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Evidence of a topographic signal in surface soil moisture derived from ENVISAT ASAR wide swath data

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ABSTRACT

The susceptibility of a catchment to flooding is affected by its soil moisture prior to an extreme rainfall event. While soil moisture is routinely observed by satellite instruments, results from previous work on the assimilation of remotely sensed soil moisture into hydrologic models have been mixed. This may have been due in part to the low spatial resolution of the observations used. In this study, the remote sensing aspects of a project attempting to improve flow predictions from a distributed hydrologic model by assimilating soil moisture measurements are described. Advanced Synthetic Aperture Radar (ASAR) Wide Swath data were used to measure soil moisture as, unlike low resolution microwave data, they have sufficient resolution to allow soil moisture variations due to local topography to be detected, which may help to take into account the spatial heterogeneity of hydrological processes. Surface soil moisture content (SSMC) was measured over the catchments of the Severn and Avon rivers in the South West UK. To reduce the influence of vegetation, measurements were made only over homogeneous pixels of improved grassland determined from a land cover map. Radar backscatter was corrected for terrain variations and normalized to a common incidence angle. SSMC was calculated using change detection.

To search for evidence of a topographic signal, the mean SSMC from improved grassland pixels on low slopes near rivers was compared to that on higher slopes. When the mean SSMC on low slopes was 30–90%, the higher slopes were slightly drier than the low slopes. The effect was reversed for lower SSMC values. It was also more pronounced during a drying event. These findings contribute to the scant information in the literature on the use of high resolution SAR soil moisture measurement to improve hydrologic models.

1. Introduction

One factor that affects the susceptibility of a catchment to flooding is its soil moisture condition prior to an extreme rainfall event. The antecedent soil moisture affects runoff because it controls the ability of the watershed to partition rainfall between infiltration and runoff. The improved representation of antecedent soil moisture in hydrologic models should therefore improve runoff prediction. Field studies show that the distribution of a catchment's water is controlled by soil water storage, with runoff rising abruptly when a certain storage threshold is exceeded (Lacava et al., 2012). It has been argued that soil water stored in hillslope areas is released only during wetter conditions, when flow paths between the hillslope and riparian zone become connected. Therefore, monitoring the closeness to thresholds is essential to accurately predict stream responses to rainfall events. One approach to this is through the measurement of soil moisture.

This paper describes the first stage of a study attempting to improve a distributed hydrological model for a set of catchments by assimilating remotely sensed soil moisture in order to keep the model flow rate predictions on track in readiness for an intense rainfall event, and to estimate model parameters. As remotely sensed soil moisture data from passive and active radars are obtained as area averages rather than point measurements, they form a useful source of synoptic data for assimilation in ungauged catchments, the class to which the majority belong (e.g., Vorosmarty et al., 1996).

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Despite the fact that soil moisture and runoff should be correlated, it is currently an open question how much assimilation of remotely sensed soil moisture into a hydrologic model can aid runoff prediction in un-gauged basins (Parajka et al., 2005). There seem to be a number of reasons for this (Crow and Ryu, 2009). Firstly, for very intense rainfall events, antecedent soil moisture conditions may be of minor importance as the infiltration excess overland flow mechanism is dominant and rainfall runs off before it has the opportunity to infiltrate. Secondly, for basins lacking rain gauges, the main uncertainty will be due to the error in forecast rainfall rather than that due to soil moisture. Thirdly, the relationship between antecedent soil moisture and runoff is strongly non-linear and characterized by sharp thresholds that are unsuited to the application of data assimilation techniques designed for linear models (e.g., Kalman-derived filters and variational techniques).

A fourth reason that we investigate here is the low spatial resolution of the microwave soil moisture data (e.g., from ASCAT (Advanced Scatterometer), AMSR-E (Advanced Microwave Scanning Radiometer) or SMOS (Soil Moisture and Ocean Salinity satellite)) used in many previous studies (e.g., Parrens et al., 2012; Brocca et al., 2012a,b; Lacava et al., 2012) compared to the 1 km resolution of a typical hydrologic model. While a SMOS pixel (40×40 km) is a lot larger than a typical un-gauged small catchment (say 10×10 km), a 1 km resolution would allow soil moisture variations within a small catchment to be detected, and would take into account the spatial heterogeneity of hydrological processes. For example, soil moisture contribution to runoff probably depends on distance to channel and local slope.

