

**Assimilation of
space-based passive
microwave soil
moisture retrievals**

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Assimilation of space-based passive microwave soil moisture retrievals and the correction for a dynamic open water fraction

**B. T. Gouweleeuw¹, A. I. J. M. van Dijk¹, J. P. Guerschman¹, P. Dyce¹,
R. A. M. de Jeu², and M. Owe³**

¹CSIRO Land and Water, Canberra, ACT, Australia

²Vrije Universiteit Amsterdam, Faculty Earth and Life Sciences, Amsterdam, The Netherlands

³NASA/Goddard Space Flight Center, Greenbelt, MD, USA

Received: 31 December 2011 – Accepted: 7 January 2012 – Published: 18 January 2012

Correspondence to: B. T. Gouweleeuw (ben.gouweleeuw@csiro.au)

Published by Copernicus Publications on behalf of the European Geosciences Union.

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Abstract

The large observation footprint of low-frequency satellite microwave emissions complicates the interpretation of near-surface soil moisture retrievals. While the effect of sub-footprint lateral heterogeneity is relatively limited under unsaturated conditions, open water bodies, if not accounted for, cause a strong positive bias in the satellite-derived soil moisture retrieval. This bias is generally assumed static and associated with large, continental lakes and coastal areas. Temporal changes in the extent of smaller water bodies as small as a few percent of the sensor footprint size, however, can cause significant and dynamic biases. We analysed the influence of such small open water bodies near-surface soil moisture retrieval data from the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) for three areas in Oklahoma, USA. Differences between on-ground observations, model estimates and AMSR-E retrievals were compared to dynamic estimates of open water fraction, one retrieved from a global daily record based on higher frequency AMSR-E data and another derived from the Moderate Resolution Imaging Spectroradiometer (MODIS). The comparisons demonstrate that seasonally varying biases of up to 30 vol.% soil water content can be attributed to the presence of relatively small areas (< 5 %) of open water in or near the sensor footprint. These errors need to be addressed, either through elimination or accurate characterization, if the soil moisture retrievals are to be used effectively in a data assimilation scheme.

1 Introduction

Near-surface soil moisture derived from remotely sensed low-frequency microwave emissions has the ability to improve hydrological and meteorological modelling (e.g. Koster et al., 2004; Scipal et al., 2005; Crow, 2007). For example, the Land Parameter Retrieval Model (LPRM, Owe et al., 2008), a radiative transfer-based model, has demonstrated significant potential for providing independent estimates of land surface

HESSD

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parameters, such as (relative) near-surface moisture, land surface temperature (LST) and vegetation optical depth (VOD). Satellite retrievals of these parameters may be combined with simulated and observed data in an assimilation scheme in order to generate the best possible data fields (e.g., Walker and Houser, 2001; Reichle et al., 2007; Scipal et al., 2008a). These data may then be used to initialize numerical weather prediction or land surface models, drive continuous atmospheric forcing correction or, in case of systematic error, assist in model structure development/improvement (Drusch, 2007; Brocca et al., 2010; Van Dijk and Renzullo, 2011). Key to such efforts is the error characterization of the assimilation variable, in the particular case discussed here, the LPRM-derived soil moisture. Several studies have reported on this issue, traditionally using in situ validation for specific regions (e.g. De Jeu et al., 2003; Draper et al., 2009) and, more recently, employing triple collocation techniques, assessing the relative error of multiple global soil moisture data sets by means of reference (Scipal et al., 2008b; Dorigo et al., 2010). Recently, an analytical solution based on error propagation in the partial derivatives of the radiative transfer function found, conform to theory, increasing soil moisture retrieval error at higher VOD (Parinussa et al., 2011).

Apart from dense vegetation, conditions under which soil moisture cannot be accurately retrieved from passive microwave sensors include precipitating clouds, snow cover, frozen soil and (inland) surface water (e.g. Njoku et al., 2003; Pellarin et al., 2003; Gao et al., 2006; Owe et al., 2008). Typically, quality control masks are provided to screen data affected by these conditions. While most of these masks are dynamic and can be derived from ancillary data, the mask for open water is generally static and considers coastal areas and large continental lakes only. Due to the high dielectric constant of water, however, even a small sub-pixel fraction of open water, may result in a non-negligible soil moisture overestimation (e.g. Walker et al., 2006; Davenport et al., 2008; Loew, 2008).

