Remotely Sensed Soil Moisture over Australia from AMSR-E

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EXTENDED ABSTRACT

Soil moisture can significantly influence atmospheric evolution. However the soil moisture state predicted by land surface models, and subsequently used as the boundary condition in atmospheric models, is often unrealistic. New remote sensing technologies are able to observe surface soil moisture at the scales and coverage required by numerical weather prediction (NWP), and there is potential to improve modelled soil moisture, and ultimately atmospheric forecasts, through assimilation of this remotely sensed data into NWP models.

Remotely sensed soil moisture is currently derived over Australia from passive microwave brightness temperatures from the Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR-E), on NASA's Aqua satellite. In collaboration with NASA, the Vrije Universiteit Amsterdam (VUA) are producing soil moisture separately from C-band (6.92 GHz) and X-band (10.65 GHz) AMSR-E data. Due to radio frequency interference (RFI) in the C-band microwave frequencies over north America, NASA also produce a soil moisture product from X-band data only, using a different algorithm.

The three soil moisture products identified above are assessed in this paper by comparison to i) in-situ soil moisture timeseries from the Murrumbidgee Soil Moisture Monitoring Network (MSMMN), and ii) spatial patterns of antecedent precipitation. Specifically, the three products are assessed to determine their relative performance, and whether any are sufficiently accurate for use in NWP models. The benchmark against which they are assessed is the current scheme used to initialise soil moisture in the Australian NWP model: the Limited Area Prediction System (LAPS).

Within the microwave spectrum, lower frequencies are theoretically better suited to sensing soil moisture, and a priori the soil moisture derived from C-band AMSR-E data was expected to be superior to that from X-band data. However, this analysis has revealed only a minimal difference between the VUA-NASA soil moisture derived from C- and X- band data. Both had realistic spatial behaviour, and a high correlation to the MSMMN soil moisture timeseries, and both out-performed the soil moisture currently used in LAPS. In contrast, the soil moisture derived at NASA from X-band AMSR-E data is persistently very low, and has a low correlation with the MSMMN data. It does not offer an improvement over the current soil moisture used in LAPS. This poor performance is believed to be due to the algorithm used in the retrieval, rather than the use of higher frequency brightness temperatures, since the VUA-NASA product based on X-band data performed comparatively well.

This analysis concludes that the VUA-NASA soil moisture derived from AMSR-E C-band data is the most appropriate for use in assimilation experiments with the Australian NWP system, since it had the best performance, and lower microwave frequencies are theoretically favoured for sensing soil moisture. However, in regions where RFI prevents the use of C-band data, the VUA-NASA X-band product could be used, since it performed comparably in this assessment.

INTRODUCTION

Soil moisture is an important control over atmospheric evolution, since it controls the partitioning of incoming radiation into latent and sensible heating. To model accurate surface heat fluxes, numerical weather prediction (NWP) models must ultimately have accurate soil moisture fields. Yet soil moisture is typically initialised indirectly in NWP models using atmospheric data (e.g., Viterbo and Beljaars, 1995), resulting in frequently unrealistic soil moisture fields (e.g., Douville et al, 2000). Novel remote sensing technologies are able to observe surface soil moisture at the scales and coverage required by NWP (Wagner et al, 2007a), and there is potential to improve modelled soil moisture through the assimilation of such remotely sensed data (e.g., Walker et al, 2003; Reichle and Koster, 2005).

The most promising methods for remote sensing of soil moisture utilise the passive microwave spectrum. Within the microwave spectrum, lower frequencies are less affected by vegetation and can sense a deeper soil layer, and so are better suited to sensing soil moisture. The lowest frequency radiometer currently in orbit is the Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR-E) instrument, on NASA's Aqua satellite. AMSR-E has been the focus of efforts to remotely sense soil moisture, and is the only sensor from which a soil moisture product is routinely derived over Australia.

AMSR-E observes the passive microwave signal at 6 dual polarised frequencies, the lowest of which is C-band (6.92 GHz). It provides global coverage in two days or less, with the exception of regions of dense vegetation or frozen ground cover. The (C-band) brightness temperature is observed on an overlapping 45x75 km grid, and then re-sampled onto 25 km grid. Vertically, the observations relate to moisture in the uppermost ~1 cm of the surface. Unfortunately radio frequency interference (RFI) from surface communication networks, particularly in the C-band frequencies, has made AMSR-E data unusable in many urban areas including much of North America (Njoku et al, 2005).

