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On the value of combining different modelled soil moisture products for European drought monitoring

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SUMMARY

In the context of evaluating the occurrence of drought events over Europe, soil moisture maps provide an invaluable resource to quantify the effects of rainfall deficits on vegetated lands. Spatially distributed models represent one of the main options, alongside satellite remote sensing, to successfully monitor this quantity over large areas in a cost effective way. This work has the double aim of: (i) intercomparing three soil moisture outputs obtained by different land-surface models (LISFOOD, CLM and TESSEL) through long (at least 6 years of data between 2001 and 2011) in-situ measured datastreams, and (ii) quantifying the added value of combining the estimates of these three models by means of a simple ensemble approach. Generally, the three models return similar soil moisture anomalies over most of Europe, with few notable exceptions during summer in Mediterranean regions. The comparison with in-situ data suggests no substantial differences among the models, with LISFLOOD slightly outperforming the other two in terms of correlation as also supported by a pairwise comparison. The combined soil moisture anomalies obtained via the ensemble-mean approach are characterized by an increase of both the correlation and the accuracy in retrieving extreme events compared to the single models; however, the number of observed extreme events actually captured by the ensemble model does not increase significantly if compared to the single models. Overall, the ensemble model results are skillful, with an all site average skill score of about 0.4.

1. Introduction

Historically, precipitation shortages have been considered a minor issue for a large part of Europe; however, drought has become an increasingly frequent and widespread phenomenon in the European Continent in recent decades, and climate change scenarios suggest a further worsening of this situation. During the eighties, Mediterranean regions were the most affected by droughts, but the last decades have shown that all EU countries can be confronted by drought issues. Estimates (European Commission, 2007) say that from 2000 to 2006 an average of 15% of the EU territory had been affected by drought and 10% of the total EU area was affected by water scarcity, concerning about 17% of EU population.

Drought has been commonly monitored using precipitation-derived indices, such as the standardized precipitation index (SPI; McKee et al., 1993), or simplified water balance approaches (i.e., Palmer indices; Palmer, 1965). It is obvious that while a shortage in precipitation is the main driver of drought conditions, a detailed modelling of the soil water status and the monitoring of vegetation greenness made through remotely-sensed vegetation indices (e.g., normalized vegetation index, NDVI, and fraction of absorbed photosynthetically active radiation, fAPAR) are better indicators of the actual effects on vegetated lands. In order to provide an operational assessment of the different aspects of drought at continental scale, the Joint Research Centre (JRC) of the European Commission developed the European Drought Observatory (EDO, http://edo.jrc.ec.europa.eu) with the aim of integrating drought information at different scales (e.g., continental, Member States, River Basins). This portal includes drought indicators based on precipitation data, satellite data and modelled soil moisture, as well as a combined drought indicator (Sepulcre-Canto et al., 2012).

There is a large consensus in the literature that a robust estimate of drought impacts on vegetation can be obtained by monitoring the root zone soil moisture shortage that severely limits the water available to plants (Mishra and Singh, 2010; Seneviratne et al., 2010). In this framework, reliable and continuous information on the spatial and temporal variability of soil moisture in the plant root zone assumes a crucial role. A variety of approaches is commonly used to monitor soil moisture,

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including both thermal and microwave remote sensing data and either distributed hydrological approaches or global circulation model land-surface schemes (see e.g., Anderson et al., 2007; Houborg et al., 2012; Mo et al., 2010; Sheffiled et al., 2004).

Remote sensing-based approaches, including both microwave and thermal data, have the undeniable appeal of an extensive spatio-temporal coverage (Schmugge et al., 2002), however among the major limits we can list the capability to explore only the first few centimeters of soil in the case of microwave (Jackson, 2006), the lack of coverage during cloudy conditions in the case of thermal data (Matsushima et al., 2012), and a generally decreasing sensitivity of the data to the moisture signal with the increase of vegetation coverage. On the other hand, diagnostic models have the advantage to provide a continuous datastream at different soil horizons, but their accuracy is strongly constrained by uncertainties in input meteorological forcing, parameterization, model complexity and simplified assumptions, which essentially affect all the main state variables (Samaniego et al., 2013). The temporal length of the available time series is a further advantage of land-surface models as compared to remotely-sensed data at the current state.

Even if the attempts to validate soil moisture modelled datasets with in-situ observations are numerous in the literature (e.g., Xia et al., 2014; Albergel et al., 2012; Albergel et al., 2013; Brocca et al., 2010; Robock et al., 2003), very few works aim at the specific needs related to drought monitoring (e.g., Choi et al., 2013). In fact, the use of soil moisture as drought indicator commonly aims at capturing the difference of the current moisture status compared to the usual status of the soil based on the past history; focusing on anomalies reduces some of the problems related to the original soil moisture records (e.g., bias), whereas it usually increase discrepancies in terms of correlation compared to non-standardized time series due to the removal of part of the covariance related to the seasonal cycle. The limited number of assessments specifically focused on drought is most likely related to the lack of long in-situ records, spatial representativeness of in-situ data and mismatching in vertical resolution of the modelled and observed time-series. This limit can be partially overcome by taking advantage of the strong connection between soil moisture and other vegetation-related quantities measured by in-situ installations (e.g., normalized evapotranspiration fluxes).