The LPRM screens data for snow and frozen surface conditions to flag those pixels where the model's LST is estimated to be at or below 273 K (Owe et al., 2008). Further, a mask is applied to remove those data affected by dense vegetation ($VOD > 0.8$), or

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where convergence between modelled and observed brightness temperature is considered insufficient (>0.25 K) (De Jeu et al., 2008). Additionally, in line with other global coarse scale soil moisture data sets based on space-based microwave observations, a static mask is used delineating coastal areas and (large) permanent inland lakes (Njoku et al., 2003; Scipal et al., 2008a). While static water bodies cause a constant positive bias and do not affect temporal patterns, temporal changes in open water fraction are not accounted for. Jones et al. (2009) released a global daily record of land surface parameters retrieved from AMSR-E, which does include a dynamic open water fraction, based on 18.7 GHz H and V polarized brightness temperatures.

In this study, the influence of open water on soil moisture retrieval data (Owe et al., 2008; Jones et al., 2009) was investigated by comparison to on-ground station observations and land surface models (LSMs) estimates for three areas in Oklahoma, USA (Fig. 1). Differences between the ground or model estimates and LPRM retrievals were further evaluated against dynamic estimates of open water fraction.

2 Data

On-ground observations

Soil moisture observations were taken from 11 stations in the Mesonet observational grid in Oklahoma, USA (Brock et al., 1995). The selected stations are all located within three areas of $4 \times 0.25^\circ$ lat/long grid cell size (Fig. 2), which are spatially representative of the predominant types of land cover in the area. These are (wooded) grassland and cropland (East), cropland (West), and wooded grassland (South-Central), as classified by the 1 km global vegetation data set of the University of Maryland re-sampled to a predominant vegetation type 0.125° grid resolution map (<http://ldas.gsfc.nasa.gov>). The selection does not include an area of evergreen forest in the South-East corner of the state of Oklahoma, due to the relatively low density of ground- observation stations in this part (1 per 0.5° grid cell). The selected 0.25° grid cells all contain 1 or more

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stations, in which case the observations are simply averaged. If the observations of multiple stations within a 0.25° grid cell differ greatly, both the individual station and the average are considered (e.g. stations PORT and HASK, Table 1). The 5 cm profile soil moisture content is measured using Campbell Scientific 229-L devices, made available every half hour (Illston et al., 2008). The AMSR-E overpass is at night-time (descending orbit ~01:30 LT, i.e. ~08:30 Coordinated Universal Time (UTC)) and at day-time (ascending orbit ~13:30 LT, i.e. ~20:30 UTC).

Model estimates

The Land Information System (LIS), developed at NASA Goddard Space Flight Center, is an interoperable platform capable of integrating the use of LSMs, data management techniques and high performance computing (Kumar et al., 2006). The community Noah land surface model (Ek et al., 2003) and the Community Land Model, version 2:0 (CLM2) (Dai et al., 2002; Zeng et al., 2002) are two of the LSMs currently supported by LIS. Both are stand-alone, 1-D models and are freely available from the Noah from the National Centers for Environmental Prediction (NCEP) and CLM2 from The National Center for Atmospheric Research (NCAR), respectively.

The LSMs simulate a range of water- and energy balance variables, of which near-surface soil moisture is of interest for the present analysis. The models apply finite difference spatial discretization methods and (semi-)implicit time-integration schemes to numerically integrate the governing equations of the physical processes of the soil-vegetation-snow pack medium, including the surface energy balance equation, the Richards' equation for soil hydraulics, the diffusion equation for soil heat transfer, the energy-mass balance equation for the snow pack, and equations for the conductance of canopy transpiration.

The LSMs can be applied in either coupled or uncoupled mode. In this study, the models were applied in uncoupled mode, meaning that some (atmospheric forcing) data is used as input, rather than as a dynamic variable themselves. Here, three sets of forcing data were used, i.e. the NCEP Global Data Assimilation System (GDAS);

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corresponding with the satellite data and atmospheric forcing data for the model simulations (i.e. 2003).

All data contaminated by precipitating clouds were removed by visual inspection of the LPRM retrieved surface temperature fields and by comparison to ground-observed surface temperature for Oklahoma (Gouweleeuw et al., 2007). Most of the cloud-contaminating conditions occur at day time in summer, when convection is strong. While this eliminated about 1–3 % of the data set, frozen soil conditions in winter took out the bulk of the data (over 30 %) at this time of year.

