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Correction of real-time satellite precipitation with multi-sensor satellite observations of land surface variables

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ABSTRACT

Precipitation is an important hydro-meteorological variable, and is a primary driver of the water cycle. In large parts of the world, real-time ground-based observations of precipitation are sparse and satellite-derived precipitation products are the only information source.
We used changes in satellite-derived soil moisture (SM) and land surface temperature (LST) to reduce uncertainties in the real-time TRMM Multi-satellite Precipitation Analysis product (TMPA-RT). The Variable Infiltration Capacity (VIC) model was used to model the response of LST and SM on precipitation, and a particle filter was used to update TMPA-RT. Observations from AMSR-E (LPRM and LSMEM), ASCAT, SMOS and LST from AMSR-E were assimilated to correct TMPA-RT over the continental United States.
Assimilation of satellite-based SM observations alone reduced the false detection of precipitation (by 85.4%) and the uncertainty in the retrieved rainfall volumes (5%). However, a higher number of observed rainfall events were not detected after assimilation (34%), compared to the original TMPA-RT (46%). Noise in the retrieved SM changes resulted in a relatively low potential to reduce uncertainties. Assimilation of LST observations alone increased the rainfall detection rate (by 51%), and annual precipitation totals were closer to ground-based precipitation observations. Combined assimilation of both satellite SM and LST, did not significantly reduce the uncertainties compared to the original TMPA-RT, because of the influence of satellite SM over LST. However, in central United States improvements were found after combined assimilation of SM and LST observations. This study shows the potential for reducing the uncertainties in TMPA-RT estimates over sparsely gauged areas.

1. Introduction

Precipitation is an important hydro-meteorological variable, which has a large impact on the global energy and water cycle and thus on weather, climatology, hydrology and ecosystems. Obtaining accurate ground-based measurements of precipitation is difficult, due to the high spatial and temporal variability of precipitation (McCollum & Krajewski, 1998; Tustison, Harris, & Foufoula-Georgiou, 2001). Real-time ground-based observations of precipitation with sufficient accuracy and availability are even sparser. However, real-time observations of precipitation are important for real-time monitoring and forecasting of floods and drought (Gebremichael & Hossain, 2010; Hong, Adler, Hossain, Curtis, & Huffman, 2007; Hossain & Huffman, 2008; Pan, Li, & Wood, 2010; Su, Hong, & Lettenmaier, 2008). Satellite-based precipitation products like the real-time Tropical Rainfall Measuring Mission Multi-satellite Precipitation Analysis products (TMPA-RT, Huffman et al., 2007; Huffman, Adler, Bolvin, & Nelkin, 2010), Climate Prediction Center MORPHing product (CMORPH, Joyce, Janowiak, Arkin, & Xie, 2004), and Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN, Hsu, Gupta, Gao, & Sorooshian, 1999; Sorooshian et al., 2000), provide a solution to obtain real-time precipitation data for many sparsely gauged regions in the world. TMPA-RT gives the 3-hourly precipitation between 50°N and 50°S through combing rainfall estimates from microwave sensors (Kummerow, Olson, & Giglio, 1996; Kummerow et al., 2001; Olson, Kummerow, Hong, & Tao, 1999) and infrared imageries (Joyce, Janowiak, & Huffman, 2001). Precipitation products like TMPA-RT usually suffer from the fact that they depend on satellite retrievals for their observations and thus require a satellite overpass. TMPA-RT products are derived from satellite overpasses in a 3-hour window (Huffman et al., 2007) and not all precipitation events are captured, since some precipitation events may have a smaller temporal scale than 3 h. This is especially true for highly dynamic events (e.g. convective rainfall events), which occur in tens of minutes and could vanish in a similar time period. Some of these events can be missed by the TMPA-RT, while they can have a significant impact on the land surface and the related processes. Although convective precipitation events might have a small spatial scale, they can have a large contribution to the annual precipitation totals (e.g. Blamey & Reason, 2012; Laurent, D'Amato, & Lebel, 1998). Especially in summer conditions with unstable atmospheric boundary layers, these events occur regularly and will impact the land

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surface. Also, various other types of errors also occur in satellite precipitation products (Sapiano & Arkin, 2009; Villarini & Krajewski, 2007).

To correct for the problem of missed precipitation events and uncertainties in rainfall totals, TMPA is post-processed and corrected with ground-based observations (Huffman et al., 2010). This correction is not possible for real-time version of TMPA which is used by real-time applications, which require observations of no less than a couple of hours after sensing.

The observations of several other land surface variables are available in near real time and they can potentially be used to help reduce the uncertainty in satellite precipitation. For example, soil moisture (SM) observations could provide valuable information on the spatial pattern of precipitation. An additional advantage is the fact that the wetting of the surface soil moisture could be detected for longer time periods (up to several days) and could be used to estimate the precipitation volume. The change in soil wetness at larger scales can be detected by space-born microwave sensors. Change detection in soil moisture is occasionally hampered when pre-storm soil moisture content is close to saturation or fully saturated. In these conditions additional precipitation will not result in increased soil wetness, hence no change in soil moisture can be detected. Several studies showed the potential to reduce precipitation uncertainties using soil moisture retrievals from a single sensor (Brocca, Moramarco, Melone, & Wagner, 2013; Brocca et al., 2014; Crow & Bolten, 2007; Crow, Huffman, Bindlish, & Jackson, 2009; Crow, van den Berg, Huffman, & Pellarin, 2011; Pellarin, Ali, Chopin, Jobard, & Bergs, 2008; Pellarin, Louvet, Gruhier, Quantin, & Legout, 2013).

