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# How far are we from the use of satellite rainfall products in landslide forecasting?

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ABSTRACT

Satellite rainfall products have been available for many years (since '90) with an increasing spatial/temporal resolution and accuracy. Their global scale coverage and near real-time products perfectly fit the need of an early warning landslide system. Notwithstanding these characteristics, the number of studies employing satellite rainfall estimates for predicting landslide events is quite limited.

In this study, we propose a procedure that allows us to evaluate the capability of different rainfall products to forecast the spatial-temporal occurrence of rainfall-induced landslides using rainfall thresholds. Specifically, the assessment is carried out in terms of skill scores, and receiver operating characteristic (ROC) analysis. The procedure is applied to ground observations and four different satellite rainfall estimates: 1) the Tropical Rainfall Measurement Mission Multi-satellite Precipitation Analysis, TMPA, real time product (3B42-RT), 2) the SM2RASC product obtained from the application of SM2RAIN algorithm to the Advanced SCATterometer (ASCAT) derived satellite soil moisture (SM) data, 3) the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Network (PERSIANN), and 4) the Climate Prediction Center (CPC) Morphing Technique (CMORPH). As case study, we consider the Italian territory for which a catalogue listing 1414 rainfall-induced landslides in the period 2008–2014 is available.

Results show that satellite products underestimate rainfall with respect to ground observations. However, by adjusting the rainfall thresholds, satellite products are able to identify landslide occurrence, even though with less accuracy than ground-based rainfall observations. Among the four satellite rainfall products, CMORPH and SM2RASC are performing the best, even though differences are small. This result is to be attributed to the high spatial/temporal resolution of CMORPH, and the good accuracy of SM2RSC. Overall, we believe that satellite rainfall estimates might be an important additional data source for developing continental or global landslide warning systems.

## 1. Introduction

Worldwide, rainfall-induced landslides occur every year causing fatalities, considerable damage and relevant economic losses. Italy is one of the countries most prone to landslide risk (Guzzetti et al., 2005) and where the population is heavily affected. In the 50-year period 1964–2013, 1354 people died due to landslides (Salvati et al., 2014). Moreover, climate changing is expected to exacerbate the impact of landslides, mostly due to the increase in heavy rainfall (Fischer and Knutti, 2015; Ciabatta et al., 2016; Gariano and Guzzetti, 2016). In order to mitigate landslide risk, early warning systems for the prediction of rainfall-induced failures were developed in several countries based on different approaches and input data sets (Keefer et al., 1987; Baum and Godt, 2010; Rossi et al., 2012; Lagomarsino et al., 2013; Segoni et al., 2015; Piciullo et al., 2016). The forecast of rainfall-induced landslides relies upon physically-based (e.g., Baum et al., 2010; Lepore et al., 2013; Segoni et al., 2010; Alvioli and Baum, 2016) or empirical rainfall thresholds (e.g., Caine, 1980; Innes, 1983; Aleotti, 2004; Guzzetti et al., 2007; Guzzetti et al., 2008; Brunetti et al., 2010; Peruccacci et al., 2012). Empirical rainfall thresholds are calculated analyzing past rainfall events that have or have not resulted in landslides. In operational landslide warning systems, empirical rainfall thresholds are compared with rainfall measures, estimates, and forecasts to evaluate the possible occurrence of failures. Guzzetti et al. (2007) grouped empirical rainfall thresholds in three main categories: (i) thresholds using rainfall measures for a specific rainfall event (e.g., mean rainfall intensity-rainfall duration *ID* thresholds, Aleotti, 2004; Brunetti et al., 2010; Berti et al., 2012; Martelloni et al., 2012; Rosi

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et al., 2012); (ii) thresholds considering the antecedent conditions (e.g., explicitly including rainfall and/or SM, Crozier, 1999; Glade et al., 2000; Ponziani et al., 2011; Brocca et al., 2012; Chen et al., 2017); and (iii) other thresholds. To date, the *ID* and the cumulated rainfall-rainfall duration *ED* thresholds (e.g., Peruccacci et al., 2012; Vennari et al., 2014; Gariano et al., 2015; Giannecchini et al., 2016) are the most used worldwide.

