Atmospheric Forcing of Debris Flows in the Southern Swiss Alps

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ABSTRACT

This article addresses the role of large-scale circulation and thermodynamical features in the release of past debris flows in the Swiss Alps by using classification algorithms, potential instability, and convective time scale. The study is based on a uniquely dense dendrogeomorphic time series of debris flows covering the period 1872–2008, reanalysis data, instrumental time series, and gridded hourly precipitation series (1992–2006) over the area. Results highlight the crucial role of synoptic and mesoscale forcing as well as of convective equilibrium on triggering rainfalls. Two midtropospheric synoptic patterns favor anomalous southwesterly flow toward the area and high potential instability. These findings imply a certain degree of predictability of debris-flow events and can therefore be used to improve existing alert systems.

1. Introduction

Debris flows are mass movements involving a rapidly flowing mixture of rock debris and water occurring in steep, confined channels all over the world (VanDine and Bovis 2002). Their sudden and unexpected occurrence, as well as the high energies involved, represents a considerable threat to human life and infrastructures. Debris flows are normally triggered by rainfall events of either high intensity (duration of hours) or long duration (some days), but the triggering mechanisms and associated large-scale atmospheric circulation patterns related to their release are still poorly understood (e.g., Schneuwly-Bollschweiler and Stoffel 2012 and references therein).

Previous work on the connection between atmospheric circulation patterns and rainfall-induced hydrological hazards has focused mainly on flood events, and the link between rainfall and atmospheric dynamics was mostly examined at monthly to seasonal time scales and/or over large spatial areas (e.g., Quadrelli et al. 2001; Xoplaki et al. 2004; Bardossy and Filiz 2005; Jacobeit et al. 2006; Petrow et al. 2009). At the catchment scale, in contrast, research was basically limited to the identification of triggering weather situations for individual events (e.g., Buzzi et al. 1998; Ferretti et al. 2000; Marchi et al. 2009; Stucki et al. 2012). Except for Stucki et al. (2012), however, these small-scale studies address single events and provide neither insight into the general connection with synoptic weather situations associated with flood events nor insights into temporal changes of their frequency.

The aim of this study is to contribute to the understanding of the link between large-scale atmospheric circulation and the triggering of debris flows in the southern Swiss Alps (Schneuwly-Bollschweiler and Stoffel 2012) since 1872, mainly in terms of thermodynamical aspects of the atmospheric circulation leading to the release of

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debris flows in the area and temporal changes of the identified large-scale patterns.

2. Data and study site

The study is focused on the Zermatt Valley, a north–south-oriented inner-alpine valley in the southern Swiss Alps (Fig. 1). The area is characterized by high relief with over 3000 m of difference between the summits and the valley floor. Eight torrents, located within a distance of 12 km (see the figure of Bollschweiler and Stoffel 2010), show recurrent debris-flow activity originating from periglacial sediment sources. Loose material for the formation of debris flows is readily available, and triggering is principally limited by the input of water through precipitation. The debris-flow season currently lasts from mid-May to the end of October, with a peak in activity in July and August (Stoffel et al. 2008, 2011; Schneuwly-Bollschweiler and Stoffel 2012). The region has an average total precipitation during the debris-flow season of about 392 mm, with a standard deviation of about 77 mm (climate data were obtained online from MeteoSwiss in 2010).

The analysis is based on a dense and long database of 113 debris flows covering the period 1872–2008. Event dates were either gathered (Stoffel and Bollschweiler 2008) from local archives (18% of the events) or by using tree-ring records of trees affected by past debris-flow activity (Bollschweiler and Stoffel 2010). The position of a debris-flow injury as well as tangential rows of traumatic resin ducts can be used to identify the timing of the debris-flow occurrence (Bollschweiler et al. 2008). The calendar date and the duration of the triggering rainfall event (1, 2, or 3 days) were assessed through the intra-annual position of the damage in the tree ring and on the basis of daily precipitation records from three meteorological stations located in or next to the Zermatt Valley (Table 1; for more details, see also Schneuwly-Bollschweiler and Stoffel 2012).

