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Improving satellite soil moisture estimates by combining passive and active microwave observations (1992–2008)

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Abstract We propose a methodology to blend soil moisture retrievals from passive (SSM/I, TRMM and AMSR-E) and active (ERS and ASCAT) microwave satellite observations and obtain an improved long-term (1992–2008) global product. The first step is to merge the three passive microwave data sets into a single “passive” product and two active microwave data sets into a single “active” product. This avoids the issue of differences in sensor specifications resulting in different absolute soil moisture values. Next, both data sets are adjusted against a common reference (GLDAS-Noah), which scales both data sets to the same dynamic range and allows the generation of a blended product. The proposed approach has the potential to be applied to existing as well as new missions.

Key words soil moisture; microwave; satellite observations; long term

INTRODUCTION

Both passive and active microwave satellites have been shown to provide useful retrievals of near-surface soil moisture variations at regional and global scales. A series of operational satellite-based microwave sensors have been available since 1978, e.g. SMMR (1978–1987), SSM/I (since 1987), TRMM (since 1997), AMSR-E (since 2002), ERS-1/2 (since 1992) and ASCAT (since late 2006). New satellite missions with low frequency microwave instruments (e.g. SMOS, SMAP, Aqarius and DESDynl) are expected to bring soil moisture retrievals with higher accuracy.

How to effectively combine and analyse these soil moisture products is a challenge. One option is to merge passive and active microwave products into a single long-term product with the information content of both passive and active microwave sensors. This merged product may advance our understanding of the role of soil moisture in the hydrological cycle.

There are several issues that need to be resolved in accomplishing this objective. First, differences in sensor specifications result in different absolute soil moisture values, which prevent direct merging of soil moisture estimates from different instruments. Second, the currently available global passive and active microwave products are conceptually different, providing absolute and relative soil moisture, respectively. Third, the comparative accuracy of soil moisture retrievals differs spatially between passive and active microwave sensors.

Our aim was to use the currently available passive and active microwave soil moisture products and develop an approach that addresses these three problems and generate one blended long-term global data set.

DATA SOURCES

Soil moisture products used in this analysis include the passive microwave retrievals by VU University Amsterdam–NASA (VUA-NASA) (Owe *et al.*, 2008), and active microwave products by Vienna University of Technology (TUW) (Wagner *et al.*, 1999). Model simulations for the top layer (10 cm) from GLDAS-Noah (Rodell *et al.*, 2004) were used as an independent reference. All soil moisture products are re-sampled to 0.25° with a daily interval. Relevant characteristics of these data sets are shown below.

Table 1 Major characteristics of soil moisture data sets used in this study.

	Passive microwave products			Active microwave products		Model product
	SSM/I	TRMM	AMSR-E	ERS	ASCAT	GLDAS-Noah
Time period used	Jan 1992–Dec 2007	Jan 1998–Dec 2008	Jul 2002–Dec 2008	Jan 1992–Dec 2006	Jan 2007–Dec 2008	Jan 2000–Dec 2008
Channel used	19.3 GHz	10.7 GHz	6.9 GHz	5.3 GHz	5.3 GHz	---
Original spatial resolution (km^2)	69 × 43	59 × 36	76 × 44	50 × 50	50 × 50	25 × 25
Swath width (km)	1400	780/897	1445	500	1100 (550×2)	
Equatorial crossing time	Descending: 0630	Varies (non polar-orbiting)	Descending: 0130	Descending: 1030	Descending: 0930	---
Unit	m^{3}m^{-3}			%		m^{3}m^{-3}

METHODOLOGY AND RESULTS

Reconstructing passive microwave product

Before merging all three passive microwave data sets into one product, we first investigated their agreements in temporal variations. The AMSR-E soil moisture retrievals are expected to be more accurate due to its relatively low measuring frequency, and therefore was selected as the reference to which TRMM and SSM/I products are compared. Over the regions with strong seasonal cycles, these may dominate the correlation between products. To account for this issue, we decomposed the original time series into seasonality and anomalies (Fig. 1).

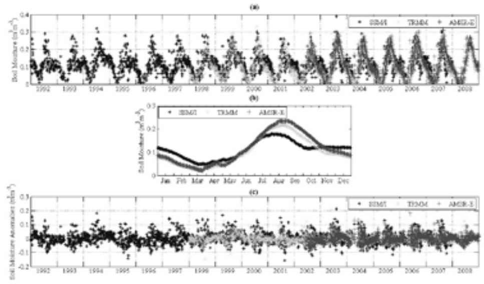

Fig. 1 Example illustrating how (a) the original time series was decomposed into (b) seasonality and (c) anomalies. The grid cell is centred at 13.875°N, 5.875°W.

