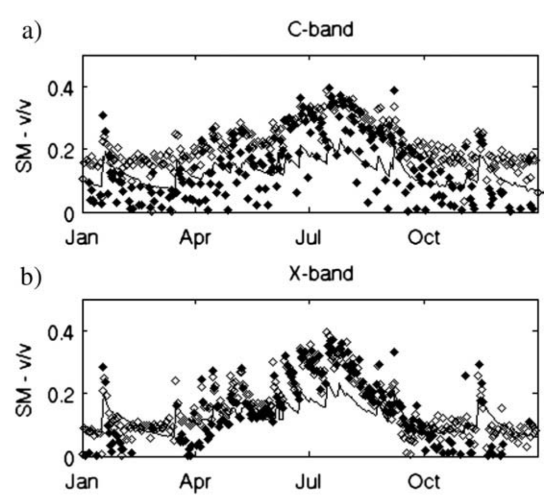

Fig. 3. Comparison of (original) AMSR–E soil moisture timeseries, for a) C-band, and b) X-band to in-situ data at Kyeamba for 2006. Filled (unfilled) diamonds are for the descending (ascending) pass.

Table 1
Statistics of fit between (original) AMSR–E soil moisture timeseries, and data from the Murrumbidgee and Goulburn Monitoring stations for 2006

Site (# of stations, where greater than 1)		C-band						X-band					
		Descending			Ascending			Descending			Ascending		
	# Obs.	Bias	RMSD	*r*	Bias	RMSD	*r*	Bias	RMSD	*r*	Bias	RMSD	*r*
M1 Cooma	282	0.16	0.19	0.75	0.16	0.17	0.82	0.10	0.13	0.77	0.12	0.14	0.80
M2 Canberra	200	0.15	0.18	0.78	0.16	0.19	0.67	−0.01	0.07	0.45	0.03	0.08	0.79
M3 Cottamundra	216	0.03	0.07	0.81	0.07	0.09	0.73	0.07	0.10	0.83	0.09	0.11	0.82
M4 W. Wyalong	255	0.02	0.05	0.92	0.04	0.05	0.89	0.03	0.06	0.92	0.03	0.05	0.88
M5 Balranald	262	0.04	0.08	0.84	0.07	0.08	0.77	0.05	0.09	0.84	0.06	0.08	0.77
M6 Hay	258	0.06	0.09	0.67	0.06	0.08	0.68	0.07	0.10	0.68	0.06	0.08	0.65
M7 Griffith	271	0.06	0.09	0.79	0.09	0.10	0.73	0.09	0.11	0.80	0.09	0.10	0.79
M8 Yanco	269	0.06	0.08	0.88	0.08	0.09	0.82	0.07	0.09	0.88	0.07	0.08	0.84
M9 Kyeamba (5)	240	0.01	0.08	0.75	0.09	0.10	0.80	0.01	0.08	0.81	0.03	0.06	0.83
M10 Adelong (4)	259	0.12	0.15	0.80	0.19	0.20	0.82	0.02	0.08	0.74	0.04	0.08	0.78
G1 Merriwa (3)	258	0.14	0.15	0.74	0.16	0.17	0.48	0.12	0.13	0.71	0.11	0.13	0.60
G2 Krui (10)	267	0.10	0.11	0.73	0.13	0.15	0.50	0.06	0.09	0.69	0.07	0.10	0.62

The number of observations is the mean at each site from the C- and X-band, and the ascending and descending Aqua pass.

area average soil moisture. Additionally, the vertical soil moisture gradient can be steep close to the surface, and the volumetric water content of the thinner layer observed by AMSR will differ from the deeper layer observed by the in-situ stations. There will also be biases due to errors in the retrieval algorithm or brightness temperature observations for AMSR–E (which may be responsible for the difference between the biases in Table 1 for the C- and X-band soil moisture at M1, M2, and M8). The biases in Table 1 show substantial variation across the monitoring stations, however, they show no obvious relationship to likely predictors of error, such as vegetation density (nor do the other diagnostics considered below).