Two different soil moisture retrieval algorithms for AMSR-E have been investigated here; one developed at NASA, following Njoku and Chan (2003), and one developed collaboratively by Vrije Universiteit Amsterdam (VUA) and NASA, following Owe et al (2007). Due to RFI in C-band frequencies across north America, the NASA product is based on higher frequency 10.65 GHz (X-band) AMSR-E brightness temperatures. In contrast, two separate VUA-NASA soil moisture products are generated, one each from C-band and X-band AMSR-E brightness temperatures.

While surface soil moisture has been successfully derived from AMSR-E data, the ability to remotely sense soil moisture will be enhanced from 2008, when the European Space Agency is scheduled to launch the first dedicated soil moisture remote sensing mission, the Soil Moisture Ocean Salinity (SMOS) mission. SMOS will also utilise microwave radiometry, and will carry a radiometer capable of 1.4 GHz (L-band) observations, which is considered ideal for sensing soil moisture. Much of the current research into the development and application of AMSR-E derived soil moisture is in anticipation of the availability of SMOS data.

Until SMOS data is available, Australia offers a unique testing ground for assessing the current passive microwave soil moisture retrieval algorithms. No significant RFI has been detected over Australia (Njoku et al, 2005), which combined with the scarcity of dense vegetation and frozen cover, leads to Australia having an unusually complete coverage of high-quality AMSR-E data. Hence, this paper presents an assessment of the current capacity for deriving soil moisture from radiometric data over Australia. Specifically, the VUA-NASA soil moisture products derived from C-band (VUA-NASA-C) and X-band (VUA-NASA-X) brightness temperatures, and the NASA (NASA-X) product have been assessed for the year 2005, using in-situ soil moisture data and spatial precipitation data. The assessment is focussed on determining the relative performance of each of these products, and in particular whether any of them is sufficiently accurate to be useful for assimilation into the Australian operational NWP model, the Limited Area Prediction System (LAPS). A priori, the VUA-NASA C-band product is expected to be superior, as it utilises a lower frequency microwave signal.

1. METHODS AND DATA

1.1. Spatial Precipitation Data

Verification of remotely sensed soil moisture is made difficult by the scarcity of ground-based reference data, both in Australia and globally. To check that the AMSR-E derived soil moisture describes a sensible spatial pattern across Australia, it has been visually compared to maps of the previous day's precipitation (in the absence of in-situ soil moisture data for most of Australia). Precipitation maps have been derived from the

Australian Bureau of Meteorology's daily 0.25° rain gauge analysis (Weymouth et al, 1999), which provides precipitation in the 24-hours prior to 9 am. This has been compared to AMSR-E data from the ascending Aqua pass, which observes Australia several hours later, at approximately 1:30 pm. Since precipitation is the dominant forcing of soil moisture, a strong spatial relationship is expected between the two fields. The AMSR-E data presented here has not been filtered for factors such as dense vegetation or mixed land / water pixels, which are known to violate the radiative transfer assumptions of the soil moisture retrieval algorithms.

1.2. MSMMN Ground-Based Soil Moisture

Time-series of each of the AMSR-E derived soil moisture products have been compared to in-situ observations of soil moisture from the Murrumbidgee Soil Moisture Monitoring Network (MSMMN; see http://www.oznet.unimelb.edu.au for details). The surface (0 – 7 cm) soil moisture is observed at 17 of the MSMMN stations, which are shown in Figure 1. Observations are taken every 30 minutes, and these have been sub-sampled through 2005 at the approximate time of Aqua overpasses for Australia, and then compared to the soil moisture derived from the co-located AMSR-E pixel. In Figure 1 there are eight locations with a single soil moisture station, and two locations with clusters of stations (five at Kyeamba and four at Adelong). Each of these clusters is within a single AMSR-E pixel, and the average of all stations within each cluster has been used in the comparison at these locations. As with the spatial comparison, only the AMSR-E data from the ascending Aqua pass has been used.

Before use in data assimilation, remotely sensed soil moisture data are often re-scaled to match the internal variability of the receiving model to account for the inherent differences between modelled and observed soil moisture fields (e.g. Reichle and Koster, 2005). The temporal behaviour of remotely sensed soil moisture is then considered to be more important here than the absolute values. Consequently, the AMSR-E soil moisture products have been re-scaled to match the range of the MSMMN at each station (with the range defined as lying between the 5^{th} and 95^{th} percentiles).

