Earth-Science Reviews 162 (2016) 227–252

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Invited review

Landslides in a changing climate

Stefano Luigi Gariano [a,b], Fausto Guzzetti [a,*]

[a] CNR IRPI, via della Madonna Alta 126, 06128 Perugia, Italy
[b] Università degli Studi di Perugia, Department of Physics and Geology, via A. Pascoli, 06123 Perugia, Italy

ARTICLE INFO

Article history:
Received 26 April 2016
Received in revised form 17 July 2016
Accepted 17 August 2016
Available online 20 August 2016

Keywords:
Climate change
Landslide
Climate variables
Modelling
Hazard
Risk

ABSTRACT

Warming of the Earth climate system is unequivocal. That climate changes affect the stability of natural and engineered slopes and have consequences on landslides, is also undisputable. Less clear is the type, extent, magnitude and direction of the changes in the stability conditions, and on the location, abundance, activity and frequency of landslides in response to the projected climate changes. Climate and landslides act at only partially overlapping spatial and temporal scales, complicating the evaluation of the climate impacts on landslides. We review the literature on landslide-climate studies, and find a bias in their geographical distribution, with large parts of the world not investigated. We recommend to fill the gap with new studies in Asia, South America, and Africa. We examine advantages and limits of the approaches adopted to evaluate the effects of climate variations on landslides, including prospective modelling and retrospective methods that use landslide and climate records. We consider changes in temperature, precipitation, wind and weather systems, and their direct and indirect effects on the stability of single slopes, and we use a probabilistic landslide hazard model to appraise regional landslide changes. Our review indicates that the modelling results of landslide-climate studies depend more on the emission scenarios, the Global Circulation Models, and the methods to downscale the climate variables, than on the description of the variables controlling slope processes. We advocate for constructing ensembles of projections based on a range of emissions scenarios, and to use carefully results from worst-case scenarios that may over/under-estimate landslide hazards and risk. We further advocate that uncertainties in the landslide projections must be quantified and communicated to decision makers and the public. We perform a preliminary global assessment of the future landslide impact, and we present a global map of the projected impact of climate change on landslide activity and abundance. Where global warming is expected to increase the frequency and intensity of severe rainfall events, a primary trigger of rapid-moving landslides that cause many landslide fatalities, we predict an increase in the number of people exposed to landslide risk. Finally, we give recommendations for landslide adaptation and risk reduction strategies in the framework of a warming climate.

Contents

* Corresponding author.
E-mail address: fausto.guzzetti@irpi.cnr.it (F. Guzzetti).

http://dx.doi.org/10.1016/j.earscirev.2016.08.011

1. Introduction

The assessment of the effects of climate change on the natural environment challenges the scientific community and poses thought-provoking problems to decision makers and politicians. Global warming is unequivocal (Diffenbaugh and Field, 2013; IPCC, 2014; LoPresti et al., 2015), but the effects of global warming, and the related changes in climate, on geo-hydrological hazards (e.g., floods, landslides, droughts) remain difficult to determine, and to predict. There is the need to understand and measure how climate variables and their variability affect geo-hydrological hazards, including landslides.

A landslide is a type of mass wasting process that acts on natural and engineered slopes. It is the movement of a mass of rock, debris, or earth down a slope, under the influence of gravity (Cruden and Varnes, 1996; Hungr et al., 2013). Landslides involve flowing, sliding, toppling, falling, or spreading, and many landslides exhibit a combination of different types of movements, at the same time or during the lifetime of the landslide. Landslides are present in all continents, and play an important role in the evolution of landscapes. In many areas they also pose a serious threat to the population (Petley, 2012).

Different phenomena influence the stability of slopes and cause landslides, including e.g., precipitation, snow melting, temperature changes, earthquake shaking, volcanic activity, and various human actions. Climate and its variations control or influence some of these phenomena, and chiefly precipitation and temperature (Dhakal and Sidle, 2004; Sidle and Ochiai, 2006; Crozier, 2010). It is therefore expected that climate (and its changes) influences slope stability at different temporal and geographical scales (Seneviratne et al., 2012). However, little is known about the effects of climate and its variation on slope stability, landslides, landslide hazards, and the related risk (McInnes et al., 2007; Crozier, 2010; Dijkstra and Dixon, 2010; Coe and Godt, 2012).

The fifth synthesis report of the Intergovernmental Panel on Climate Change (IPCC, 2014), like the previous four, did not provide a global overview on landslides. Landslides were considered in the IPCC special report "Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation" (Seneviratne et al., 2012), where one reads that "There is *high confidence* that changes in heat waves, glacial retreat, and/or permafrost degradation will affect slope instabilities in high mountains, and *medium confidence* that temperature-related changes will influence bedrock stability. There is also *high confidence* that changes in heavy precipitation will affect landslides in some regions". Considerations on local or regional landslide conditions were given in the reports of IPCC working group II published in 2007 (Parry et al., 2007) and 2014 (Field et al., 2014; Barros et al., 2014). Significantly, the IPCC (2014) synthesis report provided evaluations on flood risk to the population, and concluded that the number of people exposed to rare flood events is expected to increase worldwide. A similar global assessment for landslide risk to the population is still missing.

Since the release of the first assessment report of the IPCC (Houghton et al., 1990), the number of scientific papers dealing with landslides and climate change has increased steadily, with more than ten articles per year published in the recent years (Fig. 1). The interest is not limited to the Earth, and De Blasio (2010) examined landslides on Mars to obtain indications on past climate conditions on the planet. Remarkably, in recent years the percentage of articles on landslide-climate studies (Fig. 1, 1990–2016) is lower than for the entire landslide literature (Fig. 1, Wu et al., 2015, 1991–2014).

In this paper, we review published works that have investigated the past, current, and future (expected, projected) impact of climate change on landslides. The literature on the subject is broad and diversified, and we limit our review to peer-reviewed articles published in scientific journals, in the proceedings of technical conferences, and in multi-authored books (Fig. 1), excluding the grey literature. We focus primarily on the expected or projected future impacts of climate change on landslides, and subordinately on the analysis of ancient climate changes and their influence on slopes. Our review builds on few previous works, and particularly the works of Crozier (2010), who examined many factors linking landslides to climate change, and of Coe and Godt (2012), who analyzed different approaches to assess the impact of climate change on landslides.

