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Comparison and assimilation of global soil moisture retrievals from the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) and the Scanning Multichannel Microwave Radiometer (SMMR)

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[1] Two data sets of satellite surface soil moisture retrievals are first compared and then assimilated into the NASA Catchment land surface model. The first satellite data set is derived from 4 years of X-band (10.7 GHz) passive microwave brightness temperature observations by the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E), and the second is from 9 years of C-band (6.6 GHz) brightness temperature observations by the Scanning Multichannel Microwave Radiometer (SMMR). Despite the similarity in the satellite instruments, the retrieved soil moisture data exhibit very large differences in their multiyear means and temporal variability, primarily because they are computed with different retrieval algorithms. The satellite retrievals are also compared to a soil moisture product generated by the NASA Catchment land surface model when driven with surface meteorological data derived from observations. The climatologies of both satellite data sets are different from those of the model products. Prior to assimilation of the satellite retrievals into the land model, satellite-model biases are removed by scaling the satellite retrievals into the land model's climatology through matching of the respective cumulative distribution functions. Validation against in situ data shows that for both data sets the soil moisture fields from the assimilation are superior to either satellite data or model data alone. A global analysis of the innovations (defined as the difference between the observations and the corresponding model values prior to the assimilation update) reveals how changes in model and observations error parameters may enhance filter performance in future experiments.

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1. Introduction

[2] Surface and root zone soil moisture control the partitioning of the available energy incident on the land surface into latent and sensible heat fluxes. Through this control, soil moisture impacts local weather parameters, including the boundary layer height and cloud coverage [*Betts and Ball*, 1998]. Moreover, root zone soil moisture exhibits memory on weekly to monthly timescales [*Entin et al.*, 2000]. Accurate initialization of root zone soil moisture may therefore contribute to enhanced subseasonal prediction of midlatitude summer precipitation over land [*Dirmeyer*, 2003; *Koster et al.*, 2004].

[3] Estimates of soil moisture conditions may be derived by integrating a land surface model as it is driven with surface meteorological data derived from observations. Estimates of surface soil moisture may also be retrieved from low-frequency active and passive microwave data. Satellite retrievals alone, however, are not sufficient for weather and climate forecast initialization because of gaps in spatial and temporal coverage and because key model variables, such as (deeper) root zone soil moisture, cannot be observed from space. For the best possible estimates of soil moisture conditions, data assimilation may be used to combine satellite retrievals of surface soil moisture with estimates from the land surface model and its associated meteorological forcing inputs. In essence, the data assimilation system uses the land model to interpolate the satellite retrievals in space and in time. Via the land model, the

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system also propagates the surface information from the satellite into the deeper soil and thereby provides improved estimates of root zone soil moisture.

[4] There has been considerable progress in the methodological development of soil moisture data assimilation [*Walker and Houser*, 2001; *Reichle et al.*, 2002a, 2002b; *Margulis et al.*, 2002; *Reichle and Koster*, 2003; *Crow and Wood*, 2003; *Seuffert et al.*, 2003; *Crow and Van Loon*, 2006; *Dunne and Entekhabi*, 2006; *Pan and Wood*, 2006; *Zhou et al.*, 2006; G. J. M. De Lannoy et al., Ensemble Kalman filtering of soil moisture observations with model bias correction, submitted to *Water Resources Research*, 2006], with ensemble-based Kalman filtering and smoothing algorithms emerging as the method of choice for soil moisture data assimilation. These developments were largely based on assimilation experiments with synthetic soil moisture retrievals and field-scale studies because global satellite observations of soil moisture had been lacking. Recently, however, a number of such data sets have become available, including the official NASA soil moisture product from the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E; since 2002; *Njoku* [2006]), a research data set from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) (since 1997; *Gao et al.* [2006]), and a data set based on the historic Scanning Multichannel Microwave Radiometer (SMMR; 1978–1987; *De Jeu* [2003]). The AMSR-E and TMI products are based on X-band passive microwave observations, while the SMMR data set is based on C-band data. The effective sensing depth of X- and C-band data is roughly 1 cm. In the future, improved retrievals are expected from passive L-band sensors that measure moisture in the top 5 cm of the soil, including the Soil Moisture and Ocean Salinity Mission (SMOS; *Kerr et al.* [2001]), the NASA Aquarius mission [*Koblinksy et al.*, 2003], and established NASA soil moisture mission concepts [*Entekhabi et al.*, 2004].