To enable better comparison between the temporal behavior of the AMSR–E and in-situ soil moisture, the AMSR–E timeseries have been re-scaled to remove some of the systematic differences discussed above. Each AMSR–E observation (Θ_r) has been normalized (Θ_r') to have the same mean (m) and variance (s^2) as the in-situ data (Θ_i), according to:

$$\Theta_r' = (\Theta_r - m(\Theta_r)) \times (s(\Theta_i)/s(\Theta_r)) + m(\Theta_i). \quad (1)$$

As mentioned above, for each AMSR–E pixel, the co-located in-situ data is unlikely to reflect the absolute value of the pixel-average soil moisture. Consequently, the inter-pixel differences in the in-situ data do not necessarily represent the expected inter-pixel differences in the remotely sensed data (and the spatial variation in the remotely sensed data cannot be sensibly compared to that from the in-situ data). The normalization has then been done separately for each AMSR–E pixel. Prior to the normalization, the AMSR–E data was filtered to reduce the noise using a 5-day moving average filter; while a 16-day filter would be more physical for treating the noise associated with the mapping technique, it would overly dampen short-term variability. The correlation (r) and Root Mean Square Difference (RMSD) between the in-situ data and the AMSR–E soil moisture for the original and normalized/filtered AMSR–E data are provided in Tables 1 and 2, respectively. The benefit of the filter is demonstrated by the increase in correlation to the in-situ data: in most instances the correlation is increased (by up to 0.12; since the normalization is a linear transform it does not affect the correlation estimates).

Table 2
Statistics of fit between (filtered and normalized) AMSR-E soil moisture timeseries, and data from the Murrumbidgee and Goulburn Monitoring stations for 2006

Site	C-band				X-band			
	Descending		Ascending		Descending		Ascending	
	r	RMSD	*r*	RMSD	*r*	RMSD	*r*	RMSD
M1 Cooma	0.87	0.017	0.87	0.018	0.83	0.019	0.83	0.020
M2 Canberra	0.86	0.016	0.79	0.019	0.54	0.032	0.82	0.018
M3 Cootamundra	0.86	0.020	0.85	0.022	0.84	0.021	0.84	0.022
M4 W. Wyalong	0.93	0.023	0.94	0.021	0.94	0.022	0.92	0.024
M5 Balranald	0.86	0.014	0.82	0.015	0.86	0.013	0.81	0.015
M6 Hay	0.71	0.031	0.70	0.032	0.71	0.031	0.66	0.034
M7 Griffith	0.82	0.016	0.78	0.018	0.83	0.016	0.83	0.016
M8 Yanco	0.88	0.019	0.86	0.021	0.89	0.019	0.87	0.020
M9 Kyeamba	0.84	0.022	0.82	0.024	0.76	0.028	0.82	0.024
M10 Adelong	0.86	0.018	0.84	0.019	0.80	0.022	0.82	0.021
G1 Merriwa	0.77	0.042	0.62	0.055	0.75	0.043	0.70	0.048
G2 Krui	0.75	0.051	0.56	0.066	0.72	0.055	0.67	0.056

3.2. Timeseries comparison

Timeseries plots of the (filtered and normalized) AMSR–E soil moisture and the in-situ data are given in Fig. 4, for Kyeamba and Adelong in the Murrumbidgee River Basin, and Merriwa in the Goulburn River Basin. The different surface characteristics of the Goulburn and Murrumbidgee catchments are highlighted by the differences in the ground-based soil moisture timeseries from each. At the Murrumbidgee sites there is a seasonal cycle in the in-situ soil moisture, with maxima in winter that closely follow the local