The paper is organized as follows. In Section 2, we review works dealing with the impacts of climate change on landslides, including evaluations of slope stability exploiting climate projections, and analyses of landslides and climate records, and of landslide paleo-evidences. This is followed, in Section 3, by an analysis of how climate factors control/condition the stability of slopes (Crozier, 2010), and the possible variations in landslide hazard in response to climate changes. Next, in Section 4.1, we discuss what we consider advantages and limitations of the approaches adopted to evaluate slope stability using downscaled climate projections, the joint analysis of landslide and climate records, and ancient landslide evidences. This is followed, in Section 4.2, by a preliminary global evaluation of the expected changes in landslide activity, abundance, and types in response to the projected climate changes and, in Section 4.3, by recommendations for climate adaptation and

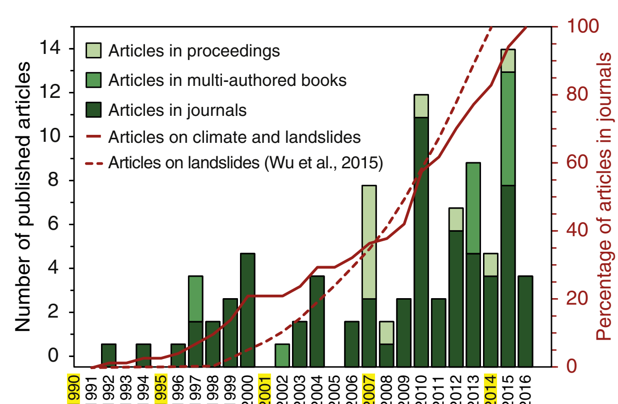

Fig. 1. Bar chart (left y-axis) shows the number of articles on landslide-climate studies published in scientific journals, multi-authored books and conference proceedings, from 1990 to 2016. Articles were searched using Elsevier's Scopus and Google Scholar. Red lines (right y-axis) show percentages of articles on landslide-climate studies from 1990 to 2016 (this study, continuous line) and landslide studies published in scientific journals from 1991 to 2014 (Wu et al., 2015, dashed line). Years of the five IPCC assessment reports are shown in yellow along the x-axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

landslide risk reduction strategies. We conclude, in Section 5, summarizing the lessons learnt.

2. Approaches to evaluate the effects on landslides of climate change

Only a few authors have attempted systematic, critical reviews of studies, concepts, ideas, and results of analyses on the impact of climate change on landslides (Dikau and Schrott, 1999; Sidle and Ochiai, 2006; McInnes et al., 2007; Crozier, 2010; Coe and Godt, 2012). In this work, we build on, and attempt to expand these works.

Dikau and Schrott (1999) summarized the results of the 3-year TESLEC – Temporal Stability and activity of Landslides in Europe with respect to Climatic change – project, funded by the European Commission in the 5th European Community Framework Programme. The project focused on three main objectives: (i) defining criteria for the recognition of landslides, (ii) reconstructing past distributions of landslides and their relationships to climatic variables, and (iii) developing a combined hydrological and slope stability modelling framework to evaluate the effects of climate variation on landslides. Eight study sites in England (1), France (1), Italy (2), Portugal (1), and Spain (3), were investigated in the period 1850–2000. The main result of the project was the impossibility to establish a single, "universal law" and a unique method to analyze the relationship between landslides and climate in Europe, due to complexity of the problem.

Sidle and Ochiai (2006), in an evaluation of the variables and processes affecting landslide phenomena, discussed the influences of climate change on landslides, and concluded that the increase in mean air temperature and changes in regional annual and seasonal precipitation were the most relevant climate variations that may affect landslides. They also considered the effects of climate change on vegetation, soil, land use and land cover, but acknowledged that the related feedback processes introduced more complex interactions in an already difficult evaluation.

McInnes et al. (2007) edited the proceedings of the International Conference on Landslides and Climate Change, held in Ventnor, UK, in 2007. The proceedings presented the results of historical analyses of the impact of climate change on landslides (and other natural hazards), methods for landslide modelling, assessments of landslide hazards and hazard management, and risk management and governance experiences in the framework of a changing climate.

Crozier (2010) was first to list and to examine systematically the mechanisms by which climate change can affect landslides, and more generally the stability conditions of slopes, assessing the impact of the predicted climate changes on landslides and engineered slopes. A significant conclusion of the work was that, regardless of the approach used, the inherent incompleteness of old climate and landslide records limits the possibility to evaluate the impact of the expected environmental and climate changes on landslide frequency, and on to estimate variations in the associated risk. Another important conclusion was that impacts of climate change on landslides were in places likely minor, compared to impacts from human disturbance.

Coe and Godt (2012) identified fourteen different approaches to assess the impact of climate change on landslides, and grouped them into three broad categories, including: (i) long-term monitoring, (ii) retrospective approaches, and (iii) prospective approaches. A relevant finding of the work was that all the considered studies that have attempted to predict the activity of rainfall-induced, shallow landslides and debris flows have high uncertainties; a result of the difficulty in predicting short-term extreme storms. Conversely, studies that have attempted to predict landslide activity using air temperature and annual/seasonal rainfall exhibit a lower uncertainty; a result of the fact that air temperature and annual/seasonal rainfall can be predicted with less uncertainty.

Overall, we have found in the literature and have analyzed 103 papers dealing with the effects and the consequences of climate change and landslides published between 1983 and 2016. Fig. 2 shows the geographical distribution of the considered case studies. Five continents are represented, with a large number of studies in Europe (69 studies), and chiefly in Italy (23), France (16), and United Kingdom (13), followed by North America, with 8 studies in Canada and 2 studies in the USA, Asia (7), South America (4), Oceania (3), and Africa (1). The Alps are the most investigated physiographic area, including the French (16), Italian (13), and Swiss (7) Alps. British Columbia (Canada) is the most studied administrative area. In many regions, the number of studies is larger than the number of study areas, with more than one study per area, introducing a bias in the geographical significance of the results.