For the analysis of the atmospheric forcing, daily geopotential height at 500 hPa (Z500), sea level pressure (SLP), air temperature and specific humidity at 500 and 850 hPa, and 6-hourly convective available potential energy (CAPE) were retrieved from the Twentieth Century Reanalysis project (Compo et al. 2011). In addition, for the period 1992–2006, 3-hourly CAPE was also retrieved from the Interim European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-Interim; Dee et al. 2011). The spatial dimensions of the large-scale fields are 20°–70°N, 52°W–52°E. Moreover, a recently released high-resolution (2 km) hourly gridded precipitation dataset for Switzerland (Wüest et al. 2010), covering the period 1992–2006, was used to investigate the convective time scales.

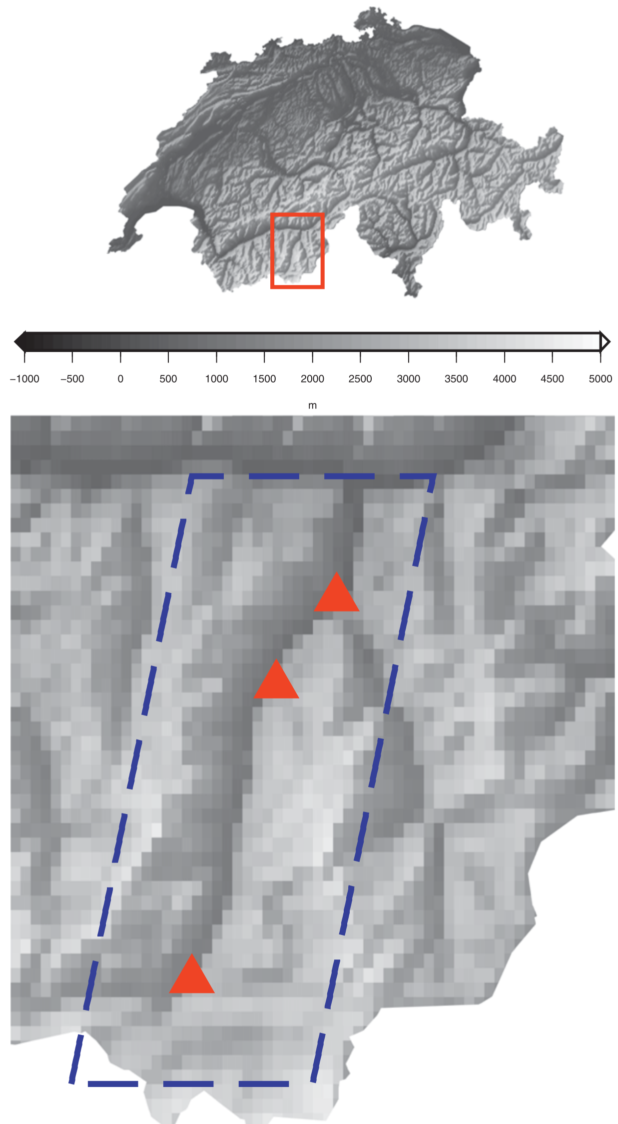

FIG. 1. Maps of (top) Switzerland and (bottom) the Zermatt Valley. The grayscale is associated with the orography [Global Land One-kilometer Base Elevation (GLOBE) project digital elevation model; GLOBE Task Team 1999]; the scale goes in 500-m increments from −1000 (darkest shade) to 5000 (lightest shade) m. The red triangles represent the three weather stations (Grächen, Ackersand Stalden, and Zermatt) used for the date and the duration of the triggering rainfall events.

3. Methods

The main features of the large-scale atmospheric circulation can be identified by clustering daily gridded anomalies of Z500 and SLP data during debris-flow events. Anomalies are derived for each grid point by removing the mean seasonal cycle, estimated with a penalized spline (Krivobokova and Kauermann 2007) over the entire period. The clustering procedure is a genetic

TABLE 1. Total number of debris flows classified by duration of the triggering rainfall event and by month.