To partly overcome the limitation of soil moisture retrievals we propose the use of observations of land surface temperatures (LST) to detect areas with precipitation amounts exceeding the storage capacity of the unsaturated zone. With increased water storage the soil temperatures will decrease, since more energy is required to warm the earth surface. This change could be detected in satellite-derived land surface temperature based on microwave retrievals from the higher frequencies (Holmes, Jeu, de Owe, & Dolman, 2009).

The objectives of this paper are to study the potential of remotely sensed observations of land surface variables to correct for uncertainties in satellite-derived precipitation. More specifically, do multi-sensor remotely sensed soil moisture retrievals and land surface temperature observations have the potential to correct real-time satellite-based precipitation estimates? Additionally, we study the effect of the correction of precipitation with both soil moisture and land surface temperature changes and the potential gain obtained by either of these sources.

To fulfill these objectives, TMPA-RT was perturbed and used to force a land surface model. Changes in modeled soil moisture content and land surface temperature are compared with observations from satellites. The optimal realization was selected using a particle filter-based approach to update TMPA-RT to a newly corrected real-time precipitation estimate. Although the potential gain of this approach may be large in poorly gauged regions like the continent of Africa, ground-based observations with high spatial and temporal resolutions for validation are lacking. Therefore, the analysis was performed over the Continental United States (CONUS) to enable a comparison between the TMPA-RT, corrected estimates and a high quality ground-based observational precipitation dataset. The precipitation data from Northern Land Data Assimilation System project phase 2 (NLDAS-2; Xia et al., 2012) was used as a best estimate of the precipitation over the Continental United States.

Changes in modeled soil moisture and land surface temperature were compared to observed precipitation to test the sensitivity of these observations to precipitation. Observations of satellite-derived soil moisture and land surface temperature have been assimilated to corrected precipitation and results were compared to ground-based observations of NLDAS-2 for the period 2010–2011. Uncertainties were evaluated and compared to the uncertainties of the original uncorrected TMPA-RT.

2. Material and methods

2.1. Study area

The Continental United States (CONUS) was used as a study area, covering the mainland of the United States and excluding Hawaii and Alaska. High quality ground-based observations are available for CONUS making it a suitable area for evaluation of the potential improvements of assimilation of satellite-derived soil moisture (SM) and land surface temperature (LST). Although observations of land surface parameters are in some areas hampered by the topography and dense vegetation (Rocky Mountains, Appalachian Mountains and dense forest in the East). It is assumed that potential gains will only be larger for areas with less complex terrain properties and low rain gauge densities, e.g. the Sahel in Africa, than gains obtained over CONUS.

Meteorological forcing data from NLDAS-2 (Xia et al., 2012) are used to force the land surface model, which are available on an hourly time step with a spatial resolution of 0.125° (aggregated to 3-hourly and 0.25° to match TMPA-RT resolution) for the entire CONUS. The precipitation fields in NLDAS-2 combine the estimates from radars and ground gauges (NOAA Stage IV product) as well as regional reanalysis (for gap filling). We treat the NLDAS-2 precipitation as the best ground truth and use it for validation purposes.

2.2. Land surface model

The Variable Infiltration Capacity (VIC) model (version 4.0.5) is used to simulate the hydrological responses of the land surface to precipitation for the period 2010–2011. VIC is a spatially distributed grid-based land surface model that simulates the response of soil moisture, land surface temperature and other land surface variables at the land surface–atmosphere interface (Liang, Lettenmaier, Wood, & Burges, 1994; Liang, Wood, & Lettenmaier, 1996). Subgrid-scale variability in soil properties is represented by a spatially varying infiltration capacity such that the spatial variability in soil properties at scales smaller than the grid is represented statistically. Movement of moisture between the soil layers is modeled as gravity drainage, and the unsaturated hydraulic conductivity is a function of the degree of saturation of the soil. The VIC model solves the full energy balance to obtain land surface temperature.

VIC is used with a three hourly time step to allow a better comparison between VIC and the different satellite products. The model was forced with meteorological forcing from NLDAS-2 (aggregated to 3-hourly time step and 0.25° resolution) over the continental United States. The meteorological forcing fields being used from NLDAS-2 consist of air temperature, vapor pressure, atmospheric pressure, wind and downward shortwave and longwave radiation.

2.3. Remotely sensed precipitation

The real-time Tropical Rainfall Measuring Mission Multi-satellite Precipitation Analysis products (TMPA-RT, Huffman et al., 2007) were used as baseline precipitation products. TMPA-RT (3B42RT) relies on multi-channel microwave and infrared observations to estimate precipitation rates. TMPA-RT is available from 50°S to 50°N with a 3-hourly time step and a spatial resolution of 0.25°.

2.4. Remotely sensed soil moisture and land surface temperature

Remotely sensed soil moisture and land surface temperature data from three satellite sensors are used to reduce uncertainties in satellite precipitation, namely AMSR-E, SMOS and ASCAT. Changes between consecutive overpasses have been used to infer the occurrence and amount of precipitation events. For all observations the difference in consecutive descending and ascending overpasses have been separated.

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