Our literature analysis revealed that the study of the impacts of climate change on landslides is attempted adopting modelling, empirical, or combined approaches (Fig. 2, Table 1). Figs. 3 and 4 summarize the temporal distribution and range, the physiographical setting, and the

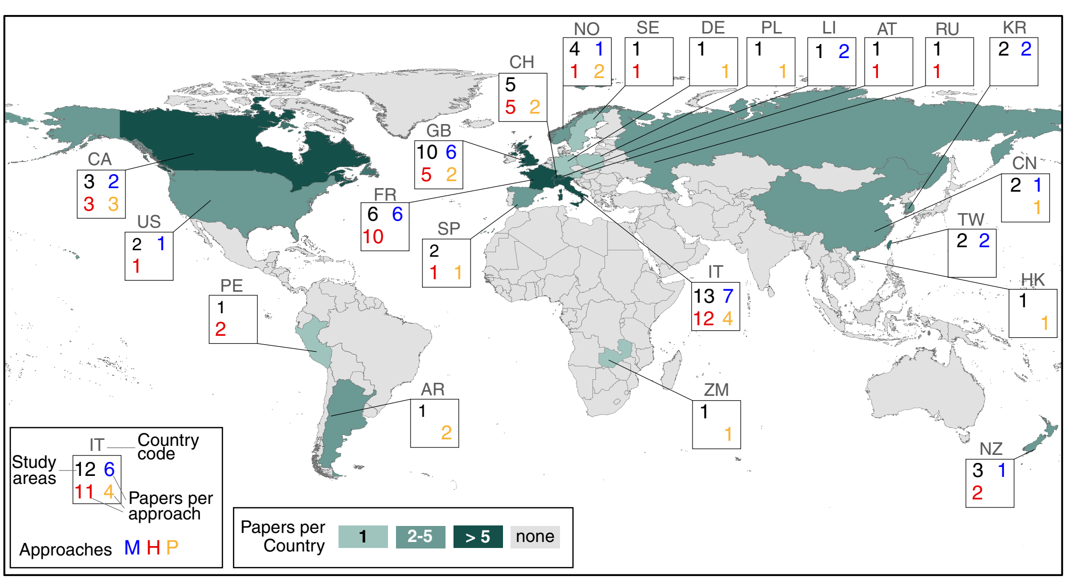

Fig. 2. Geographical distribution of landslide-climate studies. Countries coloured based on the number of published papers, in three classes. For each country, the number of study areas and the number of papers for three different approaches are given. Approaches: M (blue), modelling approach; H (red), historical analysis; P (orange), analysis of paleo landslide evidences. Countries shown with two-letter ISO 3166-1 alpha-2 code. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
List of the main works and approaches considered in this work to assess the impact on landslides of climate change. The approach, the location (area, country, continent), the morphological settings, the landslide type studied, and the type of climatic data or the dating technique used are listed. Approach: M, modelling (SS, slope stability model; SM, statistical model; RM, regional model); H, historical (analysis of historical landslide and climate records); P, analysis of landslide paleo-evidences. (1) Buma and Dehn (1998), (2) Dehn (1999), (3) Collison et al. (2000), (4) Tacher and Bonnard (2007), (5) Chang and Chiang (2011), (6) Coe (2012), (7) Melchiorre and Frattini (2012), (8) Comegna et al. (2013), (9) Rianna et al. (2014), (10) Villani et al. (2015), (11) Dixon and Brook (2007), (12) Jakob and Lambert (2009), (13) Jomelli et al. (2009), (14) Turkington et al. (2016), (15) Schmidt and Glade (2003), (16) Gassner et al. (2015), (17) Ciabatta et al. (2016), (18) Evans and Clague (1994), (19) Rebetez et al. (1997), (20) Flageollet et al. (1999), (21) Jomelli et al. (2004), (22) Chiarle et al. (2007), (23) Polemio and Petrucci (2010), (24) Huggel et al. (2012), (25) Stoffel et al. (2014), (26) Chiarle et al. (2015), (27) Gariano et al. (2015a), (28) Polemio and Longiro (2015), (29) Paranunzio et al. (2016). (30) Innes (1983), (31) Innes (1985), (32) Bovis and Jones (1992), (33) González Díez et al. (1996), (34) Lateltin et al. (1997), (35) Margielewski (1998), (36) Trauth et al. (2000), (37) Schmidt and Dikau (2004), (38) Soldati et al. (2004), (39) Stoffel and Beniston (2006), (40) Matthews et al. (2009), (41) Borgatti and Soldati (2010), (42) Yin et al. (2014), (43) Sewell et al. (2015). Legend: countries shown with two-letter ISO 3166-1 alpha-2 codes, and continents with two-letter ISO codes. Size, SZ: 0, [0–1] km^2; 1, [1–10] km^2; 2, [10–10^2] km^2; 3, [10^2–10^3] km^2; 4, [>10^3] km^2. Morphological settings (MS): hm, high mountain; m, mountain; h, hill. Landslide type (LT): DF, debris flow; DS, deep-seated landslide; EF, earthflow; MS, mud slide; RF, rock/ice fall; SL, shallow landslide; ML, multiple landslide types; NA, not available. Climate data: RH, hourly rainfall; RD, daily rainfall; RM, monthly rainfall; R, rainfall (unknown temporal resolution); TH, hourly temperature; TD, daily temperature; TM, monthly temperature; T, temperature (unknown temporal resolution).