	May	Jun	Jul	Aug	Sep	Oct	All months
1 day	2 (50%)	13 (65%)	17 (61%)	24 (60%)	4 (31%)	3 (38%)	63 (56%)
2 days	0 (0%)	6 (30%)	10 (36%)	13 (32%)	5 (38%)	2 (25%)	26 (32%)
3 days	2 (50%)	1 (5%)	1 (4%)	3 (8%)	4 (31%)	3 (38%)	14 (12%)

K-means method (Krishna and Narasimha-Murty 1999) that is able to overcome the dependence of the K-means method on the random initialization of the centroids, combined with the silhouette statistic (Kaufman and Rousseeuw 1990) for the selection of the number of clusters. Once the atmospheric patterns associated with debris flows are identified, their significance and their link with debris flows can be assessed by analyzing the occurrence of these patterns during no-debris-flow rainy days (i.e., days with total precipitation greater than 1 mm without the release of a debris flow, identified by using the available stations in the area; Schneuwly-Bollschweiler and Stoffel 2012). Since this is a pattern classification problem, a nonlinear support vector classifier (nSVC; Schölkopf and Smola 2002) is applied. Combining separating hyperplanes with the Mercer kernel map (for more details, see Schölkopf and Smola 2002), the nSVC is able to assess whether a daily Z500 (SLP) field during no-debris-flow rainy days can be classified as one of the atmospheric patterns associated with debris flows. Following Cacciamani et al. (2000), the vertical structure of the atmosphere (and its destabilization) is investigated over the entire period by using a potential instability index:

$$\mathrm{PI} = \theta_{\mathrm{eq}500} - \theta_{\mathrm{eq}850}, \quad \theta_{\mathrm{eq}} = \theta \exp[L_v S_h (c_p T)^{-1}], \qquad (1)$$

where θ denotes potential temperature at a specific level (i.e., 500 or 850 hPa), T and S_h are respectively temperature and specific humidity at the same level, c_p is the specific heat at constant pressure, and $L_v = 2.54 \times 10^6\,\mathrm{J\,kg^{-1}}$.

For the period 1992–2006, an additional thermodynamic analysis of the atmosphere is carried out by using CAPE (from the Twentieth Century Reanalysis and ERA-Interim) interpolated in time at hourly resolution (Molini et al. 2011) and hourly precipitation. This analysis cannot be performed over the entire period (1872–2008) because of unavailability of hourly precipitation data. For the identified debris-flow events in the subperiod 1992–2006 (i.e., 14), convective regimes are investigated. As pointed out by Done et al. (2006), the existence of an equilibrium between the production of CAPE by the large-scale system and the stabilization by convection implies higher predictability of the associated rainfall events. A characterization of convective regimes can be given in terms of the convective time scale (Done et al. 2006; Molini et al. 2011; Zimmer et al. 2011):

$$\begin{aligned}\tau_c &\sim \mathrm{CAPE}[d(\mathrm{CAPE})/dt]^{-1} \\ &= 2^{-1} c_p (L_v)^{-1} \rho_0 T_0 g^{-1} (\mathrm{CAPE})(\mathrm{rr})^{-1}, \qquad (2)\end{aligned}$$

where T_0 and ρ_0 denote reference values of temperature and density, L_v and c_p have been previously defined, g is gravitational acceleration, and rr is the rainfall intensity that is provided by the available gridded hourly dataset. The factor 2^{-1} is based on the assumption that free-tropospheric heating and boundary cooling equally contribute to the reduction of CAPE (Zimmer et al. 2011, and references therein). The use of CAPE data from a reanalysis product is forced by the unavailability of radiosonde data. To separate equilibrium regimes from nonequilibrium regimes, a threshold has to be introduced in the convective time scales. Although there is no consensus (and different thresholds have been used), here a 6-h threshold is used (Molini et al. 2011).