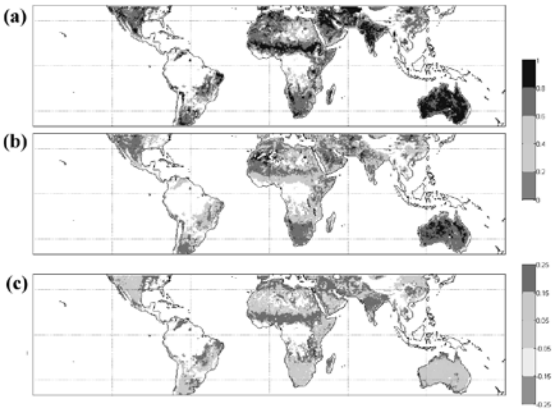

Fig. 2 Correlation coefficient between TRMM and AMSR-E soil moisture for (a) original values and (b) anomalies after removing seasonality for the period July 2002 through December 2008. (c) The difference between (a) and (b) (i.e. a minus b).

Correlation coefficients between TRMM and AMSR-E show that both products capture similar soil moisture processes, i.e. seasonal cycle, inter-annual variations and wet/dry processes responding to rainfall (Fig. 2). Although SSM/I retrievals are expected to be less accurate, the correlation coefficients between SSM/I and AMSR-E anomalies over sparsely vegetated regions are reasonably high, i.e. generally higher than 0.4, and 50% higher than 0.6 (Fig. 3(b)). However, the seasonal cycles captured by SSM/I are frequently different from AMSR-E and TRMM (Fig. 3(c)), most likely due to the atmospheric effects on the high frequency of SSM/I. To address this problem, the seasonal cycle of SSM/I and TRMM was replaced with that of AMSR-E based on the assumption that the seasonal cycle does not obviously change during the study period.

Thus the three passive microwave products can be reconstructed on a pixel basis according to the following steps:

- Decompose soil moisture time series into the seasonality and anomalies (Fig. 1).
- Rescale anomalies of SSM/I and TRMM against AMSR-E based on the data during their individual overlapping period with AMSR-E using the cumulative distribution function (CDF) matching technique (Fig. 4(a)) (Liu *et al.*, 2010).
- Combine rescaled anomalies of SSM/I and TRMM with AMSR-E (Fig. 4(b)). AMSR-E is used for the period July 2002–December 2008, while TRMM is used between January 1998 and June 2002 over the regions between 38°N and 38°S. Otherwise SSM/I product is utilized.
- Add the seasonality of AMSR-E (Fig. 1(b)) to the combined anomalies in step 3 (Fig. 4(c)).

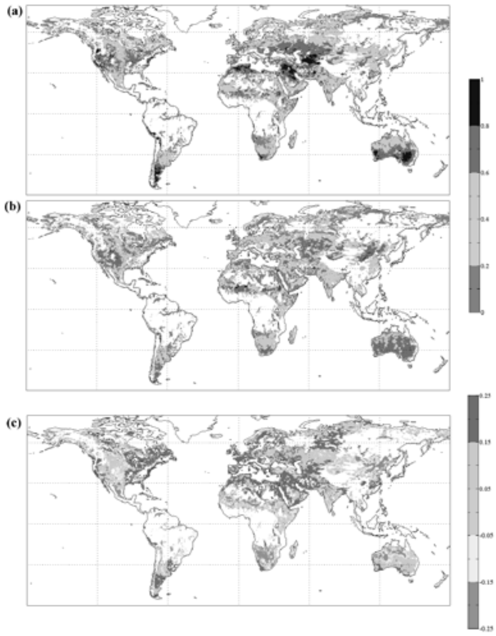

Fig. 3 Same as Fig. 2, but between SSM/I and AMSR-E from July 2002 through December 2007.

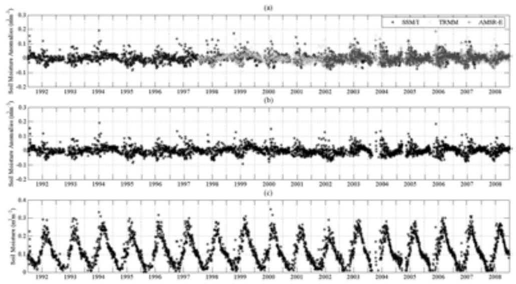

Fig. 4 Example illustrating how the passive microwave soil moisture product was reconstructed. (a) Rescaled anomalies of SSM/I and TRMM (see Fig. 1(c)) against AMSR-E. (b) Combined rescaled anomalies of SSM/I and TRMM with AMSR-E. (c) Reconstructed time series after adding the seasonality of AMSR-E.

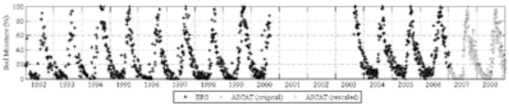

Fig. 5 Example illustrating how the active microwave soil moisture product was reconstructed. Black represents the original ERS soil moisture; while black and grey represent the original and rescaled ASCAT respectively. The reconstructed time series consists of the original ERS (black) and rescaled ASCAT (grey) soil moisture

Reconstructing active microwave product

The ERS and ASCAT soil moisture variations are calibrated between the lowest (0%) and highest (100%) values of their individual operational period, which requires further adjustment to combine them. The limited overlapping period between ERS and ASCAT in time (a few months) and space (only Europe, northern America and northern Africa) rules out the possibility of an adjustment method which is applicable globally based on the overlapping information.