For the frequencies observed by AMSR-E, vegetation is the main limitation on the observability of the surface. Vegetation density at the MSMMN sites, as indicated by the average leaf area index (LAI; Lu et al, 2003) across the sites, is above the 90th percentile of the LAI across Australia (average LAI of MSMMN: 0.91, of Aus: 0.36). Consequently, the quality of the microwave signal, in terms of its accurately representing the soil surface, at the MSMMN sites is representative of (or worse than) that of most of Australia.

1.3. Soil Moisture in LAPS

For remotely sensed soil moisture data to be usefully assimilated into a model it must be more accurate than the soil moisture fields currently being used to initialise that model. In the LAPS land surface scheme, soil moisture is initialised using a local adaptation of the land surface scheme developed by Viterbo and Beljaars (1995). The adapted scheme uses a back-ground field based on antecedent precipitation and climatological evaporation, following Pescod et al (1994), which is then 'nudged' according to low-level forecast humidity errors, following the original Viterbo and Beljaars (1995) scheme.

To test how the performance of the current soil moisture initialisation in LAPS compares to that of remotely sensed soil moisture, the moisture from the 0 – 7 cm soil layer in the newly initialised LAPS model (at 10 am) has been used as the benchmark for assessment of the AMSR-E fields.

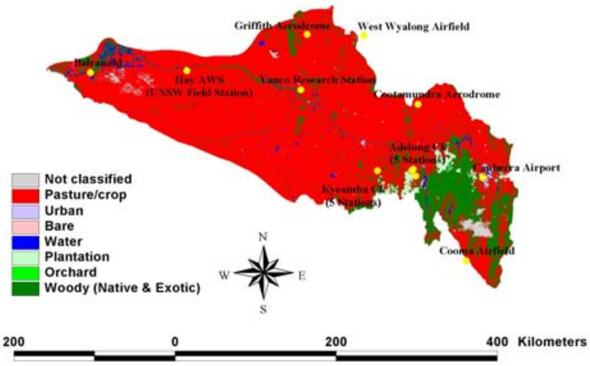

Figure 1: The Murrumbidgee River basin. The ten Murrumbidgee Soil Moisture Monitoring Network station locations used in this study are marked in yellow; the overlay is land-cover.

2. RESULTS AND DISCUSSION

2.1. Spatial Comparison

Inter-comparison of the spatial behaviour in the AMSR-E soil moisture products shows that the use of different retrieval algorithms generates larger differences than the use of different frequency wavebands in the retrieval. In general, VUA-NASA-C and VUA-NASA-X have higher absolute

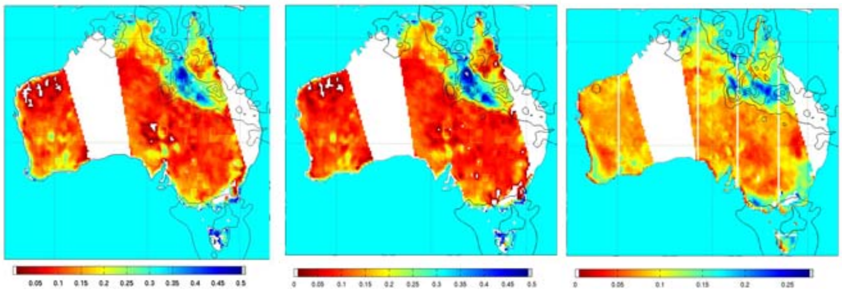

Figure 2: Maps of soil moisture on 6 January, 2005, derived from (left to right) VUA-NASA-C, VUA-NASA-X, and NASA-X. The black lines are 20 mm precipitation contours from the previous 24 hours, and the resolution is 0.25°.