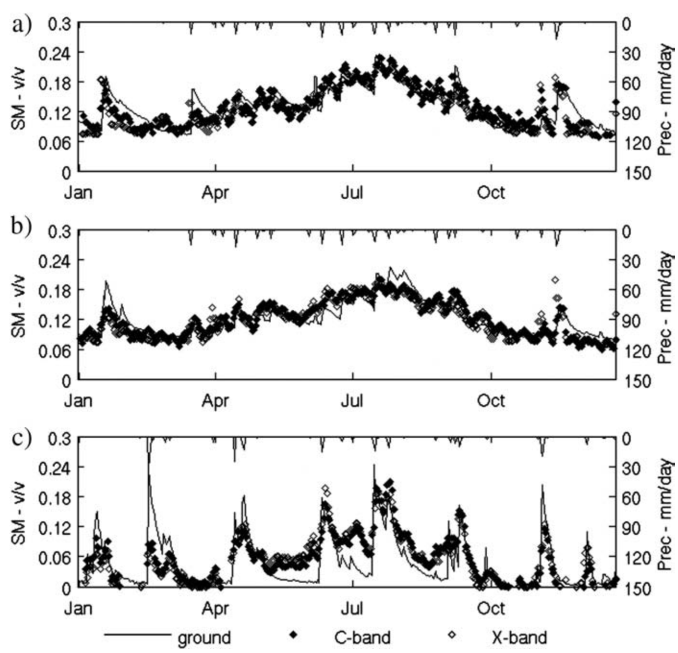

Fig. 4. Soil moisture derived from C- and X-band descending pass AMSR–E data for 2006 at a) Kyeamba, b) Adelong, and c) Merriwa. Daily precipitation is shown on the upper axis.

precipitation regime. In contrast, the Goulburn precipitation is dominated by larger events, typically occurring in the warmer months, and the ground-based soil moisture timeseries has a low and reasonably constant base value year round, modified only by a series of precipitation-induced peaks.

The C- and X-band AMSR–E timeseries both have a good visual fit to the in-situ data in Fig. 4. The AMSR–E timeseries in general depict the rapid increase in soil moisture following precipitation events (e.g., late January in Fig. 4a), but the subsequent dry down is often too rapid compared to the in-situ data (e.g., December in Fig. 4b). This rapid dry down is due to the shallower remotely sensed layer responding more quickly to atmospheric forcing than the deeper layer observed by the ground probes. The AMSR–E soil moisture better reflects the in-situ data at the two Murrumbidgee sites (Fig. 4a,b) than it does at Merriwa in the Goulburn (Fig. 4c). At Merriwa the precipitation-induced soil moisture peaks in the AMSR–E timeseries are too small (this is exacerbated here by the use of the moving average filter), and there is an artificial upwards drift (of ~0.15 vol/vol) in the between-precipitation soil moisture through the first half of the year.

The examples provided in Fig. 4 are representative of the results at all of the monitoring sites, as demonstrated by the statistics in Table 2. For the Murrumbidgee sites, the fit between the in-situ data and AMSR–E is consistently very good, with correlations typically greater than 0.8 and RMSDs typically less than 0.03 vol/vol for each of the C- and X-band products, and each of the descending and ascending Aqua passes. For the Goulburn sites, while there is still a clear relationship between the AMSR–E and ground-based soil moisture, the relationship is not as good as at the Murrumbidgee sites. The upwards drift in