3 Methods

First, time series of the on-ground, modelled and satellite-derived top soil moisture estimates for the three areas were plotted and visually inspected to examine the level of agreement. Next, outliers were identified, inspected and, if justified, removed. As noted above, most of the outliers in the satellite-derived estimates could be related to precipitating cloud and soil freezing conditions. Further noise or short-lived events were averaged-out by applying a 14-day simple mean low pass filter to the time series plots (Fig. 3). Next, seasonal effects were identified which could potentially cause temporal bias in the satellite retrievals, viz. (1) the vegetation cycle (2) land surface temperature and (3) open water. This is explored in more detail in the Discussion section. With regard to (3), the effect of the open water fraction (OWF) in the passive microwave footprint was assessed in two ways, viz. (a) using 1 km 16-day composite MODIS reflectance data; and (b) from an open water fraction estimate, based on 18.7 GHz H and V polarized AMSR-E brightness temperature (Jones et al., 2009), made available by the University of Montana (hereafter referred to as OWF_{UM}).

The approach to map open water extent from MODIS data computes an Open Water Index (OWI) from the Nadir-BRDF Adjusted Reflectance (NBAR) product (MCD43B4). This MODIS product provides a 1 km 16-day composite of land surface reflectance, corrected for Bidirectional Reflectance Distribution Function (BRDF) and atmospheric

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affects. The OWI is computed as the difference of the Global Vegetation Moisture Index (GVMI) and the Enhanced Vegetation Index (EVI), if $EVI < 0.2$. If $EVI \geq 0.2$, $OWI = 0$ (Guerschman et al., 2008). Validation against higher resolution Landsat mapping suggests this method performs as good as or better than other commonly used methods (Guerschman et al., 2009). The OWF_{MODIS} is computed as the number of 1 km pixels of $OWI > 0$ in a grid cell, divided by the total number of pixels.

4 Results

Comparison of on-ground, modeled and satellite-derived soil moisture

Figure 2 shows two examples of 0.25° gridded maps of AMSR-E derived soil moisture using LPRM (hereafter referred to as Vrije Universiteit Amsterdam, VUA) of Oklahoma at night time (descending orbit) for 2 April and 28 July 2003, together with the three areas of $4 \times 0.25^\circ$ cell grid size within which ground-observed data is sampled. The early spring images shows a distinct East-West gradient (2 April), which is persistent throughout the year, but less pronounced in summer, as shown for 28 July. Figure 3 illustrates the dynamics of this East-West gradient for the year 2003, plotted together with the AMSR-E retrievals from Jones et al., 2009 (hereafter referred to as University of Montana, UoM), ground-observed and mean modeled soil moisture for the 0.25° grid cells in the Western area (PUTN), South-Central area (BYAR-VANO) and Eastern area (HECT-BIXB). In the Eastern and South-Central areas, AMSR-E VUA soil moisture is much higher than all the other estimates, most notably in the first and last three months of the year. The AMSR-E UoM retrievals show the lowest soil moisture estimated for all areas, with the exception of the start of the year in the South-Central area. While the satellite-derived soil moisture data sets make use of the same sensor, the UoM applies a different method to solve the microwave radiative transfer function for land surface variables, using a combination of multi-frequency polarizations and ratios (Jones et al., 2009). Additionally, it employs an open water fraction derived from higher frequency

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AMSR-E data to correct for positive bias. Despite these differences, some seasonality is also present in the UoM retrievals in the South-Central and Eastern area, albeit less pronounced and at a lower level than in the VUA retrievals. Tables 1 and 2 indicate RMSE for the UoM retrievals vs. ground-observed and modeled soil moisture is higher for the Western area and lower for the other two areas. Figure 2 shows the CLM2 simulations are relatively dry with a high dynamic range, which is explained by the shallow top soil layer in the model adjusted to ~ 2 cm to match the AMSR-E sampling depth. The soil layer depth in the Noah model cannot be changed and is fixed at a 10 cm top soil layer, prompting higher average moisture content with a lower dynamic range. The Mesonet observations taken at a 5 cm depth mostly plot somewhere in between the Noah and CLM simulations. In the Western area, the AMSR-E VUA retrievals generally plot closest to the CLM simulation, which agrees with their comparable sampling depth.