Even if other quantities that can be used as reference to evaluate the performance of soil moisture models are routinely monitored, they rarely represent a true proxy of root zone soil moisture. Microwave blended satellite products (i.e., Liu et al., 2011) represent only skin soil moisture (up to a few mm depth), which is not always straightforwardly related to root zone average values (Li and Islam, 1999). The literature on vegetation greenness covers a large variety of indices (e.g., NDVI, fAPAR and leaf area index to name just few of them) capable to quantify the response of vegetation to a precipitation deficit; however, there is no consensus neither on a “best” proxy of soil moisture status nor on the temporal lag between soil moisture status and greenness indices (Adegoke and Carleton, 2002). In addition, products aiming at monitoring the same quantity often show considerable differences (D’Odorico et al., 2014). For these reasons, here we prefer to focus the analysis on in-situ measurements that can be easily linked to the root zone soil moisture dynamic.

Following these considerations, in this paper three soil moisture models were selected to be tested against in-situ measurements of soil moisture data, as well as versus a proxy variable of the soil water status derived from micrometeorological measurements (i.e., evaporative fraction). The three models include a distributed hydrological precipitation–runoff model, LISFLOOD, a detailed land-surface model, CLM, and an atmospheric-coupled land-surface scheme, TESSEL. These models are similar to a certain degree, but represent three different ways of characterizing the water exchange processes in the top soil layer (treatment of infiltration, drainage, uptake by roots and soil evaporation). The intercomparison was specifically designed to account for the specific characteristics of drought in evaluating the performance of the models.

Additionally, previous studies of the Global Soil Wetness Project (GSWP) and the U.S. National Land Data Assimilation System (NLDAS), suggest that ensemble averages of the products from different models depict a more accurate scenario of water and energy budget conditions compared to the one from individual modelling schemes (Dirmeyer et al., 2006; Mo et al., 2011). Multi-model ensemble strategies range from a simple equal-weight combination of the individual models (Hagedorn et al., 2005) over an optimized weighted average according to *a priori* performance of the single models (Rajagopalan et al., 2002) to statistical ensemble techniques able to account for the dependence among model errors, which usually vary both in space and time (Chowdhuri and Sharma, 2009). The optimal weighting approach is usually defined on the basis of the analysis of the covariance matrix; when the off-diagonal entries are reasonably close to zero, simple weighting procedures based on the variance of each model can be adopted, while weights estimated using the covariance terms are adopted when models have similarities in modelling processes. In addition, the spatio-temporal variability in weighting factors can be accounted for when spatially-distributed observations are available; this is the case of the approaches recently implemented for meteorological forecasts, where spatially distributed information on forecast errors are available (e.g., Khan et al., 2014).

Due to the limited density of ground truth data, simple weighted combinations are usually adopted in operational hydrological applications (see e.g., Crow et al., 2012) by means of spatio-temporal invariant weighting approaches. On the basis of these considerations, we also explored the extent of the added value related to the combination of the three models into a single ensemble-mean estimation for an operational estimate of soil moisture anomalies to be adopted as practical tool for drought monitoring.

2. Methodology

In this section a brief overview of the tested models is reported (Section 2.1), as well as a description of the approach adopted for the intercomparison of the models (Section 2.2) and the characteristics of the in-situ data adopted for the validation process (Section 2.3).

2.1. Soil moisture modelling

2.1.1. LISFLOOD

LISFLOOD (de Roo et al., 2000) is a distributed hydrological rainfall–runoff model, specifically developed by the flood group of the JRC of the European Commission to reproduce the main hydrological processes that occur in large and trans-national European river catchments. Although the main output of the model is river water discharge, LISFLOOD provides also valuable information on soil moisture status in two layers, namely top-soil (corresponding to the plant root zone) and sub-soil. Infiltration of effective precipitation, soil evaporation and plant transpiration all take place in the top-soil layer, whereas slow runoff (i.e., deep percolation) and groundwater recharge occur instead in the sub-soil layer. The modelling of the water redistribution out of the sub-soil and between the two sub-layers is gravity-driven, following the assumption of a 1-D vertical flow regulated by the Darcy’s law and by the van Genunchten retention curve (van Genuchten, 1980).

LISFLOOD is currently running operationally over Europe within the European Flood Awareness System (EFAS; Thielen et al., 2009)