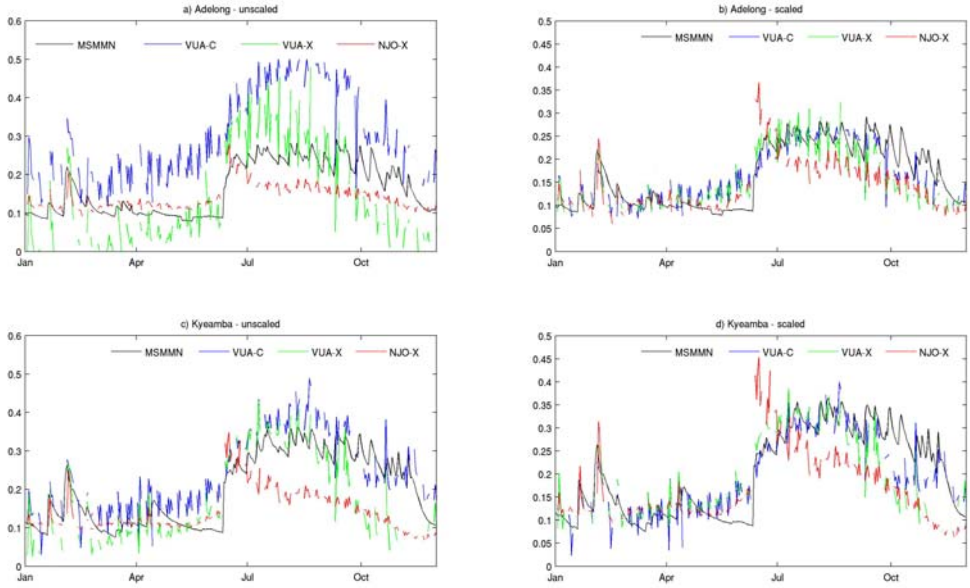

Figure 3: Comparison of AMSR-E derived soil moisture to MSMMN observations for 2005, at Adelong (top) and Kyeamba (bottom). The AMSR-E data is unscaled in the left panels, and scaled in the right panels.

values and a more direct relationship to precipitation than does NASA-X. For example, Figure 2 shows the three AMSR-E soil moisture products, together with precipitation on the 6 January, 2005. While both the NASA and VUA-NASA retrieval algorithms specify a soil moisture range of 0 – 0.5 vol/vol, the NASA-X soil moisture has a strong tendency to remain low. For example there were just 25 days in 2005 when NASA-X exceeded 0.4 vol/vol at any point in Australia. Consequently little variation can be seen in NASA-X data if it is plotted with the full contour range of 0 – 0.5 vol/vol, as has been done for the VUA-NASA data (see colour bars in Figures 2a,b). Instead, NASA-X has been plotted using a narrower contour range of 0 – 0.28 vol/vol (Figure 2c), which is the range of the NASA-X data on 6 January 2005.

All three ASMR-E soil moisture products show the expected climatological pattern of soil moisture, with an extremely dry surface over in-land arid zones, and a moister surface in the humid coastal zones. In Figure 2, there are additional moist areas associated with a rain-band over south-east Queensland, with the VUA-NASA products showing a stronger co-location between the regions of greatest soil moisture and precipitation. All three panels in Figure 2 show several small in-land moist regions which are not associated with recent rainfall. These false moist regions, which are persistent across time, indicate regions of high surface salinity. For example, the yellow and green region to the north of Spencer Gulf in South Australia is the Lake Torrens salt pan.

2.2. Temporal Comparison

Figure 3 compares the soil moisture timeseries derived from AMSR-E and from the MSMMN at the two MSMMN locations with multiple monitoring stations; Adelong and Kyeamba. The

MSMMN soil moisture time-series demonstrate the strong control of precipitation over soil moisture. At all of the MSMMN sites, soil moisture was persistently low during autumn, when little precipitation was recorded (<4 mm at Adelong between mid-April and early June). Then in the fortnight beginning 11 June, 123 mm of rain was recorded and soil moisture increased rapidly, and remained high through winter, before decreasing again in late spring.

Comparison of the AMSR-E soil moisture products to the MSMMN timeseries again indicates that the greatest differences between the soil moisture retrievals are the result of using different retrieval algorithms, rather than different observation frequencies. Also, the VUA-NASA products again appear to be more realistic. The NASA-X data continues to be much lower than that from the VUA-NASA, with an average value across all of the MSMMN sites of 0.12 vol/vol (compared to 0.21 and 0.17 vol/vol for VUA-NASA-C and -X). The VUA-NASA timeseries reflect the main temporal dynamics of the MSMMN data better than the NASA-X timeseries does, as demonstrated by the examples in Figure 3. All three products show the rapid increase in June, while the subsequent dry-down (and intermittent precipitation-induced increases) is well represented by only VUA-NASA-C, and to a slightly lesser extent by VUA-NASA-X (the premature dry down at Kyeamba in VUA-NASA-X is more marked than at other sites). In contrast NASA-X dries down too rapidly at all of the MSMMN sites, including Kyeamba and Adelong. The ability to accurately capture soil drying in remotely sensed data is important for data assimilation applications. Model error is often higher during drying since the drying process depends on adequate model physics and parametrisations, in contrast to wetting processes, which are dominated by the accuracy of the precipitation forcing. At most of the MSMMN locations, including Kyeamba and Adelong, there is an artificial drift upwards in all three AMSR-E soil moisture products during the dry autumn months, when the MSMMN data is steady. The possible reasons for this drift are currently being investigated.