Independent estimation of OWF using MODIS imagery

Figure 4 shows two RGB false color maps (band 7, 2, and 1) of Oklahoma depicting MODIS 16-day composite reflectance data (MCD43B4). The 16-day composites include the dates of the daily soil moisture retrieval maps in Fig. 2, i.e. 22 March–6 April 2003 (upper panel) and 12–28 July 2003. Pixels of OWI > 0 are colored blue, representing mostly dammed lakes/reservoirs, and the wider (> 1 km) stretches of streams. At a glance, open water extent appears to be larger in March–April, albeit only marginally.

Figure 5 shows times series of OWF_{MODIS} for the 0.25° grid cells in the Western, South-Central and Eastern Oklahoma area, as labeled in Fig. 4, together with OWF_{UoM} . As noted earlier, the AMSR-E 6.9 GHz and 10.7 GHz footprint size are substantially larger than 0.25° , so OWF_{MODIS} is also computed for larger grid cells centred in the 0.25° grid cell. Figure 5 shows OWF_{MODIS} remains about constant in the Western area, although levels vary slightly with grid cell size. The Eastern area shows a marked seasonal change in OWF_{MODIS} , which increases in level and variation with grid cell size up to 1.25° . OWF_{UoM} falls somewhere between the 0.75 – 1.5° OWF_{MODIS} and generally

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reflects a corresponding seasonal pattern, absent in the other two areas. Considering OWF_{UoM} is based on the 18.7 GHz signal of 27×16 km footprint, one would expect a better agreement with the smaller 0.25° OWF_{MODIS} . One should realize, however, the OWF estimates are based on independent data and unrelated methods. Despite that, they show an agreement in level and pattern, in that OWF is absent in the Western and South-Central area and present and dynamic in the East. By contrast, in the South-Central area, neither MODIS nor UoM (Fig. 5, middle panel) indicate the presence of an open water fraction to account for the observed LPRM soil moisture retrieval over-estimation (Fig. 3, middle panel), with the exception of a small increase in OWF_{UoM} at around day 60. This may be explained by the different passive microwave frequencies, and hence, spatial resolutions, involved. The 6.9 and 10.7 GHz soil moisture retrieval occupies the larger footprint, an oval of diameter 43×74 km and 30×51 km (and beyond), respectively, and is prone to signal smearing, when re-sampled to a 0.25 degree grid, in this particular case from the East. This is not the case for the smaller 18.7 GHz open water fraction footprint of 27×16 km, which falls almost entirely in the 0.25 degree grid.

5 Discussion

The single year analysis presented here argues the seasonally varying extent of water bodies can explain most of the anomaly between ground observations and model estimates of near-surface soil moisture on the one hand, and LPRM-based AMSR-E satellite retrievals on the other. Of the three seasonal effects identified as potentially causing bias in the satellite retrievals, viz. the vegetation cycle, LST and varying open water extent, the latter is considered the most plausible. This is discussed in more detail below.

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moisture estimate. Conversely, in the cold season, it may lead to underestimation of the soil moisture estimate. Hence, a LST bias would have the inverse effect to what is observed.

Until recently, methods to correct footprints for dynamic water body effects have not been considered feasible or cost-effective on a routine global basis. This study argues temporal, regional variations in OWF could have a profound effect on these soil moisture retrievals. Temporal variations in OWF derived from 18.7 GHz AMSR-E observations (Jones et al., 2009) agreed reasonably well with estimates derived within the soil moisture product grid cell using the MODIS optical bands. Even better agreement is achieved when considering that the re-sampling of 6.9/10.7 GHz footprint data (of 43×74 km/ 30×51 km size) into a 0.25 degree grid has led to considerable signal smearing in the LPRM-based soil moisture retrievals.

Figure 7 shows the time series from 2003 to 2010 of UOM, and to mid-2010 of VUA, soil moisture and VOD retrievals. Although on-ground soil moisture observations and model simulations have not been analysed, the general patterns observed for 2003 are replicated in the longer time series. The South-Central and Eastern area (two lower panels) show a seasonal positive bias in VUA soil moisture, which for the latter area coincides with an increase of open water fraction most of times, a notable exception the first half of 2006, for which no OWF_{UoM} data were available. From the time series for the Eastern area (lower panel), however, it appears an OWF_{UoM} increase is not equally proportional to positive bias of VUA soil moisture over time. This could indicate an interaction with, or possibly reinforcement of, soil moisture retrieval error at higher VOD. As mentioned earlier, however, the times series clearly show VOD (and hence the associated soil moisture retrieval error) in reverse phase with the observed positive soil moisture bias.