4. Results

Two configurations characterize the large-scale circulation associated with debris-flow events over the past 140 years. As shown in Fig. 2, they have similar features over the study site embedded in a different large-scale environment. Indeed, both clusters show anomalous southwesterly flow toward the study area favoring moisture fluxes form the North Atlantic Ocean and the Mediterranean Sea Basin. This flow is driven by 1) a midtropospheric trough extending from the British Isles toward the western Mediterranean [cluster 1 (CL1)], and 2) an anomalous closed cyclonic-circulating area centered over the Bay of Biscay [cluster 2 (CL2)]. SLP clusters are similar to Z500 clusters (not shown). CL1 is more prominent in terms of frequency of occurrence in short-duration rainfalls (1 day), whereas CL2 dominates the longer-lasting rainfall events (3 days; Fig. 3a). The 2-day interval events seem to be a mixture of both clusters, with a quasi balance between CL1 and CL2 occurrence. In June, July, and August, CL1 is more frequent than CL2. In contrast, CL2 dominates in May and September (Fig. 3b). Changes in the occurrence are

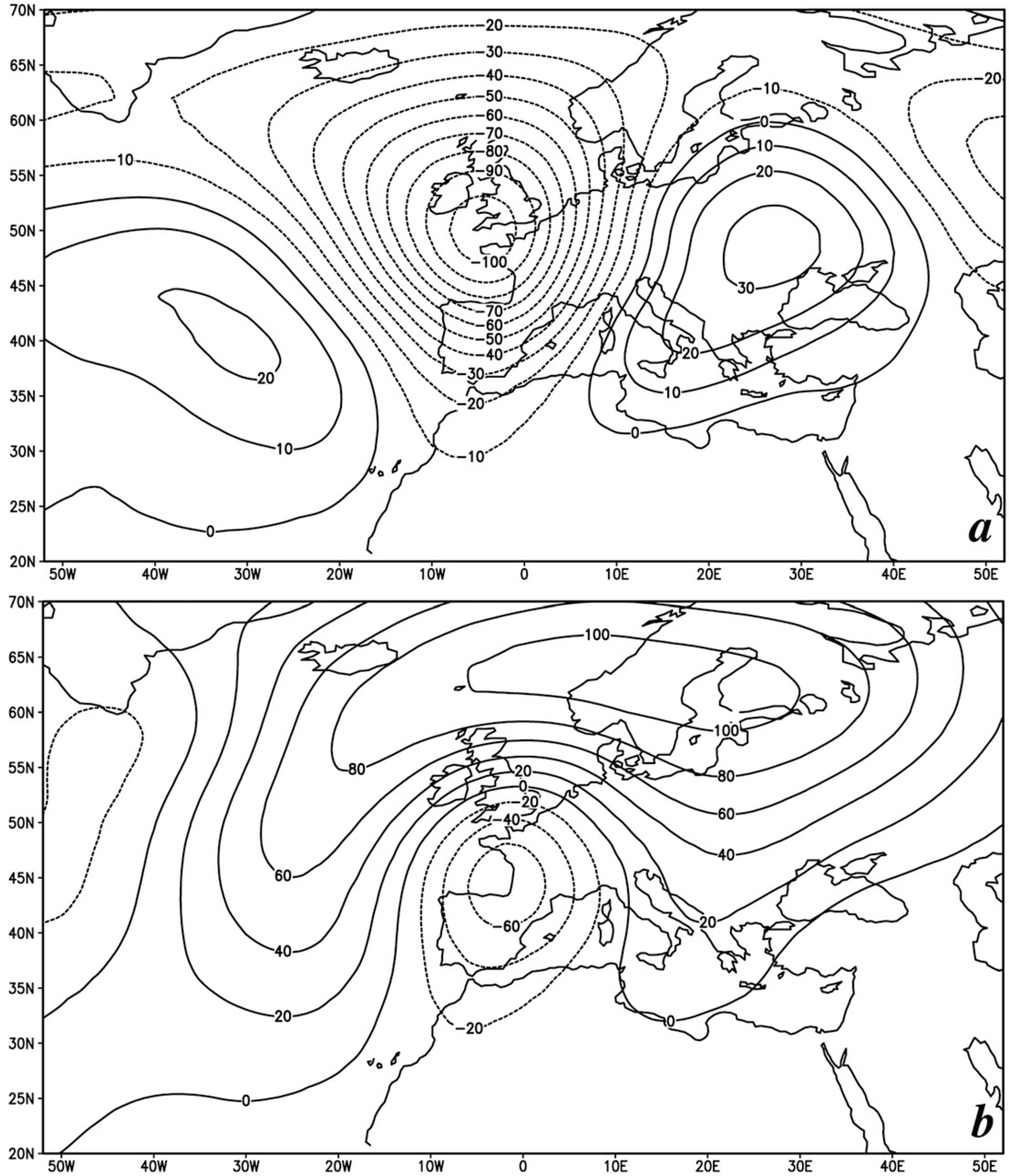

FIG. 2. Identified atmospheric patterns (anomalies of geopotential height at 500 hPa; Z500) associated with debris flows in the southern Swiss Alps: (a) CL1 and (b) CL2.