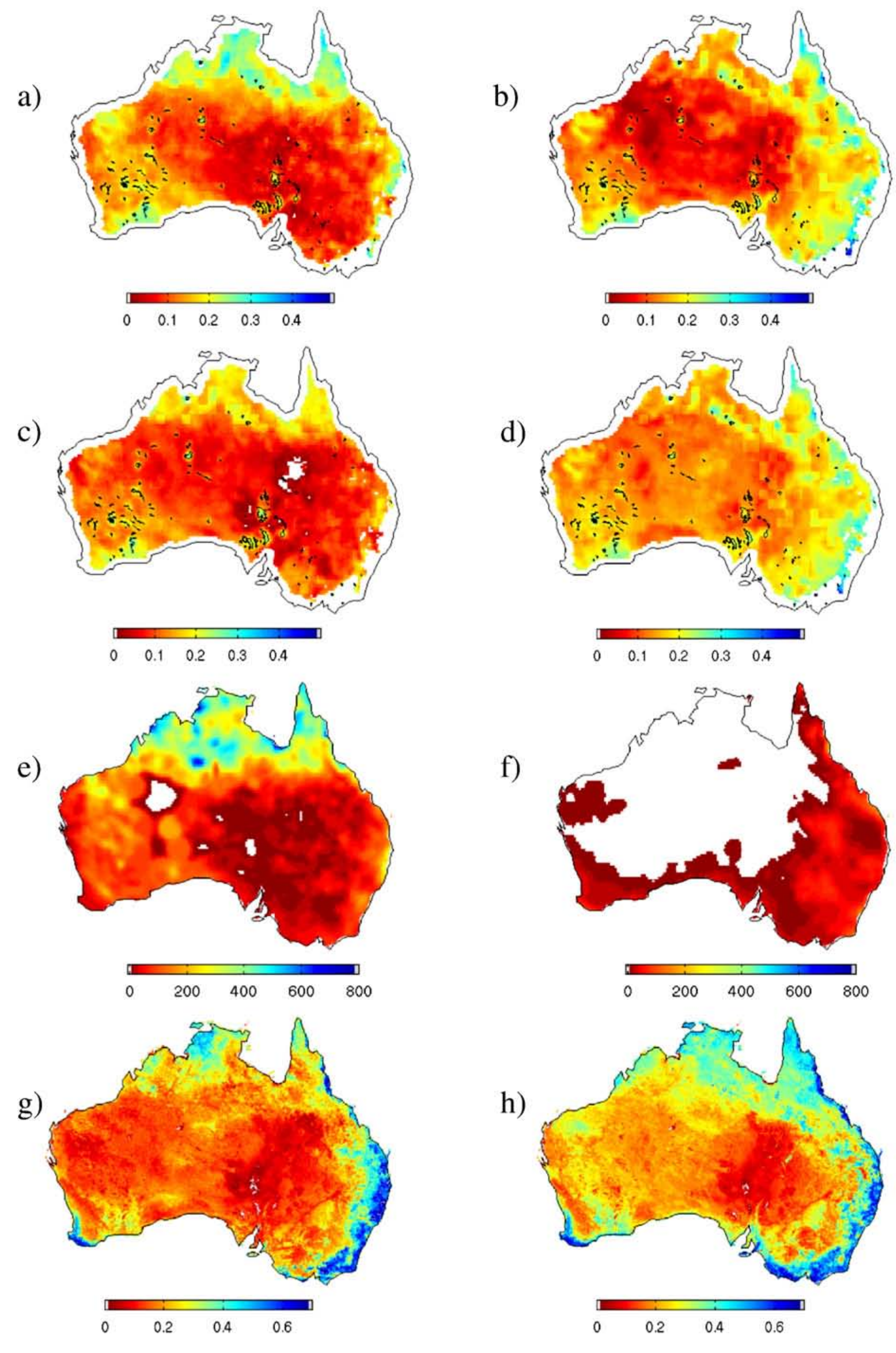

Fig. 5. Monthly mean AMSR–E C-band soil moisture (vol/vol) across Australia, from the ascending (first row) and descending passes (second row), with monthly precipitation (in mm; third row) and NDVI (fourth row), for January (left) and June (right), 2006.

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the AMSR–E data during the first half of the year in Fig. 4c occurred at both of the Goulburn sites, resulting in lower correlations (typically 0.6–0.7) and higher RMSDs (>0.04 vol/vol) than for the Murrumbidgee. The only Murrumbidgee site with similarly poor statistics is Hay, where there was a similar artificial drift in the AMSR–E data, resulting in correlations of ~0.7 and RMSD of 0.03–0.035 vol/vol (the poor performance at Canberra for the X-band descending overpass is due to missing data: soil moisture values were available at that pixel on only 107 days in 2006).