Pellarin et al. (2003), using L-band passive microwave observations, estimated that more than a third of the Earth's terrestrial surface has $>1\%$ open water, defined in that case as persistent open water. Open water area, however, is by no means static and may vary for shorter or longer periods of time through e.g. flooding, irrigation, and the

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seasonal recharge and drying of dammed lakes and wetlands. The results in this study and previous studies (e.g. Walker et al., 2006; Davenport et al., 2008; Loew, 2008) suggest that ignoring 1 % open water fraction in the retrieval can lead to a bias of about $0.04\text{--}0.05\text{ m}^3\text{ m}^{-3}$.

5 The soil moisture missions by ESA (SMOS) and NASA (SMAP) that are currently in progress have set a target accuracy of $\pm 0.04\text{ m}^3\text{ m}^{-3}$. To achieve this, constant and seasonally varying extent of open water within the footprint will need to be identified and corrected for in the retrieval. This study provides an indication that higher frequency AMSR-E data provide sufficient spatial resolution to correct for open water
10 fraction contribution on a 0.25 degree grid. On higher spatial resolutions (500 m–1 km) standard MODIS reflectance product are suitable for further verification. Alternatively, it has been shown that high-resolution active radar observations are well suited for open water mapping (Wagner et al., 2007, Ticehurst et al., 2009).

15 Taken together, it would seem that strong gains in the quality and error characterization of passive microwave soil moisture retrievals can be made by a combination of assimilating remote sensing observations of open water area and more sophisticated signal re-sampling approaches (e.g. Gu and England, 2007).

6 Conclusions

20 Open water has a strong passive microwave signature and therefore can produce positive biases in top soil moisture content estimated from passive microwave remote sensing. Seasonal variations in the fraction of open water may further complicate the agreement and accuracy of top soil moisture retrievals. The magnitude of this effect was investigated using top soil moisture estimates for 0.25° grid cells in Oklahoma, derived from on-ground station observations, land surface models, and the AMSR-E
25 passive microwave satellite instrument. Differences between the ground or model estimates and remote sensing retrievals were compared to dynamic estimates of open water fraction retrieved from a global daily record based on higher frequency AMSR-E

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data (Jones et al., 2009) and derived from MODIS (Guerschman et al., 2009). The comparison indicates seasonally varying biases of up to 30 % (relative) soil water content can be attributed to the presence of relatively small areas (< 5 %) of open water in the (nominal) footprint. Given the widespread distribution of small water bodies over the Earth's land surface and the large satellite footprint, it is plausible that more often than not current soil moisture products have considerable positive bias and systematic noise. It is shown that retrievals can be improved by considering temporal observations of open water area, but the source of the satellite signal needs to be considered when re-sampling into spatial grid resolutions that are smaller than the source area.

Acknowledgements. This research is funded under the Water Information Research and Development Alliance (WIRADA) between CSIRO and the Bureau of Meteorology (BoM), Project 3.1 "Water Resources Assessment and Water Use Accounting".

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Table 1. RMSE of VUA soil moisture retrievals vs. ground-observed and modeled soil moisture estimates.

RMSE	Grid/Station	MESO-NET	CLM2				Noah			
			ECMWF	GDAS	NLDAS	Mean	ECMWF	GDAS	NLDAS	Mean
Western area	PUTN	0.12	0.056	0.073	0.051	0.056	0.12	0.14	0.11	0.12
	WEAT	0.11	0.056	0.075	0.055	0.056	0.12	0.14	0.11	0.12
	WATO	0.072	0.071	0.064	0.076	0.065	0.065	0.080	0.058	0.067
	HINT	0.064	0.071	0.066	0.079	0.066	0.075	0.094	0.067	0.078
Eastern area	HECT-BIXB	0.15	0.17	0.17	0.19	0.18	0.12	0.12	0.12	0.12
	PORT	0.19	0.19	0.19	0.22	0.20	0.14	0.13	0.15	0.14
	PORT-HASK	0.13	0.19	0.19	0.22	0.20	0.14	0.13	0.15	0.14
	HASK	0.093	0.088	0.088	0.107	0.091	0.070	0.074	0.068	0.069
	OKMU	0.092	0.084	0.095	0.091	0.088	0.090	0.10	0.082	0.089
South-Central area	BYAR-VANO	0.14	0.17	0.17	0.19	0.18	0.15	0.13	0.16	0.14

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Table 2. RMSE of UoM soil moisture retrievals vs. ground-observed and modeled soil moisture estimates.

