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Forecasting earth-flow reactivation using a hydro-climatological model and CMIP3+ data, Montaguto earth flow, southern Italy.

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INTRODUCTION

Earth flows (Varnes, 1978) occur in many of the word's hilly and mountainous areas and can be considered the most common mass-movement phenomena in nature (Keefer and Johnson, 1983). In complex geological and climatic environments, earth flows exhibit often a complex long-term pattern of activity characterized by long periods of relatively slow movement or quiescence and relatively rapid surges in movement that might be triggered by heavy meteorological events (Keefer and Johnson, 1983; Zhang et al., 1991; Guerriero et al., 2013a); often this activity has a seasonal trend and it is related to a regional climatic pattern (Coe, 2012) with a higher susceptibility to movement, in form of reactivations, occurring in the spring or in the winter (Guerriero et al., in review).
Short-term and seasonal variability in earth-flow movement is controlled by rainfall, snowmelt and, for very short periods, air pressure-driven groundwater fluctuation (Coe et al. 2003; Schulz et al. 2009). Earth-flow response to rainfall or snowmelt is often delayed and, in several cases, long periods of cumulated precipitations are required to trigger a reactivation (Iverson 1986; Iverson and Major 1987).
Several authors (e.g. Doglioni et al. 2012; Guerriero et al., in review) investigated the activity history of landslides using empirical models developed using historical and climatic data. Especially, Guerriero et al. (in review) analyzed historical data and climatic time-series of meteorological stations around the Montaguto earth flow in southern Italy (Guerriero et al. 2014) using a statistical-empirical approach in order to develop the Landslide Hydrological Climatological indicator (LHC), an indicator capable of acting as a proxy of earth-flow activity. Results from Guerriero et al. (in review) indicate that reconstruction of the past earth-flow activity is a very challenging issue and that the LHC indicator was able to reconstruct very well the history of activity of the Montaguto earth flow with only a few false-positives over a very long period of application (more than 60 years). On this basis, we considered the possibility to use the LHC combined with available CMIP3+ data to predict the likely future activity of the Montaguto earth-flow. Forecasting of earth-flow activity is a key issue in the analysis and management of risk connected with this natural hazard and it is particularly challenging in a changing climate (Coe, 2012). This because the responsiveness of individual landslides to precipitation is dependent on their geometry; stratigraphic, structural, and hydraulic properties; soil moisture and groundwater characteristics; and the frequency, duration, and intensity of precipitation (Coe, 2012).

The Montaguto earth flow

The Montaguto earth flow affects the southern slope of La Montagna Mt. in southern Italy. It is located along the northern side of the Cervaro River valley at approximately 4566000 N and 518000 E UTM (Fig. 1). It is described as an earth flow (Varnes, 1978) because it is composed of predominantly fine-grained material and it has a flow-like surface morphology. However, most of the movement takes place by sliding along discrete shear surfaces (Guerriero et al. 2013a).

Figure 1 - The Montaguto earth flow on 27 April 2006. Photo taken from a helicopter looking south toward the earth-flow toe.

The earth flow is approximately 3 km long and involves between 4 to 6 million of m3. Its width ranges from 75 m at the earth-flow neck to 450 m in the upper part of the earth-flow source area. Total elevation difference, from the toe adjacent to the Cervaro River to the top of the 90 m high headscarp, is approximately 440 m. The average slope angle, excluding the headscarp, is approximately 7.2° (Guerriero et al. 2013a). Historical information collected by Guerriero et al. (2013a) showed that the Montaguto earth flow has been periodically active during at least the last 69 years. From a preliminary analysis of the relationship between rainfall and earth-flow reactivations completed by Guerriero et al. (2013b), it appears that the most important earth-flow reactivations occurred after at least two wet hydrologic years. In particular, the 1958 and the 2006 extraordinary reactivations (surges) were the largest in terms of mobilized volume and changes in earth flow extension and morphology. Both reactivations followed an exceptional hydrologic year in terms of total rainfall amount (Guerriero et al. 2013b). The slope affected by the earth flow is geologically complex (Guerriero et al. 2014) and fault and fold structures locally control the slope topography. The slope is formed by the Miocene Flysch of the Faeto formation and the Pliocene Villamaina formation that widely outcrops in its upper and lower zone, respectively (Guerriero et al. 2014). The Flysch of the Faeto formation and the Villamaina formation are lithologically complex (Pescatore et al. 1996).This geological complexity influences groundwater flow. Many springs are present from 600 m above sea level to the top of the La Montagna Mt. (Diodato et al. 2014). In particular, the Caraventa spring is located adjacent to the earth flow and was analyzed by Diodato et al. (2014). The area has a Mediterranean climate characterized by hot, dry summers and cool, wet winters. The humid season spans from the end of October to March. Monthly precipitations are critical at the end of April, when rainfall intersects half of the potential evapotranspiration and prepares a dry climate for the successive month of May. Generally, the period between June and September is the driest period of the year.