<table>
<tr><th>Approach</th><th>Area | Nation | Continent</th><th>SZ</th><th>MS</th><th>LT</th><th>Climatic data/dating technique</th><th></th></tr>
<tr><td>M (SS)</td><td>Barcelonnette (Alps) | FR | EU</td><td>0</td><td>hm</td><td>SL</td><td>RM, GCM proj.</td><td>(1)</td></tr>
<tr><td></td><td>Cortina (Alps) | IT | EU</td><td>0</td><td>hm</td><td>MS</td><td>RM, MT, 4 GCM proj.</td><td>(2)</td></tr>
<tr><td></td><td>Kent | GB | EU</td><td>0</td><td>h</td><td>SL</td><td>RD, monthly GCM proj.</td><td>(3)</td></tr>
<tr><td></td><td>Triesenberg | LI | EU</td><td>1</td><td>m</td><td>DS</td><td>RD, GCM scen.</td><td>(4)</td></tr>
<tr><td></td><td>Baichi catch. | TW | AS</td><td>2</td><td>m</td><td>SLs</td><td>RM, 21 GCM scen.</td><td>(5)</td></tr>
<tr><td></td><td>San Juan, CO | US | NA</td><td>0</td><td>m</td><td>DS</td><td>RM, TM, GCM proj.</td><td>(6)</td></tr>
<tr><td></td><td>Otta | NO | EU</td><td>3</td><td>m</td><td>SLs</td><td>RD, GCM proj.</td><td>(7)</td></tr>
<tr><td></td><td>Basento River | IT | EU</td><td>0</td><td>h</td><td>EF</td><td>RD, RM, downsc. GCM, 2 IPCC scens.</td><td>(8)</td></tr>
<tr><td></td><td>Orvieto | IT | EU</td><td>0</td><td>h</td><td>DS</td><td>RD, downsc. GCM, 2 IPCC scens.</td><td>(9)</td></tr>
<tr><td></td><td>Cervinara, Orvieto | IT | EU</td><td>1</td><td>h</td><td>DS</td><td>downsc. GCM, weather generat.</td><td>(10)</td></tr>
<tr><td>M (SM)</td><td>Derbyshire | GB | EU</td><td>0</td><td>h</td><td>DS</td><td>RM, proj. from 3 UKCIPS scens</td><td>(11)</td></tr>
<tr><td></td><td>British Columbia | CA | NA</td><td>3</td><td>m</td><td>SLs, DFs</td><td>RM from 19 GCM, 3 IPCC scens.</td><td>(12)</td></tr>
<tr><td></td><td>Ecrins Massif (Alps) | FR | EU</td><td>2</td><td>hm</td><td>DFs</td><td>RD, TD downsc. 3 GCM</td><td>(13)</td></tr>
<tr><td></td><td>Barcelonnette, Fella basins | FR/IT | EU</td><td>2</td><td>hm</td><td>DFs</td><td>RD, CAPE, downs. 3 RCM, 6 GCM 2 IPCC scens.</td><td>(14)</td></tr>
<tr><td>M (RM)</td><td>Wellington, Hawke bay | NZ | OC</td><td>3</td><td>h, m</td><td>ML</td><td>RD, TD, GCM proj.</td><td>(15)</td></tr>
<tr><td></td><td>Waidhofen | AT | EU</td><td>3</td><td>m</td><td>ML</td><td>GCM, 2 scens.</td><td>(16)</td></tr>
<tr><td></td><td>Umbria | IT | EU</td><td>4</td><td>h, m</td><td>NA</td><td>RH, TH, downscaled 5 GCM</td><td>(17)</td></tr>
<tr><td>H</td><td>Canadian Cordillera | CA | NA</td><td>4</td><td>m</td><td>RF</td><td>T, glacier retreat</td><td>(18)</td></tr>
<tr><td></td><td>Ritigraben (Alps) | CH | EU</td><td>2</td><td>hm</td><td>DF</td><td>R</td><td>(19)</td></tr>
<tr><td></td><td>Barcelonnette (Alps) | FR | EU</td><td>1</td><td>hm</td><td>SL</td><td>RM</td><td>(20)</td></tr>
<tr><td></td><td>Dévoluy & Ecrins massifs | FR | EU</td><td>2</td><td>m</td><td>DF</td><td>R</td><td>(21)</td></tr>
<tr><td></td><td>Alps | IT/FR/CH | EU</td><td>4</td><td>hm</td><td>DF</td><td>R, T</td><td>(22)</td></tr>
<tr><td></td><td>Calabria | IT | EU</td><td>4</td><td>h, m</td><td>NA</td><td>RM</td><td>(23)</td></tr>
<tr><td></td><td>EU/NA/SA</td><td>3</td><td>m</td><td>RFs, DFs</td><td>T</td><td>(24)</td></tr>
<tr><td></td><td>Alps | IT/FR/CH | EU</td><td>3</td><td>hm</td><td>RFs, SLs</td><td>RM, TM</td><td>(25)</td></tr>
<tr><td></td><td>Cervinia, Alps | IT | EU</td><td>2</td><td>hm</td><td>RF</td><td>TD</td><td>(26)</td></tr>
<tr><td></td><td>Calabria | IT | EU</td><td>4</td><td>h, m</td><td>NA</td><td>RD</td><td>(27)</td></tr>
<tr><td></td><td>Apulia | IT | EU</td><td>4</td><td>h</td><td>NA</td><td>RM, TM, RD, RH (annual max.)</td><td>(28)</td></tr>
<tr><td></td><td>Alps | IT | EU</td><td>3</td><td>hm</td><td>RF</td><td>RD, TD</td><td>(29)</td></tr>
<tr><td>P</td><td>Scottish Highlands | GB | EU</td><td>3</td><td>h</td><td>DF</td><td>Lichenometry</td><td>(30)</td></tr>
<tr><td></td><td>Leirdalen, Langadalen, Austerdalen | NO | EU</td><td>3</td><td>h</td><td>DF</td><td>Lichenometry</td><td>(31)</td></tr>
<tr><td></td><td>British Columbia | CA | NA</td><td>3</td><td>h</td><td>EF</td><td>Dendrochronology, geomorphological analysis</td><td>(32)</td></tr>
<tr><td></td><td>Magdalena valley, Cantabria | SP | EU</td><td>2</td><td>m</td><td>NA</td><td>Sedimentological analysis, pollen record</td><td>(33)</td></tr>
<tr><td></td><td>Alps | CH | EU</td><td>4</td><td>hm</td><td>ML</td><td></td><td>(34)</td></tr>
<tr><td></td><td>Carpathians | PO | EU</td><td>3</td><td>m</td><td>NA</td><td>Radiocarbon</td><td>(35)</td></tr>
<tr><td></td><td>NW Andes | AR | SA</td><td>3</td><td>m</td><td>NA</td><td>Radiocarbon</td><td>(36)</td></tr>
<tr><td></td><td>Bonn area | DE | EU</td><td>3</td><td>h</td><td>NA</td><td>RD, TD, geomorphologic analysis</td><td>(37)</td></tr>
<tr><td></td><td>Dolomites | IT | EU</td><td>3</td><td>hm</td><td>ML</td><td>Radiocarbon</td><td>(38)</td></tr>
<tr><td></td><td>Valais Alps | CH | EU</td><td>2</td><td>hm</td><td>DF</td><td>Dendrochronology</td><td>(39)</td></tr>
<tr><td></td><td>Jotunheimen | NO | EU</td><td>3</td><td>m</td><td>DF</td><td>Radiocarbon</td><td>(40)</td></tr>
<tr><td></td><td>Dolomites | IT | EU</td><td>3</td><td>hm</td><td>ML</td><td>Radiocarbon, stratigraphy</td><td>(41)</td></tr>
<tr><td></td><td>Tibetan Plateu | CN | AS</td><td>3</td><td>hm</td><td>ML</td><td>Stratigraphy</td><td>(42)</td></tr>
<tr><td></td><td>Lantau Island | HK | AS</td><td>2</td><td>h</td><td>DF</td><td>Radiocarbon, luminescence</td><td>(43)</td></tr>
</table>

country of what we consider the most relevant studies reviewed in this work that adopted modelling and empirical approaches.

The modelling approach investigates variations in the stability conditions of single slopes or landslides driven by long-term rainfall and/or pore pressure variations obtained from future (synthetic) rainfall projections generated by downscaled global climate models (Wilby and Wigley, 1997; Fowler et al., 2007), used as an input to physically-based, statistical, or regional slope stability models (Table 1). Fig. 3 shows that the period covered by the investigations, and particularly model-based ones, has not changed significantly from 1998 to 2016, and that for many studies the calibration period (dark blue bars in Fig. 3) is shorter, or much shorter (e.g., Dehn, 1999; Coe, 2012; Villani et al., 2015; Gassner et al., 2015) than the projection period (light blue bars in Fig. 3). The large differences threaten the significance of the projections.