C-band passive microwave data is expected to yield more accurate soil moisture than the shorter-wavelength X-band data. However, it is difficult to discern a consistent difference between them in the timeseries plots (Figs. 3 and 4), and the statistics in Table 2 are only marginally better for the C-band timeseries. For the descending pass, the C-band AMSR–E timeseries have slightly better statistics overall, however, this result is not consistent across all sites. For the ascending pass the difference in the performance of the C- and X-band time is even less, and is actually reversed at the Goulburn sites, where the ascending C-band soil moisture is particularly poor (correlations ~0.06 and RMSD of ~0.06 vol/vol, compared to ~0.7 and ~0.05 vol/vol for X-band).

The descending (night-time) AMSR–E pass is expected to produce more accurate soil moisture than the ascending (day-time) pass, since the surface temperature is vertically and horizontally more homogenous at night time, and thus better approximated by the single pixel-averaged value used in the retrieval algorithm (Owe et al., 2001). The statistics in Table 2 support this expectation; for C-band the ascending pass typically has lower correlations and higher RMSD than the descending pass (particularly at the Goulburn sites, where the ascending C-band data is unusually poor, as mentioned above). For the X-band timeseries, the difference between the ascending and descending passes is less consistent. Significance tests comparing the difference in correlation obtained for the ascending and descending (and also the C- and X-band) timeseries did not indicate significant differences (at 5% confidence level), however the power of these tests is greatly reduced by the need to account for the high serial-correlation of the timeseries. In Fig. 3, for the original AMSR–E data, the ascending pass has a smaller range, particularly for C-band, with less graduation at the dry end (contrary to expectation that bare-soil evaporation would generate a greater tendency toward dry-end values during the day). This behavior is repeated across all the sites, suggesting that the better statistics for the descending data could be due to a greater sensitivity to soil moisture changes.

Maps of the mean monthly soil moisture across Australia for January and June are shown in Fig. 5, for both the ascending and descending pass, together with maps of the monthly precipitation and the monthly mean NDVI. At the continental scale, the mean monthly soil moisture from the descending AMSR–E pass reflects the precipitation patterns in each month. In January, the extremely high monsoonal rain (~200 to >600 mm/month) in tropical north Australia is evident in the mean monthly soil moisture, as are the smaller regions of elevated precipitation along the east coast. However, the high rainfall across Western Australia is not reflected in the soil moisture maps. This will be due in part to the episodic nature of rainfall there (most of the monthly total fell in the first 2 weeks of the month), which combined with extremely high potential evaporation[1] will reduce the precipitation signal in the mean monthly soil moisture. In June, the winter precipitation across east Australia is also reflected by the AMSR–E soil moisture. The soil moisture from the descending pass shows a much stronger relationship to precipitation than the ascending pass, and in particular the latter does not have a strong signal of the rain in tropical north Australia in January. X-band soil moisture maps have not been included in Fig. 5, however, they are very similar to the C-band maps.

[1] The Australian Bureau of Meteorology estimates the annual mean average pan evaporation across inland West Australia to be between 2000 and 4000 mm/year.

At finer spatial scales, two other features are evident in the AMSR–E soil moisture maps; ephemeral salt-lakes and vegetation cover. Inland water bodies have been outlined in black in Fig. 5a–d, and many of the arid-zone lakes are identifiable as regions of elevated soil