also analyzed through a subdivision of the investigated time period into four equally long time intervals. Figure 3c shows that CL1 frequency has apparently increased over the last 140 years. Only 32.5% of all events between 1872 and 1905 are associated with CL1, whereas in the most recent time interval (i.e., 1974–2008) that percentage is 65.2%. SLP shows the same changes over time as Z500 (not shown). For the occurrence of CL1 and CL2 during nontriggering rainy days, the pattern classification reveals small values for both patterns—18.1% and 11.8%, respectively—that highlight the strong connection between large-scale atmospheric configurations and debris-flow events.

For the vertical structure of the atmosphere, all events (there are no differences among the 1-, 2-, and 3-day classes) are characterized by high potential instability—significantly higher when compared with the other days in the same period (not shown). The destabilization of the atmosphere is likely to be caused by the southwesterly flow that increases the moisture content of the

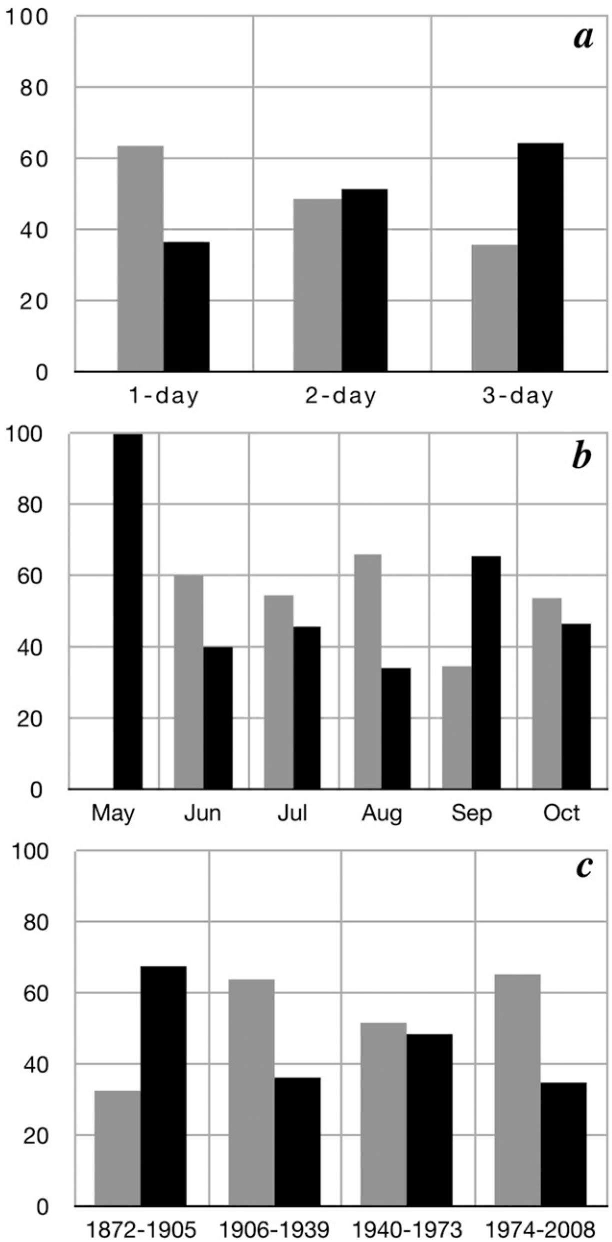

FIG. 3. (a) Frequency of CL1 (gray) and CL2 (black) for 1-, 2-, and 3-day events. (b) Frequency of CL1 and CL2 for each month from May to October. (c) Frequency of CL1 and CL2 for the four time periods.