The empirical approach analyzes records of landslide occurrences and attempts to determine geographical and temporal variations in the occurrence, frequency, or rate of (re-)activation of the landslides. Two groups of empirical approaches can be singled out, depending on the period covered by the investigation, which affects the methods used to reconstruct the landslide and climate records. A first empirical approach compares catalogues of historical landslide occurrences with climatic records, chiefly rainfall and temperature, covering a few to many decades, typically in the last two centuries ("H" in Table 1, Fig. 3). A second empirical approach exploits paleo-environmental data to reconstruct records of ancient landslides and to analyze periods of increased/decreased landslide activity. The time covered by studies that adopted this approach range broadly during the Quaternary, between the Late glacial and the Holocene, covering the period from 40,000 BP to the 20th century ("P" in Table 1, Fig. 4).

The studies differ in the extent of the investigated area (Table 1). The majority of the model-based approaches are local, and investigate a portion of a slope, a single slope, or a single landslide (Buma and Dehn, 1998, 2000; Dehn and Buma, 1999; Tacher and Bonnard, 2007; Bonnard et al., 2008; Comegna et al., 2013; Rianna et al., 2014). Some model-based approaches were applied to populations of landslides in homogeneous areas (Jomelli et al., 2004, 2007, 2009; Jakob and Lambert, 2009; Chang and Chiang, 2011; Ciabatta et al., 2016).

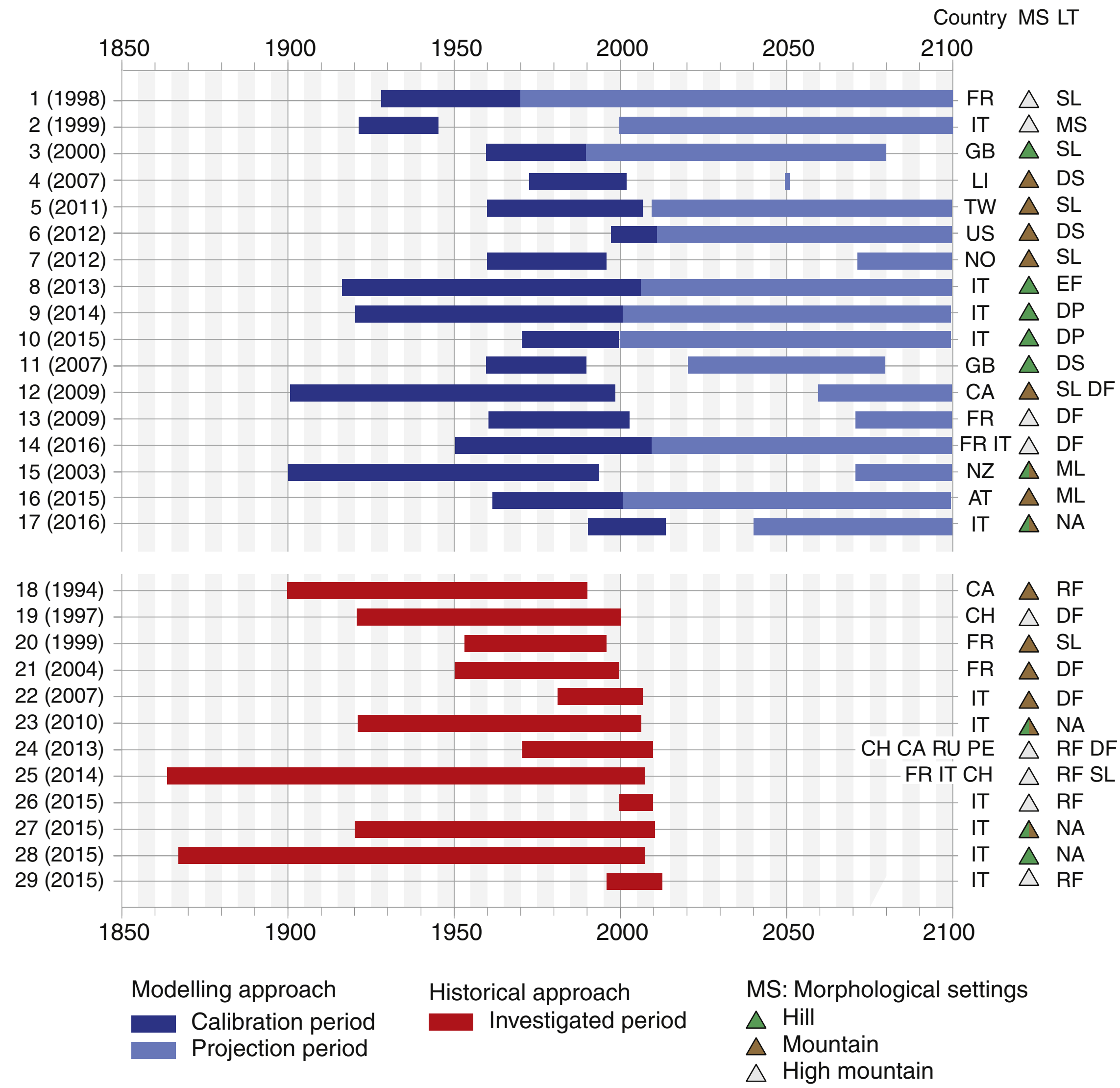

Fig. 3. Chart shows temporal distribution and range of studies reviewed in this work that adopted (i) a modelling approach (dark blue bars show calibration period, light blue bars show projection period) and (ii) an historical analysis approach (red bars). Reference number (Table 1), year of publication, period of analysis, country (shown using two-letter ISO 3166-1 alpha-2 code), morphological settings (MS), and type of landslide (LT) are given for 16 studies (blue) that used climate projections and landslide models (Section 2.1), and 12 studies (red) that used historical information on landslides and climate variables (Section 2.2). Legend: morphological settings (MS): white, high mountain; brown, mountain; green, hill. Landslide type (LT): DF, debris flow; DS, deep-seated landslide; EF, earthflow; MS, mud slide; RF, rock/ice fall; SL, shallow landslide; ML, multiple landslide types; NA, not available. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Conversely, the empirical approaches were applied at the regional scale, mostly – but not exclusively – in mountainous areas (Innes, 1985; Zimmermann and Haeberli, 1992; Evans and Clague, 1994; Sidorova et al., 2001; Bracegirdle et al., 2007; Geertsema et al., 2007; Hultén et al., 2007; Guthrie et al., 2010; Polemio and Petrucci, 2010; Allen et al., 2011; Ravanel and Deline, 2011, 2015; Fischer et al., 2013; Geertsema, 2013; Polemio and Lonigro, 2013, 2015; Saez et al., 2013; Gariano et al., 2015a; Palomba et al., 2015; Wood et al., 2015, 2016). Recently, attempts were also made to consider future climate scenarios in regional landslide susceptibility (Fan et al., 2013; Kim et al., 2014; Gassner et al., 2015; Shou and Yang, 2015) and hazard (Baills et al., 2013; Lee et al., 2014; Winter and Shearer, 2015) assessments, and for regional landslide early warning systems (Arambepola et al., 2013; Ciabatta et al., 2016).