Data and model

Precipitation and temperature data from a multi-model ensemble mean of CMIP3+ were used to calculate the Landslide Hydrological Climatological indicator (Guerriero et al., in review) form January 1951 up to December 2100. Available CIMP3+ time-series are representative of A1b future scenario. The A1 storyline describes a future world of very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies. The A1B emission scenario is characterized by a balanced use of fossil and non-fossil energy supply and improvement of end-use technologies; the predicted seasonal temperatures have a variation of +2.5°C in the winter and of +4°C in the summer for the decade 2089-2099. Temperature growing corresponds to a decrease in annual effective precipitation of 10% in the winter and 50% in the summer for the same period. Precipitation and temperature data were downloaded using climate explorer (http://climexp.knmi.nl) in form of monthly time series.
The LHC dimensionless indicator (Guerriero et al., in review) has a linear multiplicative-additive structure and depends on different factors, such as the Moisture Balance Drought Index (MDBI, Ellis et al., 2010), the temperature and the hydrological forcing corresponding to a sub-simulated groundwater discharge of the Caraventa spring (Diodato et al. 2014) located in the proximity of the Montaguto landslide. All of the factors depend on precipitation and/or temperature. The MBDI was calculated within an antecedent period which was estimated as the response time for reactivation occurrence comparing rainfall data and earth flow activity. For the Montaguto earth flow, the estimated response time was approximately 6 months. Computed time-series of Landslide Hydrological Climatological indicator from 1951 to 2100 was characterized by several peaks exceeding the mean plus two standard deviation of the series that can be considered as potential earth-flow reactivations. This statistical criterion for earth-flow reactivation detection, based on the univariate analysis of the LHC calculated-time-series, was preferred to a less flexible criterion of the fixed threshold because input modeled time series are representative of the future climatic evolution in terms of pattern of variability. Thus, a fixed threshold could be very challenging to be determined and validated over a very long time period.

Results and discussion

The LHC monthly time series, computed using CIMP3+ data, predicts numerous potential reactivations in the period from January 1951 to December 2010 (Fig. 2). Some of them correspond to actual reactivations predicted by Guerriero et al. (in review) using measured data and observed reactivations. In particular, the actual 1958 and 2010 events were predicted; the others correspond to partial reactivations (local movements) or have to be considered as false positive. From January 2011 to December 2100 more than 10 potential reactivations have been predicted and 3 peaks exceed the 99,5th percentile of the calculated series (2026, 2056, 2089; Fig. 2). Comparing the available information about earth flow activity (past to 2010) and the LHC index, it seems that the magnitude of the LHC is not correlated with the magnitude of the reactivations (Guerriero et al., in review). Conversely, the possibility that the Montaguto earth flow surges might be related with the amount of earth flow material stored into the earth-flow Body kinematic zone (Guerriero et al., 2014). On the basis of sediment-pulse analysis completed by Guerriero et al., (2014) and comparing the observed earth-flow recharge (Fig. 2), we calculated that a volume of 1 million of m3, which was mobilized during the 2006 surge, needs approximately 50 years to be stored within the earth flow Body. Therefore, it would be reasonable to consider the 2056 predicted reactivation as a surging reactivation because it is located next to the end of the recharge period (Fig. 2, white to purple panel).