lower layer of the troposphere. For the period 1992–2006, for which hourly precipitation data are available, the estimated convective time scales (Fig. 4) support a convective equilibrium for the three classes (1, 2, and 3 days), thereby pointing to the main role of large-scale circulation. When the convective time scale is equal to zero (Fig. 4) the event can be considered to be nonconvective and, therefore, included in the equilibrium-event class (Molini et al. 2011; Zimmer et al. 2011). Similarities between the convective time scales estimated by using the Twentieth Century Reanalysis and ERA-Interim (cf. Figs. 4a,b) provide further evidence to support a relevant role of the large-scale forcing, although CAPE is not observed. It is also worth highlighting that the presence of a convective equilibrium implies a higher predictability relative to nonequilibrium processes (characterized by weak synoptic forcing; Done et al. 2006).

5. Discussion and conclusions

The analysis reveals that two clusters are associated with the occurrence of debris flows in the southern Swiss Alps, both showing an anomalous southwesterly moisture transport from the North Atlantic Ocean and the Mediterranean Sea to the south of the Alps, where orographic effects favor the release of large quantities of rainfall. Moreover, their occurrence seems to have changed over time and especially in the last decades. The incidence of these two large-scale atmospheric patterns is closely related to the triggering of debris-flow events. Indeed, their frequency of occurrence during nontriggering rainy days is low (i.e., 11.8% and 18.1%) and can be further reduced by taking into consideration the high potential instability during debris-flow events. The main role of the large-scale circulation is also highlighted by the convective equilibrium identified during the analysis of convective time scales, although the results only refer to the period 1992–2006 and CAPE is based on reanalysis data. These findings can be used to develop an automatic procedure that is based on the recognition of the identified large-scale atmospheric patterns through the nSVC and the potential instability index and can be integrated into existing (or to be developed) alert systems (e.g., Badoux et al. 2009).

Cluster CL1 is more important in summer and is mainly associated with short-duration but high-intensity rainfalls. CL2 shows a negative closed anomaly which implies a slow-moving disturbance that favors the release of large quantities of rainfall over longer time periods (e.g., 3 days). A similar pattern was also identified by Massacand et al. (1998) for a torrential disaster in the wider study area that occurred in September of 1993. The increase in the frequency of CL1 might be linked to the combined effect of a positive tendency affecting the ''East Atlantic pattern'' (e.g., Barnston and Livezey 1987) and a negative tendency in the North Atlantic Oscillation series in the same period (1974–2008) and season. The former prevents the development of CL2-similar patterns, whereas the latter is favorable to the occurrence of CL1-similar patterns. Although the number of debris-flow events does not show statistically