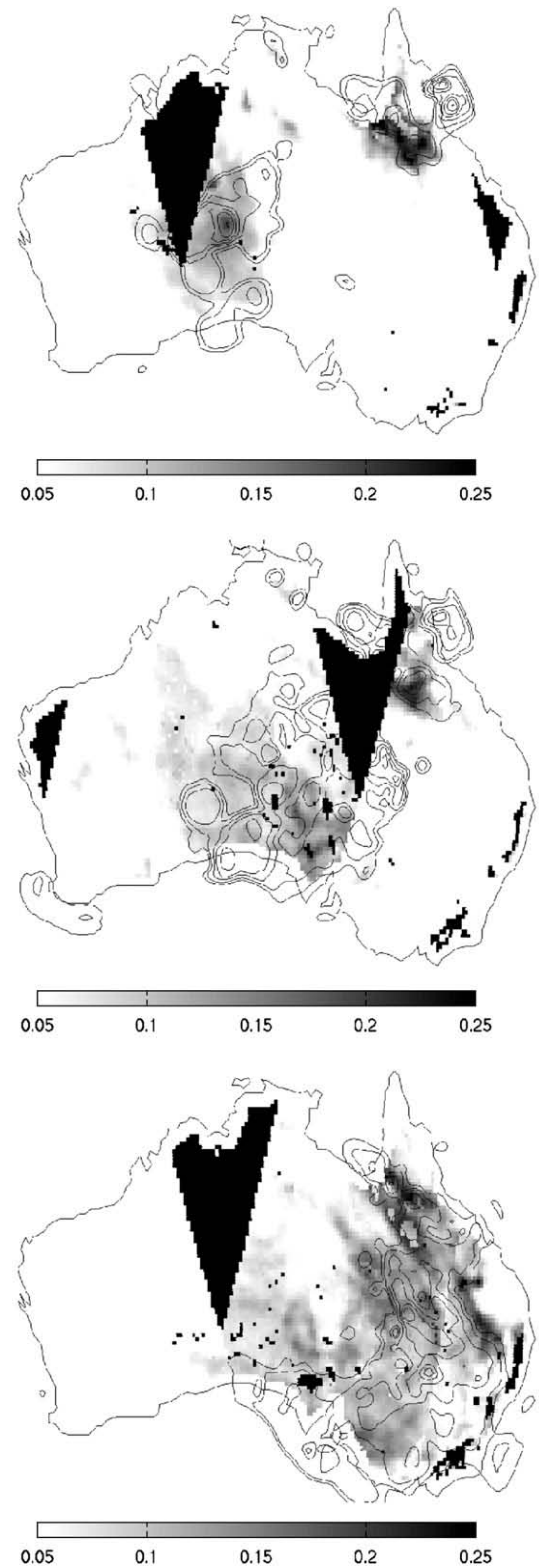

Fig. 6. Maps of the AMSR–E daily near-surface soil moisture anomaly (vol/vol), with 10 mm precipitation contours for 13–15 July, 2007. The soil moisture anomaly is calculated as the difference from the monthly mean, based on the average of the ascending and descending AMSR–E data. Black indicates no AMSR–E data.

moisture. Most of these are ephemeral salt lakes, which fill only during flood events, and the elevated soil moisture may be due to ground-water discharge, possibly combined with a surface salt crust acting to reduce surface moisture evaporation. Several other regions of elevated soil moisture stand out in Fig. 5a–d that are not related to precipitation: for example the NW–SE band south of the Gulf of Carpentaria, and the coastal sections in both north and south West Australia. Each of these regions corresponds to regions of high NDVI in Fig. 5f & g. Regions of dense vegetation, for which the soil moisture signal is potentially obscured at the microwave frequencies used here, have been screened from the soil moisture maps in Fig. 5. The mean 2006 NDVI at Adelong (0.42) was used as the upper-limit for inclusion in the soil moisture maps, since this was the highest NDVI at any of the Murrumbidgee or Goulburn monitoring sites, and the above analysis showed that the AMSR–E soil moisture at Adelong compared favorably with the station data. The strong correspondence between vegetation and soil moisture in Fig. 5 (even with densely vegetated pixels screened out of the latter) is likely due to both a true correspondence between elevated soil moisture and vegetation vigor, and to vegetation artifacts in the soil moisture retrievals.

In addition to the longer-term averages in Fig. 5, there is also a strong spatial relationship between the AMSR–E soil moisture and precipitation at much shorter timescales. In Fig. 6, examples of the positive daily soil moisture anomaly are plotted (to show daily wetting), together with 20 mm precipitation contours on each of 13 through 15 July, 2006. This period was chosen as an example of wide-spread precipitation preceded by a dry spell. In each panel of Fig. 6 there is a clear pattern of elevated soil moisture in the regions of precipitation. There is some mismatch between the locations of the elevated soil moisture and precipitation, some of which will be due to differences in the timing of the two observations (precipitation is over the 24 h to 9 am, and the AMSR–E maps are an average of the anomaly at 1:30 am and 1:30 pm — the mean was used to maximize the spatial coverage each day), however, McCabe et al. (2005) also noted a spatial mismatch between AMSR–E soil moisture fields and precipitation, despite their having investigated only precipitation events close to the AMSR–E overpass time.

