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Debris flow activity related to recent climate conditions in the French Alps: A regional investigation

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ABSTRACT

The primary objective of this study was to document the relationships between current climatic conditions and debris flow activity in the French Alps based on a large historical database of debris flow events covering 35 years up to the present. The French Alps are composed of two contrasting geographic areas so two debris flow regions with different activity patterns were defined. For the period 1970–2005, the database contains 565 debris flow events in 87 catchments in the northern part of the French Alps, and in 150 catchments in the southern part. Possible links between debris flow and climate were investigated using two different approaches. The first approach was determining the rainfall thresholds responsible for triggering debris flow events by analysing the links between the intensity and the duration of rainfall events. The second approach used a probabilistic logit model to explore the links between the triggering of debris flow events and temperature and precipitation during the active debris flow period to identify inter-annual variability. Reanalysis data were used to document climate conditions in the two study areas.

According to the results, in 80% of all debris flow events, precipitation was recorded during the three days preceding the event. However, in most cases, the quantity of precipitation associated with triggering of the debris flow was very low. Total precipitation exceeded 10 mm in only 30% of all cases. We attribute this to the convective nature of summer precipitation, which is quite difficult to model. Probabilistic analysis of the debris flow inventory in the two regions revealed that different parameters were responsible for changes in annual debris-flow activity. In the northern part of the French Alps, the number of rainy days and the maximum daily temperature affected debris flow, while in the southern part the only significant factor was mean daily temperature during the period of debris flow activity (May–October). Model scores had an accuracy of 75% and 70% in the northern and southern Alps, respectively. Our observations revealed that the increase in the above parameters has influenced changes in debris flow activity in both regions, where the number of debris flow events has doubled over the last 35 years.

1. Introduction

Debris flows (DFs) are defined as rapid flows of saturated non-plastic debris within a steep channel (Hungr, 2005). In mountainous areas like the Alps, such events are a major threat as they periodically damage infrastructure, disrupt transportation networks (Jomelli et al., 2011) and may even cause loss of life. DFs vary significantly in frequency, magnitude, intensity, and severity. In the western part of the Alps, intense and/or long-lasting precipitation is mainly responsible for triggering DFs (Guzzetti et al., 2007). However DFs are caused by interactions between meteorological and geomorphological factors, such as the local topography or the accumulation of rock debris, which makes it difficult to understand their activity. Whatever the case, the triggering process is definitely sensitive to climate change and this fact has been confirmed by numerous palaeo-DF records reconstructed from chronostratigraphy (*e.g.*, Brazier et al., 1988; Jonasson, 1993; Blikra and Nemec, 1998; Blair, 1999; Matthews et al., 2009), lichenometry (Innes, 1985; Winchester and Harrison, 1994; Helsen et al., 2002; Jomelli et al., 2002; Jomelli, 2013), and tree ring techniques (Stoffel et al., 2005, 2008; Bollschweiler and Stoffel, 2010; Lopez Saez et al., 2011). Moreover, expected future climate change may alter the dynamics of slope processes including DFs (Jomelli et al., 2009; Chiarle et al., 2011), and therefore the frequency or magnitude of extreme DF events (Stoffel, 2010). Consequently, evaluating the link between climate and DF activity is the first step in any attempt to predict future events.

Many authors who identified links between DF and climate focused on the meteorological conditions responsible for events triggered in a single catchment or in several neighbouring catchments with similar biophysical characteristics (Pelfini and Santilli, 2008; Bocchiola et al., 2010). However, links established at local scale may not be applicable to other places where the biophysical characteristics such as elevation,

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lithology, and vegetation are not the same. Fewer authors focused on the triggering of DFs related to climate conditions in very different catchments and at a large spatial scale. For example, regional thresholds of intensity/duration of precipitation events responsible for DFs and landslides were established by Caine (1980) and improved by Guzzetti et al. (2008). Based on this approach, the U.S. Geological Survey developed a landslide warning system with regional thresholds that take into account mean annual precipitation normalized by the number of rainy days (Wilson, 1997a). Other regional studies showed that temperature can be an important factor. Working in different glacial valleys in the Caucasus, Seynova et al. (2007) reported an increase in DF activity at a regional scale in recent decades caused by glacial retreat linked to warmer temperatures.

In the Alps, studies of a large number of catchments over a long time period are still rare (Guzzetti et al., 2007). Some authors focused on the meteorological/climatological conditions responsible for triggering DFs at a large spatial scale but only in special years such as 1987, which was characterised by a very large number of triggered events in the Swiss Alps (Haeberli et al., 1990; Zimmermann, 1990). Other authors focused on a few specific catchments (Borga et al., 2002; Fiorillo and Wilson, 2004; Stoffel and Beniston, 2006). In the French Alps, Jomelli et al. (2003, 2004, 2007, 2011) analysed links between climate conditions and different types of debris avalanches, corresponding to a shallow flow of partially- or fully-saturated debris that is not confined to an established channel (Hungr, 2005), as a function of their lithology or the nature of the accumulated debris. In most cases, extreme precipitation in summer and the number of freezing days in spring played a significant role in triggering debris avalanches. However, for confined DF events, such analyses are still lacking.