Vinnikov et al. (1996) have investigated the spatial and temporal length scales of soil moisture variability in deeper layers. They separated the variability of the soil moisture field into small- and large-scale components. The small-scale component is due to varying topography, soil type and land cover at the local scale. The large-scale component is due to wide-area atmospheric forcing. In the spatial domain, for the 0–10 cm soil layer, they found that 30–35% of the total variance was due to small-scale land surface-related variability, and that this had a length scale of tens of meters. On the other hand, the atmospheric-related component had a length scale of 400–800 km. This means that low resolution microwave sensors measure only the large-scale atmospheric-related component of soil moisture variations because they average out the small-scale topographic variations. Wagner et al. (1999) showed that the low correlations found between area-extensive ERS (European Remote Sensing satellite) scatterometer measurements and point field soil moisture measurements must be caused by the small-scale variability of the soil moisture field. High resolution remotely sensed soil moisture measurement should be capable of going at least some of the way toward observing this local variability.

Soil moisture can be measured at higher resolution using active SARs rather than passive sensors. Recently there has been increasing interest in estimating soil moisture at local scales using these sensors (Barrett et al., 2009). Two new active SARs suitable for catchment hydrology studies should begin producing data this year. The first of the Sentinel-1 satellites was launched in early 2014. Sentinel-1 is C-band, which will penetrate 1–2 cm into the soil. Hornacek et al. (2012) have proposed a near real-time automatic system for measuring surface soil moisture at 1 km resolution using the Interferometric Wide Swath mode of Sentinel-1. This will measure soil moisture to 6% accuracy, and should be high enough resolution for catchment-scale hydrology studies. When the second satellite of the pair is launched 18 months after the first, they should give near daily coverage over Europe. Also, the Soil Moisture Active Passive sensor (SMAP) was launched early this year (Entekhabi et al., 2010). SMAP is L-band, which will penetrate ~5 cm into the soil (Kerr et al., 2001). It is a combined low resolution radiometer and high resolution SAR, which should give 4% soil moisture accuracy in its 9 km resolution product. There is also a radar-only 3 km product which will be less accurate. However, possibly this will not be high enough spatial resolution for catchment-scale hydrology studies.

However, from the point of view of this study, obviously these cannot yet provide images of any sequence of flood events that could be analysed. For the Distributed Hydrologic Model Intercomparison project phase 2 (Smith et al., 2012), 11 years of data were needed, with a model warm-up period of 1 year, a calibration period of 6 years, and a verification period of 4 years. As a result, we have used ASAR data for this study. ASAR Wide Swath (WS) data were acquired from 2003–2011, giving a long data record. ASAR is C-band, which penetrates soil to 1–2 cm. ASAR WS has a spatial resolution of approximately 150 m (75 m pixel size) and a 400 km swath width. VV polarization images were chosen because of their higher capability of vegetation penetration compared to HH polarization (Kong and Dorling, 2008). A difficulty with ASAR WS is that the time interval between successive scene acquisitions can be irregular in many areas. For example, in the data set used in this study, there were on average two scenes per month, but in several months there were no useable scenes at all.

There appears to be scant information in the literature relating to the use of high resolution SAR soil moisture measurement to improve rainfall-runoff estimation. Previous soil moisture studies using high resolution SAR have been aimed mainly at estimating surface soil moisture content (SSMC). Considering ASAR WS data, Loew et al. (2006) have derived soil moisture from the backscattering cross-section for various agricultural land covers (including grassland), and concluded that soil moisture can be measured to 5.7 vol% over a range 15–40 vol%. Kong and Dorling (2008) used a principal component analysis to show that surface roughness, vegetation and topographic effects could be partially separated (see also Verhoest and Troch, 1998). ASAR WS data have also been used to study soil moisture variations at high resolution in an alpine valley (Greifeneder et al., 2014); to validate soil moisture measurements from passive microwave sensors at a number of Irish sites (Pratola et al., 2014); and to map surface soil moisture over parts of Tunisia (Zribi et al., 2014). Other high resolution SARs have also been applied to soil moisture measurement, for example multi-polarized RADARSAT-2 over wheat-growing areas (Yang et al., 2013). At somewhat lower resolution, ASAR global mode data have been used to estimate soil moisture at regional/continental scales in several studies (e.g., Pathe et al., 2009; Dostalova et al., 2014).

Early work to detect a topographic signal in soil moisture used airborne and ground measurements. Wang et al. (1989) used a push broom L-Band radiometer to map the spatial distribution of soil moisture. By using overlapping flight lines for several flights during a drying period, it proved possible to map the spatial patterns of soil moisture within a small watershed. This showed the top of the watershed drying out quicker than the floodplain. Roberts and Crane (1997), using ground measurements, also showed that an area on a sloping hillside dried out faster than the valley bottom below.

The object of this paper is to detect whether a topographic signal can be seen in high resolution remotely sensed soil moisture data. Such a signal may be useful information for a hydrologic model to be able to account for spatial heterogeneity in hydrological processes in relation to flood-producing rainfall-runoff events (e.g., Roberts and Crane 1997). The paper is an observational study, and contains no modeling. A subsequent paper will investigate whether the assimilation of these data into a hydrologic model is able to improve runoff prediction.