We now outline what we consider the most relevant conclusions of works dealing with (i) modelling of the future slope stability conditions exploiting downscaled climate projections in slope stability models (Section 2.1), (ii) analyses of historical records of landslides and climate variables and their combinations (Section 2.2), and (iii) investigations of paleo-evidences of the long-term effects of climate changes and landslides (Section 2.3).

2.1. Evaluation of slope stability conditions using downscaled climate projections

A number of studies have investigated the effect of climate change on landslide occurrence or (re)activation exploiting downscaled synthetic rainfall series obtained from Global Circulation Model (GCM) as input of slope stability (Buma and Dehn, 2000; Tacher and Bonnard, 2007; Bonnard et al., 2008; Chang and Chiang, 2011), hydrological (Collison et al., 2000; Coe, 2012; Comegna et al., 2013; Rianna et al., 2014), empirical/statistical (Dixon and Brook, 2007; Jakob and Lambert, 2009; Jomelli et al., 2009; Turkington et al., 2016), or regional (Schmidt and Glade, 2003; Gassner et al., 2015; Ciabatta et al., 2016) models. The studies focused chiefly on mountain and hilly terrain, and considered individual, shallow and deep-seated slope failures, or

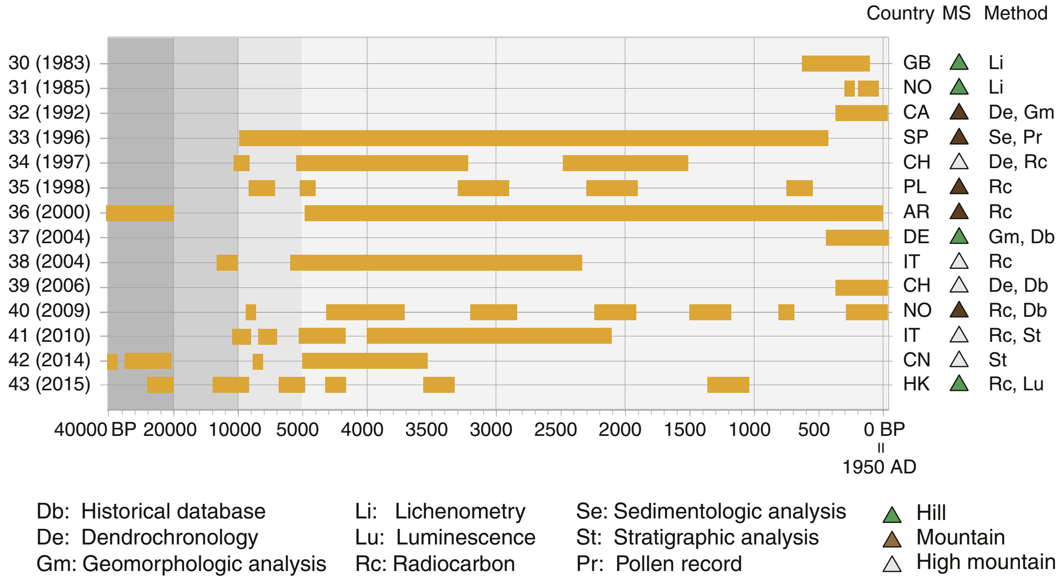

Fig. 4. Chart shows temporal distribution and range of studies reviewed in this work that analyzed "paleo landslide evidences". Reference number (Table 1), year of publication, considered period, Country (shown with two-letter ISO 3166-1 alpha-2 code), morphological settings (MS), and adopted dating method are given for 14 studies. Legend: morphological settings (MS): white, high mountain; brown, mountain; green, hill. Time scale in year BP (Before Present: year before 1950). Time-axis deformed before 4000 BP. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

populations of mainly shallow landslides. Most of the studies were conducted in Europe (22), and particularly in Italy (7), France (6), and United Kingdom (6). Studies were also conducted in Asia (5), North America (3), and Oceania (1) (Fig. 2). Conceptually, no difference exists between works that studied a single slope or landslide, and works that studied populations of landslides in a large area. The former used the results of a single cell of a downscaled GCM, whereas the latter used one or more adjacent cells.

Jelle Buma and Martin Dehn were first to exploit future (synthetic) rainfall records from a coupled ocean-atmosphere GCM (ECHAM4/OPYC3, Roeckner et al., 1996) to investigate the future stability of a landslide (Buma and Dehn, 1998, 2000; Dehn and Buma, 1999; Buma, 2000). They analyzed the recurrence intervals of a shallow landslide in the Barcelonnette basin, SE France, in the 42-year period 1928–1970, investigated using a stability model coupled with a hydrological model, and the rainfall recorded in the same period. Then, using statically downscaled rainfall from different GCM scenarios in the period 1971–2099, they found a significant reduction in the frequency of the landslide reactivations due to a slight decrease in the mean annual rainfall. Dehn (1999) and Dehn et al. (2000) proposed an early approach to transform transient GCM outputs to local precipitation scenarios exploiting a statistical downscaling technique. Next, they used the downscaled precipitation and temperature scenarios as inputs for a hydrological slope stability model to ascertain the future activity of the Alverà mudslide, Cortina d'Ampezzo, in the Italian Dolomites, an area where rainfall was predicted to decrease. Using two transient GCM experiments (HadCM2, Johns et al., 1997, ECHAM4/OPYC3, Roeckner et al., 1996) based on the IPCC emission scenario IS92a (Houghton et al., 1992), they found a substantial reduction in the landslide annual displacement rate, with a general decrease in landslide activity in the spring. These pioneering works outlined limitations in the use of GCM projections, and specifically biases and errors introduced by the climate scenarios in assessing changes in landslide activity, acknowledging at the same time the high degree of uncertainty in the obtained results.