RMSE	Grid/Station	MESO-NET	CLM2				Noah			
			ECMWF	GDAS	NLDAS	Mean	ECMWF	GDAS	NLDAS	Mean
Western area	PUTN	0.19	0.09	0.12	0.081	0.096	0.20	0.22	0.18	0.20
	WEAT	0.17	0.083	0.10	0.070	0.084	0.19	0.22	0.18	0.19
	WATO	0.19	0.079	0.10	0.068	0.083	0.18	0.20	0.17	0.18
	HINT	0.16	0.080	0.10	0.067	0.082	0.19	0.21	0.18	0.19
Eastern area	HECT-BIXB	0.14	0.12	0.13	0.10	0.12	0.18	0.18	0.17	0.18
	PORT	0.14	0.14	0.14	0.12	0.13	0.20	0.20	0.18	0.20
	PORT-HASK	0.21	0.14	0.14	0.12	0.13	0.20	0.20	0.19	0.20
	HASK	0.27	0.14	0.14	0.12	0.13	0.20	0.20	0.18	0.20
	OKMU	0.18	0.15	0.16	0.14	0.15	0.17	0.19	0.14	0.17
South-Central area	BYAR-VANO	0.15	0.11	0.12	0.096	0.11	0.13	0.16	0.12	0.13

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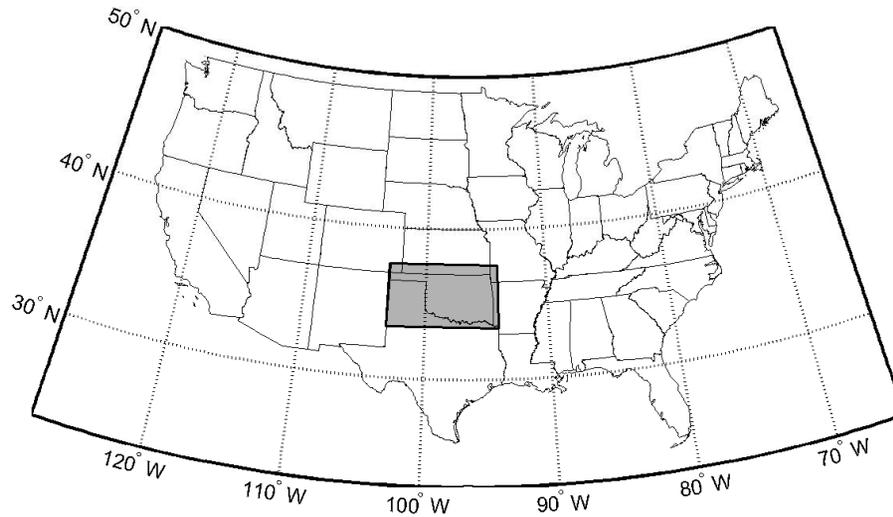
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**Fig. 1.** Location of the Oklahoma study area.[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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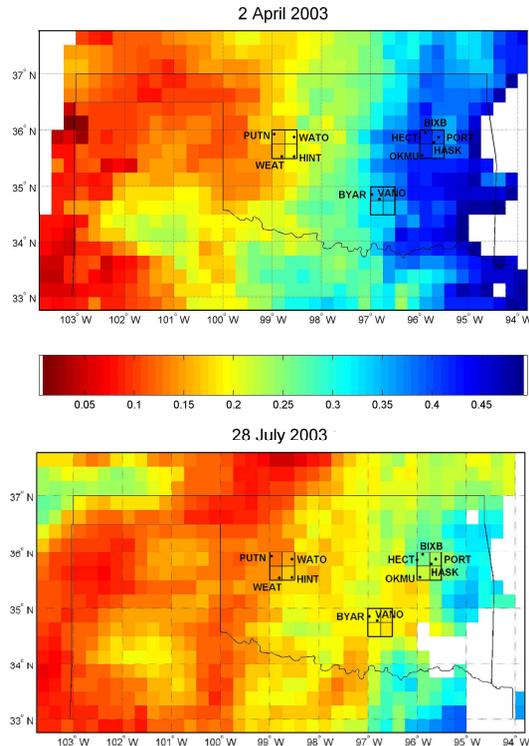


Fig. 2. AMSR-E 0.25 degree gridded soil moisture retrievals from the Land Parameter Retrieval Model (Owe et al., 2008) for 2 April 2003 (upper panel) and 28 July 2003 (lower panel). White areas indicate grid cells outside the sensor swath (upper panel, North-West corner) or masked-out grid cells of non-convergence (East and South-East).