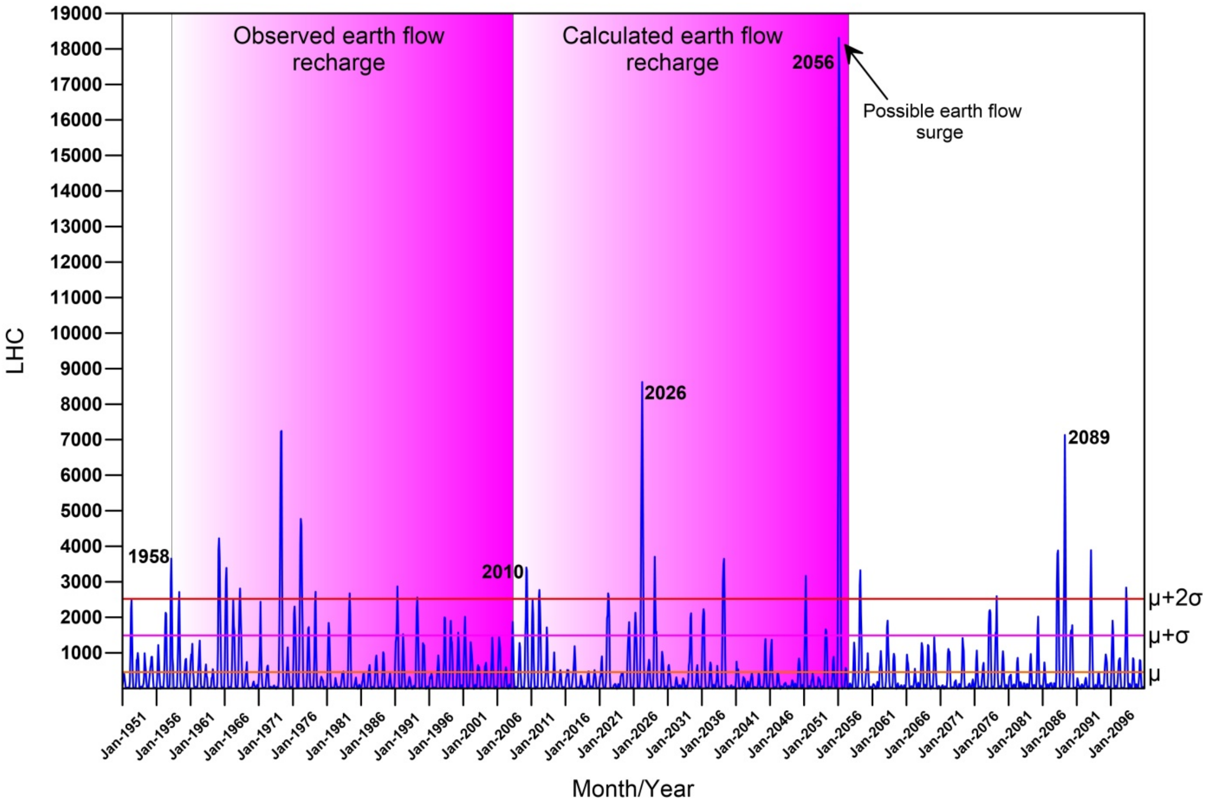

Figure 2 - Evolution of the Landslide Hydrological Climatological indicator from January 1951 to December 2100 for the Montaguto earth flow.

Conclusion

This paper presents a possible approach to earth-flow activity forecasting in a changing climate. The kernel of our approach is the Landslide Hydrological Climatological Indicator, developed by Guerriero et al. (in review) to reconstruct the history of activity of the Montaguto earth flow, which was computed using CIMP3+ data from January 1951 up to December 2100. Our forecasting-strategy is inspired to Coe (2012) that used MBDI values calculated from downscaled climate projections (Intergovernmental Panel on Climate Change A2 emissions scenario) to predict landslide movement at the Slumgullion landslide up to 2099. Our statistical indicator is more complex than the MBDI, which is used as predictor, and includes the effects of temperature and hydrological forcing on slope stability as different parameters.

It is clear that the reliability of the forecast is mainly connected with the reliability of the projected time series. Especially in very complex climatic areas, the projected time series might be not representative of the local climatic variability and needs to be downscaled.

On this basis and considering the importance to have information about the future activity of natural hazard, like earth flows, this approach would be a very interesting tool for hazard and risk assessment and management in areas were infrastructures and built-up area can be directly affected by landslide movements. However, the intrinsic uncertainty that affects modeled time-series at local scale make this forecast useful only if combined with long term monitoring of the phenomena themselves.

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