4. Discussion

Comparison of (original) near-surface soil moisture timeseries from AMSR–E to in-situ data from the Murrumbidgee and Goulburn monitoring networks shows that, while the AMSR–E timeseries have the expected seasonal cycle and response to rain events, they have i) more noise, ii) greater variability, and iii) a bias, compared to the in-situ data. These differences are due to errors in both datasets, and to the inherent differences between remotely sensed and ground-based soil moisture (most prominently, their different horizontal and vertical scales). These differences prevent meaningful comparison of the absolute value of remotely sensed and ground-based soil moisture, and so before further comparison, the AMSR–E timeseries have been re-scaled to better match the distribution of the in-situ data. In a process similar to that applied in data assimilation applications of remotely sensed soil moisture (e.g., Reichle et al., 2007; Scipal et al., 2008), each AMSR–E timeseries has been locally normalized to match the mean and variance of the in-situ data. The AMSR–E data have also been filtered to remove some of the excess noise, much of which is associated with the method used to map the AMSR–E observations onto the 0.25° grid. The benefit of applying a filter to the AMSR–E data is demonstrated by it having improved the correlation to the in-situ data (compare Tables 1 and 2), and such a filter could be beneficial to applications of the AMSR–E soil moisture data.

After the filtering and normalization, the AMSR–E timeseries have a clear visual fit to the in-situ data. This is reflected in the statistics of fit between the two: at most monitoring sites the temporal correlation between the AMSR–E soil moisture and the in-situ data was greater than 0.8, and the RMSD was less than 0.03 vol/vol (note that the RMSD depends strongly on the normalization strategy used). While the RMSD values obtained here represent nearly 5–10% of the typical soil moisture values across the monitoring sites, they are within the accuracy limit of 0.05 vol/vol specified by Walker and Houser (2004) for the assimilation of near-surface soil moisture to positively impact soil moisture forecasts, and close to the estimated accuracy of the in-situ soil moisture measurements (0.02–0.03 vol/vol). The normalization has not removed all of the systematic differences between the two datasets, and the normalized AMSR–E timeseries (Fig. 4) still dries more rapidly after rain events than the in-situ data, due to the thinner surface-layer observed by AMSR–E. This may have consequences for assimilation of AMSR–E data into land surface models, since the depth of the near surface soil layer in models is usually closer to the deeper layer observed here by the in-situ data, than to the ~1 cm layer observed by AMSR–E.

The fit between the AMSR–E and ground-based soil moisture was not as good at the Goulburn sites as it was for the Murrumbidgee sites. At the Goulburn monitoring sites, there is a tendency for the AMSR–E soil moisture to underestimate the soil moisture peaks generated by large precipitation events, and in the first half of the year there is an upwards drift in the between-precipitation soil moisture values that is not evident in the in-situ data. This drift is quite substantial, and is of the order of ~0.15 vol/vol over 6 months at Merriwa (Fig. 4c), which is approaching 50% of the total range of observed values. A similar, although less marked, drift occurred at many of the Murrumbidgee sites during the first half of 2005, when conditions in the region were extremely dry (Draper et al., 2007), and a drift was also noted at Hay, which is the only Murrumbidgee site with soil moisture values as low as those at the Goulburn sites. The recurrence of this drift for situations when soil moisture is low suggests that the retrieval algorithm cannot fully describe dry surface conditions, and the possible reasons for this are currently under investigation.