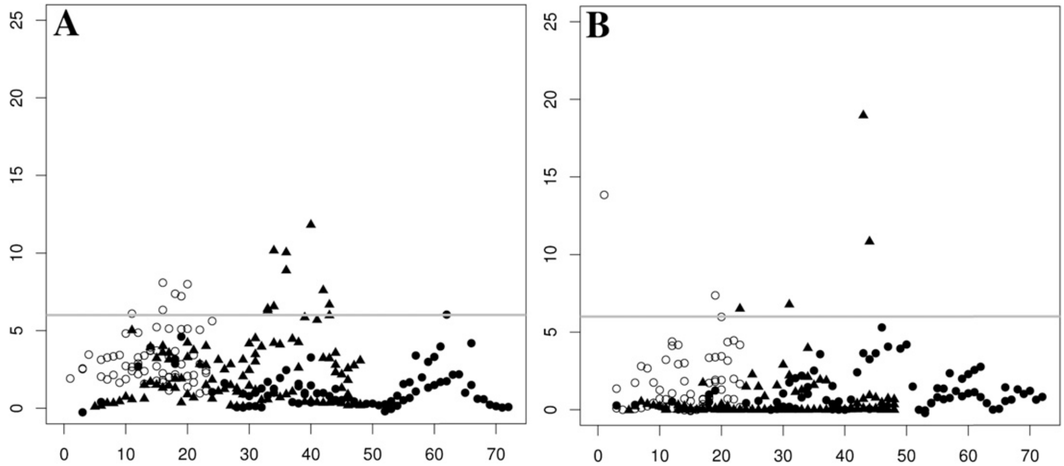

FIG. 4. Convective time scales in hours (y axis) for 1-day (open circles), 2-day (triangles), and 3-day (filled circles) events, derived by using (a) Twentieth Century Reanalysis and (b) ERA-Interim. Duration of the events (x axis) is also given in hours. The gray line represents the 6-h threshold to discriminate between equilibrium and non-equilibrium regimes.

significant tendencies over the full time period, the changes to be confirmed in the frequency of the atmospheric patterns once current and future reanalysis data become available might imply a higher risk associated with debris-flow events. Last, our findings imply a certain degree of predictability of debris-flow events and can thus be used to improve existing alert systems.

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REFERENCES

Badoux, A., C. Graf, J. Rhyner, R. Kuntner, and B. W. McArdell, 2009: A debris-flow alarm system for the Alpine Illgraben catchment: Design and performance. *Nat. Hazards,* **49,** 517–539.

Bardossy, A., and F. Filiz, 2005: Identification of flood producing atmospheric circulation patterns. *J. Hydrol.,* **313,** 48–57.

Barnston, A. G., and R. E. Livezey, 1987: Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Mon. Wea. Rev.,* **115,** 1083–1126.

Bollschweiler, M., and M. Stoffel, 2010: Changes and trends in debris-flow frequency since AD 1850: Results from the Swiss Alps. *Holocene,* **20,** 907–916.

——, ——, D. M. Schneuwly, and K. Bourqui, 2008: Traumatic resin ducts in *Larix decidua* stems impacted by debris flows. *Tree Physiol.,* **28,** 255–263.

Buzzi, A., N. Tartaglione, and P. Malguzzi, 1998: Numerical simulations of the 1994 Piedmont flood: Role of orography and moist processes. *Mon. Wea. Rev.,* **126,** 2369–2383.

Cacciamani, C., D. Cesari, F. Grazzini, T. Paccagnella, and M. Pantone, 2000: Numerical simulation of intense precipitation events south of the Alps: Sensitivity to initial conditions and horizontal resolution. *Meteor. Atmos. Phys.,* **72,** 147–159.

Compo, G. P., and Coauthors, 2011: The Twentieth Century Reanalysis Project. *Quart. J. Roy. Meteor. Soc.,* **137,** 1–28.

Dee, D. P., and Coauthors, 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quart. J. Roy. Meteor. Soc.,* **137,** 553–597.

Done, J. M., G. C. Craig, S. L. Gray, P. A. Clark, and M. E. B. Gray, 2006: Mesoscale simulations of organized convection: Importance of convective equilibrium. *Quart. J. Roy. Meteor. Soc.,* **132,** 737–756.

Ferretti, R., S. Low-Nam, and R. Rotunno, 2000: Numerical simulations of the Piedmont flood of 4–6 November 1994. *Tellus,* **52A,** 162–180.

GLOBE Task Team, 1999: Global Land One-kilometer Base Elevation (GLOBE): Digital elevation model, version 1.0. D. A. Hastings and P. K. Dunbar, Eds., NOAA National Geophysical Data Center Key to Geophys. Records Doc. 34, 147 pp. [Available online at http://www.ngdc.noaa.gov/mgg/topo/report/globedocumentationmanual.pdf.]