Retrievals from ASCAT should capture the identical season pattern as ERS due to the similar sensor characteristics, including an identical frequency (5.3 GHz). Additionally, the period of ERS (January 1992 to December 2006) covers wet and dry years; thus the range of ASCAT retrievals are expected to be within the range of ERS retrievals. We made the assumption that the cumulative distribution of ASCAT values is identical for ERS as for ASCAT, producing the rescaled ASCAT (Fig. 5).

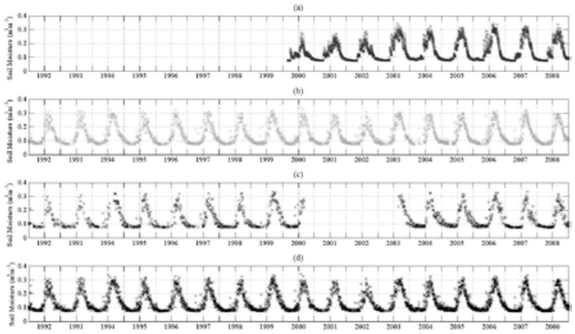

Fig. 6 Example illustrating how the reconstructed passive and active microwave soil moisture products for the same grid cell in Figs 1-3 were merged. (a) GLDAS-Noah soil moisture. Rescaled reconstructed (b) passive and (c) active products against GLDAS-Noah soil moisture. (d) The merged product.

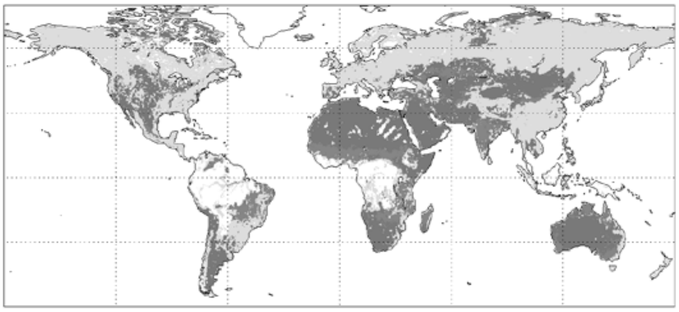

Fig. 7 Spatial coverage by passive (dark grey), active (light grey) microwave or both (medium grey) in the merged product. Tropical rain forests were masked out due to the high vegetation density.

Merging

The reconstructed passive and active microwave products provide absolute (m^3m^{-3}) and relative (%) soil moisture, respectively. To combine them together, one product needs adjustment against the other, or both require adjustment against an independent reference data set. A number of previous studies showed that VUA-NASA passive microwave products generally perform better over sparsely vegetated regions and TUW active microwave products better over moderately vegetated regions. Over the regions where the vegetation density is between low and moderate, both products display similar performance (Dorigo *et al.*, 2010; De Jeu *et al.*, 2008; Scipal *et al.*, 2008). Given this, adjusting one product against the other is troublesome.

The GLDAS-Noah soil moisture was selected as an independent reference against which both reconstructed products are adjusted, as it has the global coverage with a comparable spatial and temporal resolution with microwave products and relatively long time record, and provides reasonable surface soil moisture estimates for all land cover types (Rodell *et al.*, 2004).

The reconstructed passive and active products were rescaled against GLDAS-Noah product using the CDF matching technique based on the information over their respective overlapping periods with GLDAS-Noah (Fig. 6). Liu *et al.* (2010) demonstrated that when passive and active microwave soil moisture products are highly correlated (e.g. $R > 0.65$), combining both (i.e. taking the average when two coincident values are available, otherwise only using one product) will increase the number of observations while minimally changing the accuracy of the reconstructed soil moisture products. In the example in Fig. 6, the correlation coefficient between the two reconstructed microwave time series is higher than 0.65, and thus they were combined in the merged product (Fig. 6(d)). The vegetation density of these regions with correlation coefficients above 0.65 is used as a vegetation threshold. The passive microwave product was used over the regions with vegetation density lower than the threshold; otherwise the active microwave product was used (Fig. 7).

SUMMARY

We demonstrate a three-step approach to combine soil moisture retrievals from passive and active microwave sensors, by reconstructing passive and active microwave products from different sensors individually and then merging both reconstructed products into one data set.

The approach is expected to be applicable to both past and current microwave satellites, as well as new missions expected to bring higher accuracy soil moisture retrievals. This will enable the generation and extension of a long-term global passive/active microwave satellite-based soil moisture data set, and furthermore allow a number of experiments to be conducted. For example, the regions where passive and active microwave products are highly correlated partly correspond with the “hot spots” where strong coupling between soil moisture and precipitation are expected (Koster *et al.*, 2004). The enriched information from the merged product may enhance the understanding of land surface–atmosphere interactions and improve weather and climate prediction skills over these regions. In addition, the analysis of long-term trend and water cycle acceleration or deceleration can be carried out.

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