The accurate estimation of rainfall is the primary task in all the early warning systems mentioned above, and the reliability of the final forecasts is strongly dependent on the quality of rainfall inputs (Hong et al., 2006). Specifically, the spatial-temporal occurrence and the number of landslides are dependent on different rainfall attributes such as rainfall climatology, antecedent rainfall accumulation, rainfall intensity, cumulated event rainfall and duration. In the scientific literature, the vast majority of studies developing landslide forecasting systems used rain gauge measurements (e.g., Baum and Godt, 2010). However, it is well known that rain gauge observations are affected by several errors, primarily related to their small spatial representativeness, but also to the measurement accuracy (Nikolopoulos et al., 2014; Marra et al., 2017a). Additionally, the maintenance of real-time rain gauge networks is costly and not easy to achieve, mainly when networks operate in extreme weather conditions. The use of rain gauges for rainfall monitoring is less applicable in many parts of the world in which rain gauge networks have very low density, or even they are absent (Kidd et al., 2017). To overcome this issue, in the last three decades remote sensing observations have been used for providing rainfall estimates on a global scale at ever increasing spatial/temporal resolution and accuracy. The Satellite Application Facility on Support to Operational Hydrology and Water Management (H SAF, http://hsaf.meteoam.it/, Mugnai et al., 2013), the Tropical Rainfall Measurement Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA, Huffman et al., 2007), and the recent Global Precipitation Measurement (GPM, https://pmm.nasa.gov/GPM, Hou et al., 2014) mission are examples of project and missions addressed to the development of satellite-based rainfall products. The first attempt of using satellite rainfall product by TMPA for global landslide hazard assessment was carried out by Hong et al. (2006, 2007) who performed a preliminary analysis for assessing the capability of a global system in predicting the occurrence of large landslide events worldwide. The system was further updated and improved by Kirschbaum et al. (2009, 2012), who highlighted some issues in the original system due to the spatial resolution of the susceptibility map and the need to re-compute the *ID* threshold for better considering regional climatology. The system was made operational at https://trmm.gsfc.nasa.gov/publications_dir/potential_landslide.html and it will be updated by replacing TMPA product with the new GPM data, with expected improved performances (Sidder, 2016). Another study was carried out by Farahmand and AghaKouchak (2013) who implemented a satellite-based global landslide model but using a different precipitation product, i.e., the Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks, PERSIANN (Hsu et al., 1997; Sorooshian et al., 2000) and a machine learning approach as landslide prediction model. More recently, some authors employed satellite precipitation data for regional and local scale analyses (Liao et al., 2010; Kirschbaum et al., 2015; Robbins, 2016; Cullen et al., 2016; Rossi et al., 2017; Marra et al., 2017b; Nikolopoulos et al., 2017). Specifically, Marra et al. (2017a) investigated the effect of spatial aggregation due to satellite rainfall product in the assessment of rainfall threshold for debris flow occurrence prediction. Nikolopoulos et al. (2017) evaluated different satellite rainfall products for debris flow prediction over the upper Adige River basin in the eastern Italian Alps. A couple of studies employed both soil moisture (SM) estimates and satellite-based precipitation in order to monitor independently initial conditions and rainfall and, hence, better forecast landslide occurrence (Ray and Jacobs, 2007; Posner and Georgakakos, 2015; Cullen et al., 2016). Ray and Jacobs (2007) used the Advanced Microwave Scanning Radiometer (AMSR) for monitoring antecedent SM conditions and TMPA for estimating precipitation at three sites worldwide (California, Nepal and Philippines). A clear relationship between landslide occurrence and high SM and precipitation conditions as estimated by satellite sensors was highlighted.

Based on the brief literature review reported above, it is evident that satellite-based rainfall estimates have been scarcely used for predicting the spatial-temporal occurrence of landslides. The reasons may be attributed to: 1) the bias characterizing near real-time satellite precipitation estimates, which is temporally varying not consistently year-by-year (being dependent on the satellite sensors used for obtaining the estimates), 2) the spatial/temporal resolution, 3) the timeliness, which is often insufficient for operational purposes, and 4) a general (often not justified) skepticism in the use of satellite products for land applications (Brocca et al., 2017; AghaKouchak et al., 2015). Satellite-based precipitation records have been made available since ~15 years, spanning a period of > 30 years and with a spatial-temporal resolution that might be appropriate for landslide studies. Arguably, due to the limited spatial representativeness of point information from rain gauges, the spatial issue of remote sensing products related to their coarse resolution is also encountered with ground-based observations. However, as mentioned above, currently rain gauges are the only source of information used in landslide early warning system. Here, we test the use of satellite-based rainfall estimates through a comparative analysis of satellite-based rainfall product with rain gauge measurements.

On this basis, we intend to address here the following scientific question: How far are we from the use of satellite rainfall products for landslide forecasting? Indeed, we believe that there is a lot of unexplored potential in using such data sets for landslide prediction. Their importance will be invaluable in developing countries where early warning systems for landslides are much more useful, and needed. Connected to the main scientific question, the following objectives are explored: which satellite-based rainfall product performs best in terms of landslide prediction? How to evaluate the quality of satellite-based rainfall products in the context of landslides?

To address the above questions, we perform a thorough study in Italy where detailed information about the occurrence of landslide events is available (Brunetti et al., 2015; Peruccacci et al., 2017). Specifically, we explore a catalogue listing 1414 rainfall-induced landslides in Italy, in the 7-year period 2008–2014. Four different satellite-based precipitation products are considered: 1) 3B42-RT (version 7) by the Tropical Rainfall Measurement Mission (TRMM) Multi-satellite Precipitation Analysis, TMPA (Huffman et al., 2007), 2) SM2RAIN-ASCAT product (http://dx.doi.org/10.13140/RG.2.2.10955.18728) that is based on the application of SM2RAIN algorithm (Brocca et al., 2014) to ASCAT (Advanced SCATterometer) SM product (Wagner et al., 2013), 3) Precipitation Estimation from Remotely Sensed Information using Artificial Neural Network (PERSIANN, Hsu et al., 1997), and 4) the Climate Prediction Center (CPC) Morphing Technique (CMORPH, Joyce et al., 2004). In addition, a ground-based rainfall data set obtained from a dense network of rain gauges (~3000) spanning the entire Italian territory is used as reference (Ciabatta et al., 2017). To assess the reliability of the different rainfall products (satellite- and ground-based), their relative performance in landslides detection is compared by using the well-established *ED* threshold approach (Peruccacci et al., 2017). We note that such a system is used for the rainfall-induced landslide forecast within the National Department of Civil Protection in Italy (Rossi et al., 2012). Therefore, the results of this study could have an impact also for operational landslide forecasting systems. However, our main purpose here is to assess the quality of satellite-based precipitation products in Italy where we have detailed information on landslides events and an established modeling system.

## 2. Study area

Italy is a boot-shaped peninsula that extends for about 300,000 $km^2$ in the Mediterranean Sea including the major islands of Sicily and