There is a strong spatial correspondence between AMSR–E daily soil moisture anomalies and daily precipitation, as demonstrated by the examples given in Fig. 6, indicating that AMSR–E can accurately detect the increases in soil moisture associated with precipitation events. At longer time-scales, the strong correspondence between the monthly mean AMSR–E soil moisture (Fig. 5a–d) and monthly precipitation (Fig. 5e, f) indicates that the broad spatial patterns expected in the seasonal soil moisture climatology are also present. There is an equally strong correspondence (often with smaller scale features) between the mean monthly soil moisture maps in Fig. 5a–d and the NDVI (Fig. 5g, h). While it is likely that some of this correspondence is caused by an artificial vegetation component in the soil moisture fields, it was shown earlier that AMSR–E was still able to detect temporal changes in soil moisture at the Murrumbidgee monitoring sites in the presence of relatively dense vegetation cover.

There was not a consistent visual difference between the AMSR–E timeseries for the C-band and X-band Aqua passes (Figs. 3 & 4), although the statistics were slightly better for the C-band soil moisture (Table 2). Nonetheless, soil moisture derived from the lower frequency C-band observations is theoretically expected to be more accurate than that from X-band, and so the C-band product is recommended for use in Australia where RFI is not problematic. In other regions, where RFI prevents the use of C-band data, the results obtained here suggest that the X-band soil moisture retrieval could be used without a substantial loss of accuracy. The power of this investigation was limited by the short time-period of the available data, and repeating this comparison once more data are available may provide a more definite assessment of the difference between C- and X-band retrievals.

The timing of the Aqua over-pass was found to have a greater influence on the accuracy of the observed soil moisture than the observation frequency, and the soil moisture derived from the descending AMSR–E overpass appears to be more realistic than that from the ascending pass. The descending pass is more sensitive to temporal changes in soil moisture (Fig. 3), and to spatial variation in precipitation (Fig. 5), and it has a stronger relationship to the in-situ data (Table 2). The superior performance of the night-time data was

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expected, and Owe et al. (2001) use only the night-time data in their evaluation of the VUA–NASA algorithm. Yet the soil moisture derived from the day-time overpass still compared favorably here to other soil moisture estimates, and it could be useful for applications where more frequent observations are required.

5. Conclusions

This study has demonstrated that useful soil moisture information can be extracted over Australia from passive microwave data from the AMSR–E instrument. Temporally, the soil moisture derived from AMSR–E by VUA–NASA shows a strong correlation to ground-based soil moisture data at 12 locations across the Murrumbidgee and Goulburn Monitoring Networks for 2006, although results from the Goulburn are not as good as those from the Murrumbidgee. Spatially, the AMSR–E soil moisture has a strong correspondence to precipitation data across Australia, in both long-term averages and for individual rain events.

The correspondence between the AMSR–E soil moisture and the in-situ data from the monitoring stations is exceptionally good, given the fundamentally different quantities observed by each. In addition to showing that AMSR–E can be informative of ground-based soil moisture, this positive comparison demonstrates that data from the Murrumbidgee and Goulburn Monitoring Network can reflect the temporal dynamics of the area average (over $0.25° \times 0.25°$) near-surface soil moisture observed by AMSR–E. These monitoring networks will be valuable for future verification studies of both modeled and remotely sensed soil moisture, and in particular for validation of the Soil Moisture Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP) missions, both of which are expected to improve upon the capabilities of AMSR–E for observing soil moisture.

While in-situ soil moisture data are extremely useful for understanding the temporal characteristics of remotely sensed datasets, they are less useful for evaluating large scale spatial patterns, and the contrasting results obtained here for the Goulburn and Murrumbidgee sites also highlight that an evaluation based on in-situ data cannot necessarily be extrapolated to other regions. While AMSR–E soil moisture has been qualitatively compared to maps of precipitation and vegetation here, the strongest conclusion that can be drawn from such a comparison is that the soil moisture fields are realistic, and have no obvious significant errors. More quantitative methods to compare soil moisture to related variables, such as precipitation, for which continental-scale observations are available, would be extremely valuable here. An example of such an approach is given by Crow and Zhan (2007). Alternatively, it may be that the accuracy of remotely sensed soil moisture can only truly be verified if assimilation of this data into land surface models is shown to improve model performance.

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