The French Alps comprise two distinct geographic areas: a humid northern part with steep narrow valleys, and a drier southern part with vast, less steeply sloped mountainsides. As it is generally assumed that significant changes in DF activity are due to different climate conditions, one can assume that the two contrasted climate conditions over the French Alps are responsible for significant variations in DF activity.

The aim of this study was to analyse the effects of the two contrasting climate conditions on DF activity. The rest of the paper is organised as follows: in Section 2, we describe the study area and the DF and meteorological data we used. In Section 3, we describe the two independent statistical methods which have been used to analyse the links among the triggering of DFs, changes in DF activity and climate conditions in the two parts of the French Alps since 1970. In Section 4, we present the links we found between DF activity and climate based on the two statistical models. In Section 5, we discuss possible causes of changes in DF activity in the last 35 years, while Section 6 concludes this paper.

2. General setting and data

2.1. Study area

The study area covers a large part of the French Alps (Fig. 1a) spanning more than 16,000 km^2, with more than 800,000 inhabitants. From an administrative point of view, the study area corresponds to three administrative districts: Savoie, Hautes-Alpes and Alpes-de-Haute-Provence (Fig. 1b). Based on climatic, economic and geographical criteria (Meyzenq, 1984; ONERC, 2008; Météo-France, 2011), the region can be divided into two sub-regions, the northern and southern French Alps (Fig. 1c), with Savoie in the north and Hautes-Alpes and Alpes-de-Haute-Provence in the south.

The northern French Alps contain two large river valleys both oriented SE–NW: the upper Isère and the Arc. The catchments of these main valleys and their tributaries cover more than 6000 km^2. The climate is closely linked with the configuration of valleys and massifs. As the main valleys in the northern region are primarily oriented westward,

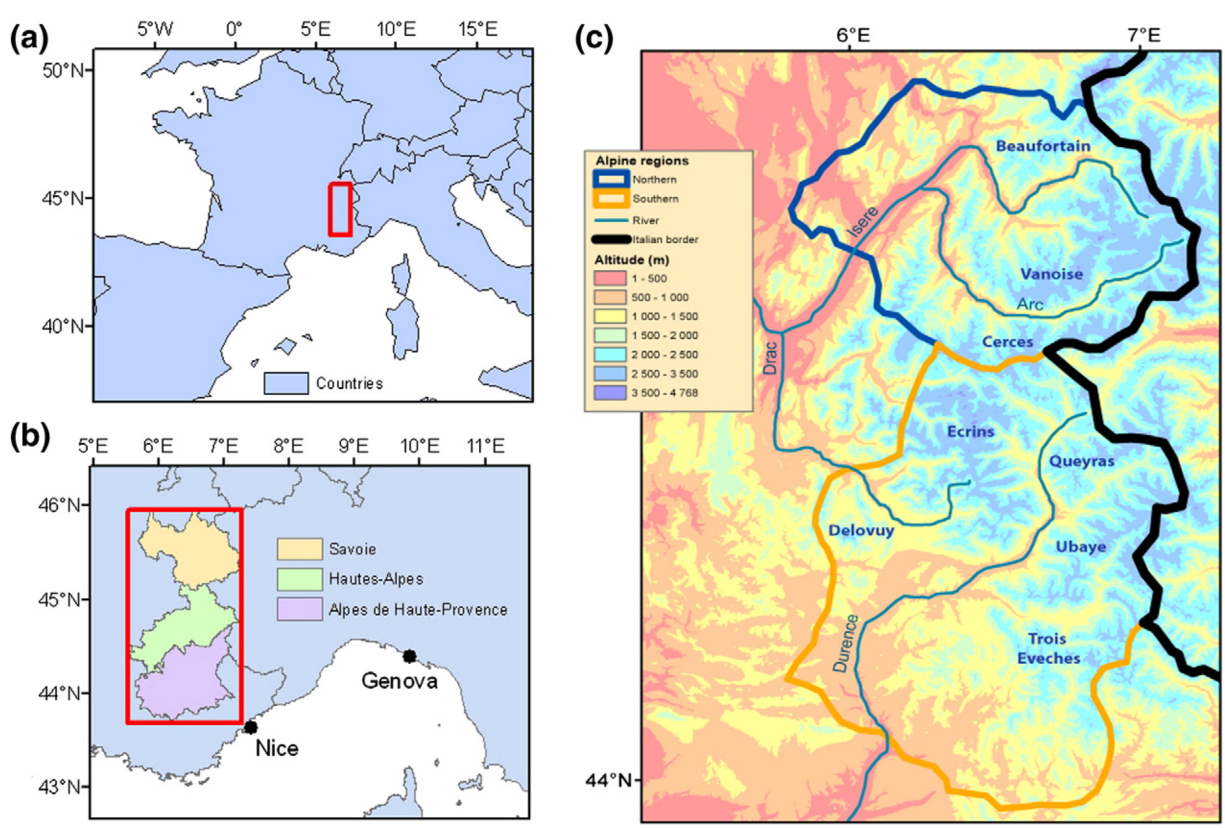

Fig. 1. Physiographic setting of the study area. (a) Location in France. (b) Administrative districts. (c) Topography.