Jacobeit, J., A. Philipp, and M. Nonnenmacher, 2006: Atmospheric circulation dynamics linked with prominent discharge events in Central Europe. *Hydrol. Sci. J.,* **51,** 946–965.

Kaufman, L., and P. J. Rousseeuw, 1990: *Finding Groups in Data: An Introduction to Cluster Analysis*. John Wiley and Sons, 368 pp.

Krishna, K., and M. Narasimha-Murty, 1999: Genetic *K*-means algorithm. *IEEE Trans. Syst. Man Cybern.,* **29B,** 433–439.

Krivobokova, T., and G. Kauermann, 2007: A note on penalized spline smoothing with correlated errors. *J. Amer. Stat. Assoc.,* **102,** 1328–1337.

Marchi, L., M. Cavalli, M. Sangati, and M. Borga, 2009: Hydrometeorological controls and erosive response of an extreme Alpine debris flow. *Hydrol. Processes,* **23,** 2714–2727.

Massacand, A. C., H. Wernly, and H. C. Davis, 1998: Heavy precipitation on the Alpine southside: An upper-level precursor. *Geophys. Res. Lett.,* **25,** 1435–1438.

Molini, L., A. Parodi, N. Rebora, and G. C. Craig, 2011: Classifying severe rainfall events over Italy by hydrometeorological and dynamical criteria. *Quart. J. Roy. Meteor. Soc.,* **137,** 148–154.

Petrow, T., J. Zimmer, and B. Merz, 2009: Changes in the flood hazard in Germany through changing frequency and persistence of circulation patterns. *Nat. Hazards Earth Syst. Sci.,* **9,** 1409–1423.

Quadrelli, R., V. Pavan, and F. Molteni, 2001: Wintertime variability of Mediterranean precipitation and its links with large-scale circulation anomalies. *Climate Dyn.,* **17** (5–6), 457–466.

Schneuwly-Bollschweiler, M., and M. Stoffel, 2012: Hydrometeorological triggers of periglacial debris flows in the Zermatt valley (Switzerland) since 1864. *J. Geophys. Res.,* **117**, F02033, doi:10.1029/2011JF002262.

Schölkopf, B., and A. J. Smola, 2002: *Learning with Kernels*. MIT Press, 626 pp.

Stoffel, M., and M. Bollschweiler, 2008: Tree-ring analysis in natural hazards research—An overview. *Nat. Hazards Earth Sys.,* **8,** 187–202.

——, D. Conus, M. A. Grichting, I. Lièvre, and G. Maître, 2008: Unraveling the patterns of late Holocene debris-flow activity on a cone in the Swiss Alps: Chronology, environment and implications for the future. *Global Planet. Change,* **60,** 222–234.

——, M. Bollschweiler, and M. Beniston, 2011: Rainfall characteristics for periglacial debris flows in the Swiss Alps: Past incidences—Potential future evolutions. *Climatic Change,* **105,** 263–280.

Stucki, P., R. Rickli, S. Brönnimann, O. Martius, H. Wanner, D. Grebner, and J. Luterbacher, 2012: Weather patterns and hydro-climatological precursors of extreme floods in Switzerland since 1868. *Meteor. Z.,* **21,** 531–550.

VanDine, D. F., and M. Bovis, 2002: History and goals of Canadian debris flow research, a review. *Nat. Hazards,* **26,** 69–82.

Wüest, M., C. Frei, A. Altenhoff, M. Hagen, M. Litschi, and C. Schär, 2010: A gridded hourly precipitation dataset for Switzerland using rain-gauge analysis and radar-based disaggregation. *Int. J. Climatol.,* **30,** 1764–1775.

Xoplaki, E., J. F. González-Rouco, J. Luterbacher, and H. Wanner, 2004: Wet season Mediterranean precipitation variability: Influence of large-scale dynamics and trends. *Climate Dyn.,* **23,** 63–78.

Zimmer, M., G. C. Craig, C. Keil, and H. Wernli, 2011: Classification of precipitation events with a convective response timescale and their forecasting characteristics. *Geophys. Res. Lett.,* **38,** L05802, doi:10.1029/2010GL046199.