Following these groundbreaking approaches, several authors exploited synthetic rainfall records from downscaled GCMs as input to slope stability or hydrological models. Most of the studies focused on single landslides. Collison et al. (2000) studied a shallow translational slide in SE England using a topographic index to distribute rainfall throughout the slope, a 1-dimension hydrological model for the estimation of the depth of the water table, and an infinite slope stability model to calculate the factor of safety. To obtain daily rainfall and temperature records from monthly GCM projections (HadCM2, Johns et al., 1997) they used a statistical downscaling approach. Results revealed an 11% increase in mean annual rainfall (mainly in winter), and a 13% increase in evapotranspiration, due to an increase in the mean annual temperature. The study concluded that variations in the rainfall and temperature regimes and the related changes in water table depths were likely to reduce the triggering of small, shallow slope failures.

Coe (2012) investigated a continuously moving deep-seated landslide (estimated volume 0.02 km^3, estimated depth 20 m) in Colorado, USA, using 12 years (1998–2011) of measurements of annual displacement, a moisture balance index and downscaled climate projections (A2 IPCC scenario, Houghton et al., 2001) for the period 2011–2099. Since temperature was projected to increase by about 0.05 °C/year, and precipitation to decreases at a rate of 0.2 mm/year, the author concluded that the landslide movement was expected to decrease gradually. The projection of a decelerating landslide behavior was based on climate projections obtained adopting a relatively high emissions scenario; but a significant conclusion of the work was that even if air temperature was predicted to increase by only half as much as projected, movements would still decrease.

Comegna et al. (2013) coupled climatic scenarios and geotechnical analysis to predict the future behavior of an active, slow moving earthflow in the Basento River valley, southern Italy. They adopted a complex approach that included (i) the calibration of a model linking weather parameters to the pore pressure regime at depth, (ii) the definition of a relationship between pore-water pressure and landslide movement, and (iii) the assessment of the long-time behavior of the landslide based on available climate scenarios. Historical analysis revealed a negative trend in daily rainfall (−2.4% per decade) and a slightly positive trend in daily temperature (+0.04% per decade). Using the COSMO-CLM regional climate model (RCM, Rockel et al., 2008) to downscale the projections of the CMCC-Med GCM (Scoccimarro et al., 2011), they simulated the climate in the area for the period 1965–2100, adopting the IPCC 20C3M scenario for the period

1965–2000, and the IPCC A1B scenario for the period 2000–2100 (Houghton et al., 2001). They found a projected decrease in precipitation and an increase in temperature, and a consequent reduction in the groundwater level of 8 mm per decade. They further calculated a decrease in the displacement rate of the earthflow in the range 1.5–3.0 mm per decade, leading to a maximum total displacement of 77 to 86 cm in the 51-year period 2010–2060. A relevant conclusion of the study was that the expected climate change did not play a relevant role in the dynamic behavior of the slow landslide in clay, due to the moderate decrease in the amount of annual precipitation and limited effect of temperature increase on evaporation and groundwater level.

Adopting the same simulation chain and global and regional climate models, Rianna et al. (2014) investigated a slow, deep-seated landslide in clay affecting the NE slope of the Orvieto hill, Umbria, central Italy. A 30-year-long monitoring record of the slide was used to establish a link between rainfall and rate of landslide movement (Tommasi et al., 2006), including a distinct reduction in the rate related to a decreasing trend in the maximum annual 4-month cumulated rainfall. Coupling historical data with high-resolution (up to 8 km) climate projections provided by COSMO-CLM for two IPCC emission scenarios (RCP4.5 and RCP8.5, Meinshausen et al., 2011), the authors obtained a quantitative estimate of the expected slope displacement until the end of 21st century, and concluded that the predicted local climate changes will be responsible for a significant deceleration of the landslide movement.

A few investigators used the physically-based modelling approach to evaluate the effects of climate change on populations of mainly shallow landslides. Chang and Chiang (2011) determined a worst-case-scenario for shallow landslide occurrence in a mountain catchment of Taiwan in the 21st century. From 21 GCMs, they selected an optimal GCM (CGCM2.3.2, Yukimoto et al., 2006), and the related monthly precipitation. They downscaled annual 24-h rainfall maxima (considered a good predictor for typhoons), and used it as input for the calculation of the stability conditions of a slope, measured by the factor of safety. They estimated an increase of about 15% in the average annual maximum rainfall from 1960 to 2008 to 2010–2099 and, as a result, a 12% increase in the average total unstable area between the considered periods.

Melchiorre and Frattini (2012) coupled a hydrological-stability model to eleven GCM scenarios and Monte Carlo simulations to evaluate changes in slope stability conditions of shallow landslides in central Norway. The GCM data were used to evaluate soil saturation conditions and pressure heads through the hydrological model, and an infinite slope stability model used to compute the factor of safety. They found diverging slope stability results for the future scenarios, and concluded that they could not quantify with certainty whether hillslopes became more or less stable, since the inherent errors in scenario-driven climate projections, and the epistemic uncertainty of the hydrological and slope stability model parameters are larger than the variations induced by climatic change.

GCM projections were also used as input to empirical/statistical models, to analyze single landslides, or populations of landslides. Dixon and Brook (2007) applied downscaled climatic scenarios to empirical/statistical rainfall thresholds based on 1-month and 6-month cumulated rainfall for a large (1 km long, 300 m large) rotational mudslide in Derbyshire, England. They exploited historical data on landslide activity and the corresponding 1-month and 6-month cumulated rainfall for the period 1961–1990, and three climate scenarios (UKCIPS, Hulme et al., 2002) for 2020, 2050, and 2080, based on the HadCM2 GCM (Johns et al., 1997). Despite a small reduction in annual rainfall, the authors found a decrease in the return time of the threshold exceedance from 4 years in the observed period to 3.5 years in the forecasting period.

Jakob and Lambert (2009) studied the effects of global warming on the relative frequency of rainfall-induced shallow landslides and debris flows in the south-western coast of British Columbia, Canada. They examined monthly mean rainfall simulations obtained from 19 GCMs, using three IPCC scenarios (B1, A1B, and B2, in ascending order of CO_2 concentration, Houghton et al., 2001). Employing a statistical technique to relate the short-term change in precipitation to total monthly rainfall changes, they found a 6% increase in the short-term precipitation by the year 2100. Comparing this result with thresholds calibrated on historical data in the period 1963–2007 they suggested an increase in the total number of debris flows of approximately 30% by the end of the 21st century.