The relative degree of fit between each of the AMSR-E products and the MSMMN soil moisture timeseries is summarised by the statistics in Table 1. VUA-NASA-C has the best fit to the MSMMN data, with an average correlation coefficient across the MSSMN sites of 0.79, with VUA-NASA-X performing nearly as well, with an average of 0.77. In contrast, NASA-X has much poorer predictive skill, with an average correlation coefficient of 0.54. The RMSE statistics (for scaled AMSR-E) in Table 1 indicate similar results, with low average RMSE for VUA-NASA-C and VUA-NASA-X (0.031 and 0.034 vol/vol), and a substantially higher value for NASA-X (0.048 vol/vol). The calculated RMSE depends on the method used to re-scale the AMSR-E timeseries, particularly since the range-matching approach used here does not explicitly remove bias. However, the resultant bias (defined by the mean error assuming MSMMN as the truth) is low, with average values across the MSMMN sites of 0.001, -0.002, and -0.015 vol/vol for VUA-NASA-C, VUA-NASA-X, and NASA-X, respectively. The larger negative bias for NASA-X is caused by the premature dry-down after the peak soil moisture is reached in July.

The agreement between the VUA-NASA soil moisture products and the MSMMN is remarkably good, given the spatial differences between remotely sensed and ground-based (point) measurements. The behaviour of soil moisture at a single MSMMN station (or the average of a modest number of stations in the case of Kyeamba and Adelong) will differ from that of a co-located remotely sensed retrieval, since the latter is an area average (over tens of km in the case of AMSR-E), and different processes control the soil moisture dynamics at each of these scales. Additional differences between the MSMMN and AMSR-E soil moisture will also arise from the differences in the vertical depths to which they respond; AMSR-E responds to a layer of ~1cm depth while the MSMMN data relate to a 7cm layer. There may be large differences in these two quantities, with the thinner layer responding more rapidly to rainfall and evaporation. This explains some of the rapid variability in the AMSR-E products that is evident in Figure 3. However, some of this variability is likely also due to noise in the microwave signal.

Table 1: Statistics describing the fit between (scaled) AMSR-E derived soil moisture and MSMMN observations. The average, minimum, and maximum value across the ten MSMMN locations is provided. Each cell contains correlation coefficient, and (RMSE in vol/vol).

	Average	Minimum	Maximum
VUA-NASA-C	0.79 (0.031)	0.68 (0.019)	0.89 (0.042)
VUA-NASA-X	0.77 (0.034)	0.65 (0.021)	0.85 (0.05)
NASA-X	0.54 (0.048)	0.34 (0.024)	0.73 (0.080)
LAPS	0.58 (0.043)	0.45 (0.029)	0.73 (0.071)

2.3. LAPS Soil Moisture

The LAPS soil moisture across Australia show similar spatial characteristics to the AMSR-E products. Since the soil moisture in LAPS is initialised using antecedent precipitation observations, it is expected to show a strong correlation to precipitation, as is demonstrated in Figure 4 for 6 January, 2005. The LAPS soil moisture has a range of 0.17 – 0.32 vol/vol, defined by the (global) wilting point and field capacity parameters in the land surface model. Comparison of the spatial soil moisture from LAPS (Figure 4) to AMSR-E (Figure 2) indicates that there is less spatial detail in the LAPS soil moisture than in the remotely sensed fields (more so than can be attributed to their different resolutions). The LAPS soil moisture shows two wet regions (not shown by AMSR-E) in north West Australia and to the west of the rainband in south Queensland, that do not correspond to the previous day's precipitation, but to heavy precipitation two days previously. The lesser detail and prolonged wetting in the LAPS soil moisture fields, compared to the AMSR-E fields, will be at least partly due to the increased memory of the deeper (7 cm) soil layer represented by the LAPS moisture fields.