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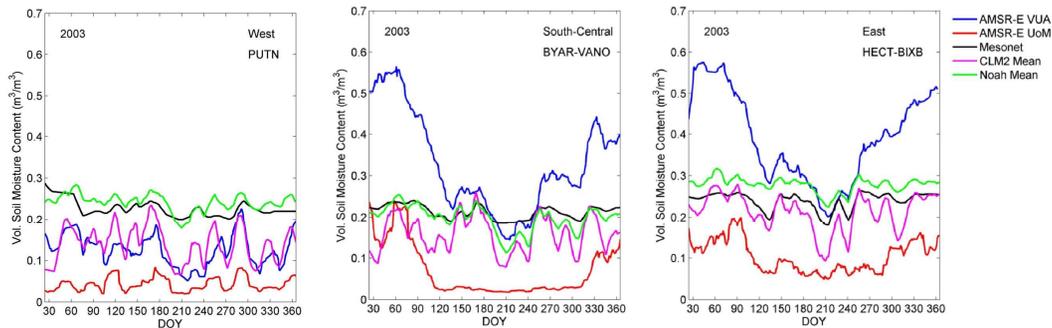


Fig. 3. AMSR-E derived, ground-observed and simulated soil moisture for 0.25° grid cells in the Western (PUTN), South-Central (BYAR-VANO) and Eastern Oklahoma area (HECT-BIXB) (low pass filter 14 days).

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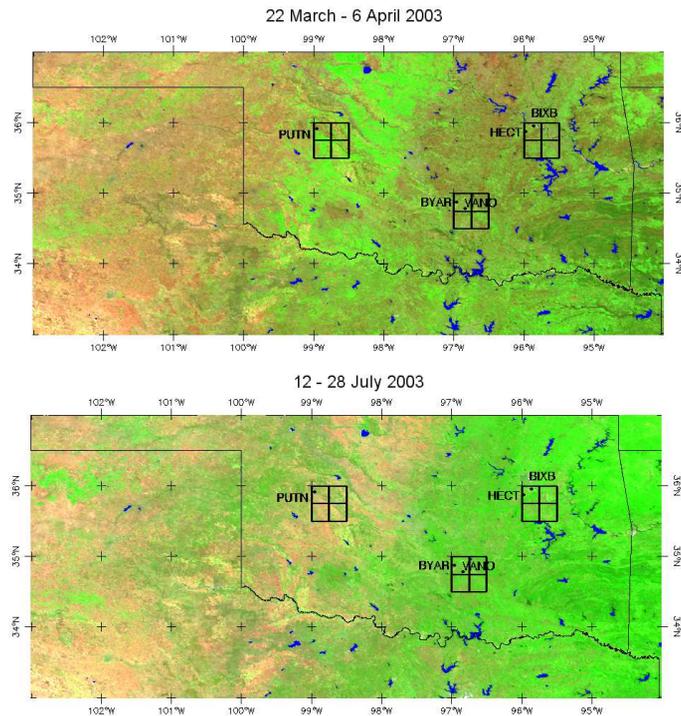


Fig. 4. RGB false colour maps (band 7, 2, and 1) of Oklahoma of 1 km 16-day composite MODIS reflectance data (MCD43B4) overprinted with the Open Water Index (OWI) map for 22 March–6 April 2003 (upper panel) and 12–28 July 2003 (lower panel). Also depicted are the three areas in the Western (PUTN), South-Central (BYAR-VANO) and Eastern Oklahoma area (HECT-BIXB). Pixels of OWI > 0 are coloured blue.