[5] Significant climatological differences have been identified between independent soil moisture data sets from in situ measurements, satellite retrievals, and model integrations of antecedent meteorological forcings. On a global scale, neither the satellite nor the model soil moisture are more consistent with the available in situ observations, implying that presently there is no agreed climatology of global soil moisture [*Reichle et al.*, 2004]. To circumvent this problem for data assimilation, scaling approaches that overcome such discrepancies have been developed [*Reichle and Koster*, 2004; *Drusch et al.*, 2005]. The central idea is to rescale the satellite data prior to assimilation by matching the satellite data's cumulative distribution function to the model's climatology. When using such rescaling, the resulting data assimilation estimates cannot be validated with mean square error measures, because the absolute value of soil moisture has become meaningless. Instead, the key information is in the anomaly time series, which in any case is of the most interest for forecast initialization. Hence validation must be approached from the perspective of (normalized) anomaly time series. Obviously, such validation relies on the availability of relatively long time series of satellite and in situ observations. With four years of data available, it has now become possible to take a climatological view of AMSR-E data and validate an assimilation product based on the assimilation of AMSR-E retrievals.

[6] It has long been argued, but rarely proven, that the assimilation of satellite retrievals of surface soil moisture into a land model does in fact yield superior estimates of soil moisture conditions when compared to model or satellite estimates alone. *Reichle and Koster* [2005] and *Drusch* [2007] demonstrated this property for large-scale soil moisture fields on the basis of the assimilation of retrievals from SMMR and TMI, respectively. Here, in addition to providing a basic comparison of the SMMR and AMSR-E retrieval data sets, we confirm this property for the first time with AMSR-E data and compare the AMSR-E assimilation results with the SMMR assimilation results of *Reichle and Koster* [2005]. The manuscript is structured as follows. Section 2 provides a brief description of the data sources used in this study and section 3 describes the data assimilation approach. Next, section 4 cross-compares the satellite retrievals and the model soil moisture, and section 5 discusses the assimilation results. Section 6 provides conclusions.

6. Summary and Conclusions

[42] It has long been argued, but rarely proven, that the assimilation of surface soil moisture retrievals into land surface models driven with observed meteorological forcing data would yield estimates of land surface conditions, including root zone soil moisture, that are better than those obtained from either the satellite or the model alone. In this paper, we demonstrate that the assimilation of surface soil moisture retrievals from AMSR-E into the NASA Catchment land surface model does indeed provide superior estimates of surface and root zone soil moisture when validated against in situ data, confirming earlier results obtained with SMMR retrievals.

[43] First, though, we compared the AMSR-E and SMMR soil moisture retrievals, and found important similarities as well as striking differences in their climatologies. While both data sets show dry and wet conditions that match climate zones as expected, the AMSR-E retrievals are considerably drier and show far less temporal variability than the SMMR data everywhere (Figures 3 and 4). The discrepancy results from differences in the calibration of the independent retrieval algorithms that were used for AMSR-E and SMMR. Given that the true climatology of large-scale surface soil moisture is unknown, we do not attempt here to determine the superior data set. The differences in the climatologies are, in any case, addressed by scaling the retrievals prior to data assimilation.

[44] We found that the model estimates agree somewhat better than the satellite data with the in situ data, and that the estimates of the recent AMSR-E years are superior to those of the historic SMMR period. Again, we demonstrated that the estimates from the assimilation are superior to those from the satellite or model data alone. This result holds not only for surface soil moisture but also for root zone soil moisture, for which any improvement requires the downward translation, via the model physics, of the surface information provided by the satellite. While modest, the improvements in time series correlation were highly statistically significant, with confidence levels exceeding 99.99% in the AMSR-E period for surface and root zone soil moisture, and confidence levels of 99.9% (80%) for surface (root zone) soil moisture in the SMMR years.