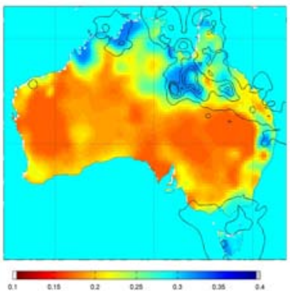

Figure 4: Map of the LAPS soil moisture on 6 January, 2005. The black lines are 20 mm precipitation contours from the previous 24 hours, and the resolution is 0.375°.

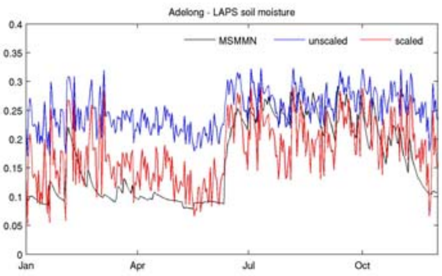

Figure 5: Comparison of the LAPS soil moisture to MSMMN data for 2005, at Adelong.

While the LAPS soil moisture has a strong relationship to precipitation, it does not compare well to the MSMMN data. The LAPS soil moisture is noisy, and has very little variability at monthly (or longer) scales. Figure 5 compares the LAPS soil moisture to the MSMMN data at Adelong, using both the original (unscaled) LAPS fields, and a scaled version (using the same range-matching approach as was used for the AMSR-E products). Little useful information can be extracted from the LAPS soil moisture timeseries as the noise has a similar amplitude to the seasonal signal. This is reflected in the statistics in Table 1: the LAPS correlation and RMSE are roughly equivalent to those for NASA-X, and indicative of a poorer fit than the VUA-NASA statistics.

3. DISCUSION

The soil moisture products derived by the VUA-NASA from C-band and X-band AMSR-E data both appear to be realistic. They show a strong correlation with the MSMMN soil moisture timeseries, and a good spatial agreement with precipitation data. The mean RMSE of both (scaled) VUA-NASA soil moisture products over 2005 across the MSMMN was 0.03 vol/vol (assuming the MSMMN data to be the truth). While the difference is minimal, VUA-NASA-C performed slightly better than VUA-NASA-X with better overall statistics. In contrast to the VUA-NASA products, the soil moisture produced by NASA from the AMSR-E X-band appears to be less realistic. It showed only a weak correlation to the MSMMN timeseries, and had a higher average RMSE of 0.05 vol/vol. Since the VUA-NASA X-band product has compared favourably, the poor performance of the NASA product should not be contributed to its use of a sub-optimal microwave frequency.

While the broad spatial behaviour of the AMSR-E soil moisture has been checked by comparison to precipitation, quantitative assessment has been based on data from only a handful of locations, and these results do not necessarily extrapolate to other regions. Furthermore, the comparison is limited by problems associated with the different spatial and vertical scales of the remotely sensed, in situ, and modelled soil moisture. However, the main findings regarding the relative performance of the different soil moisture products was consistent across all of the MSMMN sites, and was also supported by comparison to precipitation data. The superior performance of both VUA-NASA products over the NASA-X product also concurs with the findings of Wagner et al (2007b), based on soil moisture data from Spain.

The AMSR-E soil moisture presented here has not undergone any (post-processing) quality control, and a quality screen is necessary before the data is applied. In particular, the false moist regions caused by high surface salinity should be filtered out, as should regions of dense vegetation or close proximity to the coast.

4. CONCLUSIONS

The VUA-NASA soil moisture products derived from C- and X- band AMSR-E brightness temperatures are both realistic. Both compared well to other estimates of soil moisture, and are more realistic than the soil moisture fields currently being used to initialise the LAPS model. In contrast the soil moisture derived at NASA from X-band AMSR-E brightness temperature does not verify as well, and does not offer any improvement over the LAPS soil moisture. While both of the VUA-NASA products could be used in assimilation experiments seeking to improve modelled soil moisture in LAPS, the C-band product should be preferentially used in Australia, since it is theoretically superior, and it has performed slightly better in this assessment. In other regions, if RFI prevents the use of C-band data the VUA-NASA X-band product could be used, since its performance was comparable.

5. ACKNOWLEDGMENTS

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