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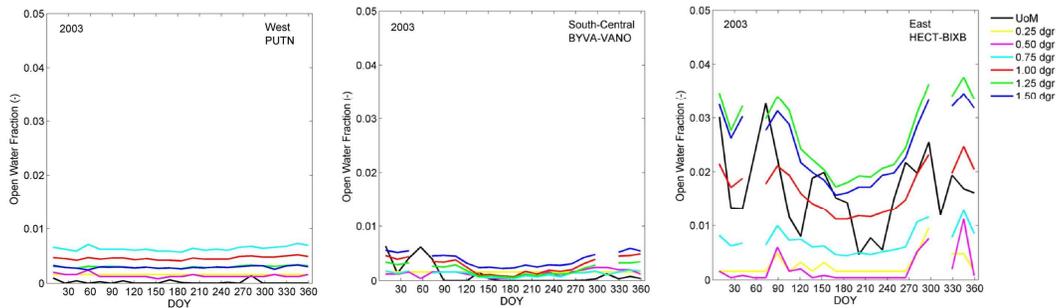


Fig. 5. Time series of the MODIS-derived Open Water Fraction for the 0.25° grids cells in the Western, South-Central and Eastern Oklahoma area for increasing grid cell sizes, together with the UoM open water fraction.

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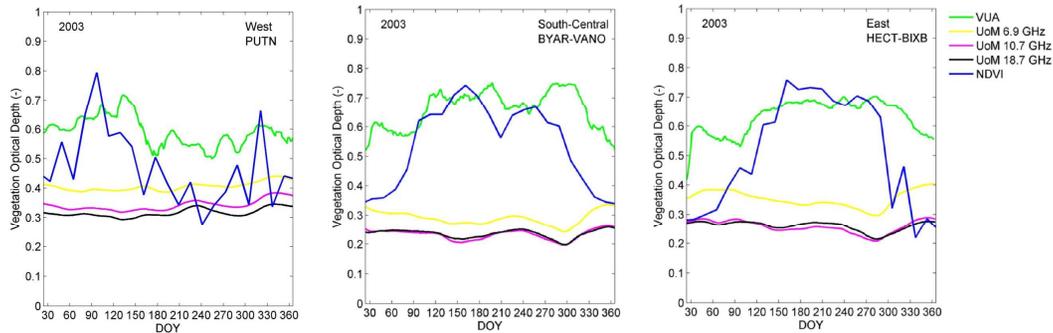


Fig. 6. The AMSR-E UoM and VUA VOD retrievals (low pass filter 30 days), together with area-averaged NDVI.

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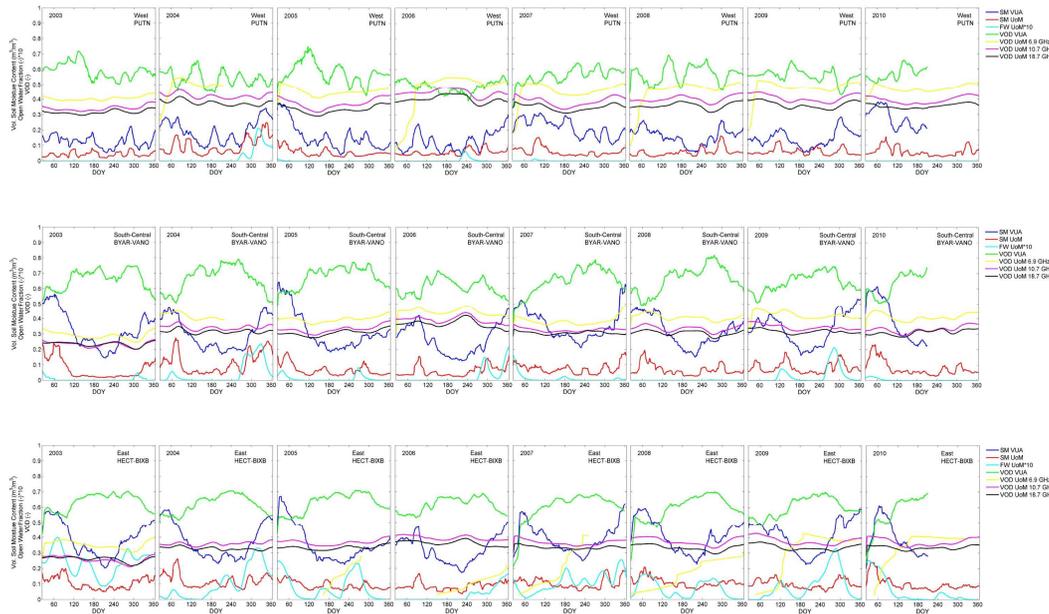


Fig. 7. Time series from 2003 to (mid-) 2010 of VUA and UoM AMSR-E derived soil moisture and VOD retrievals for the Western (top), South-Central (middle) and Eastern (lower) Oklahoma areas.

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