Jomelli et al. (2009) investigated the impact of future climate change on the geographical and temporal occurrence of debris flows in the Massif des Ecrins, in the French Alps. They used downscaled rainfall and temperature data obtained from three simulations of the ARPEGE GCM (Déqué et al., 1994), under the A2 IPPC scenario (Houghton et al., 2001), for the 30-year future period 2070–2099. The projections showed a decrease in the number of intense rainfall events and an increase in temperature, compared to the calibration period 1970–1999. Given the decrease in the number of intense rainfall events, the authors estimated a 30% reduction in the temporal occurrence of debris flows, and given the increase in temperature, they estimated a shift of the 0 °C isotherm to a higher elevation, which was expected to result in a 20% reduction in the number of slopes affected by shallow slope instabilities, and a shift in the elevation of the areas susceptible to debris flow initiation.

Turkington et al. (2016) predicted trends in debris flows activity, measured by the number of days with debris flows, for the period 2010–2099, in the Barcelonnette valley, France, and the Fella catchment, Italy, under the RCP4.5 and RCP8.5 scenarios. For their experiment, they used a probabilistic approach to determine a dependence between rainfall events and debris flow occurrence (Turkington et al., 2014), and bias-corrected climate projections of two meteorological proxies i.e., daily rainfall from 1950 to 2009, and Convective Available Potential Energy (CAPE) from 1979 and 2011. Using an ensemble of 32 climate scenarios (from 3 RCMs and up to 6 GCMs, Jacob et al., 2014) for the rainfall proxy, and eight climate scenarios (from 4 GCMs, Taylor et al., 2011) for the CAPE proxy, they found an increase of up to 6% per decade in the number of days with debris flows towards the end of 21st century, in both study areas, and acknowledged that their projections depended strongly on the proxy used, and to a lesser extent to the GCM, RCM, and the RCP scenarios.

Lastly, Ciabatta et al. (2016) investigated the impact of climate change on landslide occurrence in Umbria, central Italy, using GCM projections applied to an existing regional landslide early warning system (Ponziani et al., 2012). First, they assessed the performance of the system using a catalogue of 235 shallow landslides in Umbria from 1990 to 2013. Next, they exploited hourly rainfall and temperature records obtained from downscaled outputs of five GCMs for a baseline period (1990–2013, under the historical scenario, Meinshausen et al., 2011) and for two future 30-year periods (2040–2069, 2070–2099, under the RCP8.5 scenario, Riahi et al., 2011) as input to their landslide early warning system. They found an increase of >40% in landslide occurrence in Umbria, mainly in winter. In the cold/wet season the increase in the number of landslide events is due to an increase in rainfall amounts and a small decrease in soil moisture. Conversely, in the warm/dry season a strong decrease in soil moisture and a sensible increase in rainfall intensity do not produce a change in landslide occurrence. A significant conclusion was that the modelling results depended largely on the selection of the GCMs, the downscaling methods, the weather generators used to downscale daily rainfall and temperature data to obtain hourly time series.

2.2. Analysis of landslides and climate records

A number of investigators have analyzed historical records of landslide occurrences, and have attempted to compare them to meteorological and climatic variables, chiefly rainfall and temperature. The majority of the works focus on debris flows, shallow landslides and rock falls in mountain environments, and cover periods in the range from mid-19th century to the present (Fig. 3, Table 1). Most of the studies were conducted in the mountains of Europe (32), and particularly in the French (9), Italian (7), and Swiss (4) Alps. Studies were also conducted in North (4) and South (2) America, and in New Zealand (2) (Fig. 2). The fact that the studies are more abundant in mountain areas should not be surprising. Mountains are "sentinels of changes" and respond more promptly and effectively than other geographical environments to changes in climate (Beniston, 2003). Overall, the studies reveal a large range of influences and consequences of climate change on landslides, including contradictory, uncertain and undetermined effects (Flageollet et al., 1999; Jomelli et al., 2004; Stoffel et al., 2005; Stoffel and Huggel, 2012).

Rebetez et al. (1997) were first to analyze debris flow occurrences in the 30-year period 1966–1994 in the Ritigraben region, Swiss Alps, and climate factors, as intense and/or prolonged rainfall and snowmelt. They found a general increase in temperature and in the number of rainfall events capable of triggering debris flows in the examined period. Similar trends were observed for the 20th century in Switzerland. A drawback of this pioneering work was the short span of the investigated period, which limited the significance of the results. Working in the nearby Barcelonnette basin, SE France, and studying different landslide types, Flageollet et al. (1999) used monthly rainfall data in the 42-year period 1954–1995 to search for relationships linking climate variables to landslide activations. No significant relationship was found, and the authors concluded that the type of landslide, the season of occurrence, and the initial state of the landslides were key factors that affected the search for possible relationships. They also concluded that the inherent complexity of the landslide phenomena made it difficult to define "universal laws" to link landslides to climate variations.

A number of investigators have examined the effects of air temperature on debris flows and rock falls, chiefly in the European Alps, and found an increase in landslide activity related to an increase in air temperature (Ravanel and Deline, 2011, 2015; Stoffel and Beniston, 2006; Paranunzio et al., 2016). Jomelli et al. (2004) examined the occurrence of 319 debris flows in the 51-year period 1950–2000 in the Dévoluy and Ecrins massifs, and observed a reduction in the number of debris flows in the Dévoluy massif, and a shift towards higher elevations of the debris flows source areas in the Massif des Ecrins. The variations were attributed to a decrease in the number of freezing days caused by an increase in air temperature, which affects and decelerates the process of debris accumulation necessary to initiate new debris flows. Chiarle et al. (2007) studied the triggering conditions of 17 glacier-related debris flows in the Italian, French and Swiss Alps, between 1980 and 2007, and found an increase in the frequency of the events near the glacier margins, compared to an older historical investigation (Dutto and Mortara, 1992), which they explained with the formation of moraine-dammed lakes; a consequence of glacier retreats in the 20th century due to increasing air temperature.

Huggel et al. (2012, 2013) compared the activity of rock & ice avalanches, ice avalanches, and debris flows in the Monte Rosa massif in the Italian Alps with a record of air temperature, and found that between the end of the 1980s and the early 1990s some of the failures occurred after a significant increase in local air temperature. They also observed that the large rock failures produced significant changes in the local geo-morphological setting that influenced the subsequent failures. A significant conclusion was that in the study area slope instability conditions were favored initially by climate drivers (i.e., variations in the air temperature), and subsequently developed independently of any additional climate forcing.

To verify the hypothesis that changes in air temperature were responsible for the increase in rock slope instability, Paranunzio et al. (2016) analyzed 41 rock falls at high elevations in the Italian Alps from 1997 to 2013 without any clear or known rainfall, seismic, or human-induced trigger. Using a statistical method for the analysis of landslide occurrences in relation to climate anomalies (Paranunzio et al., 2015), they studied daily air temperature in the period before the rock falls, and found that most of the failures were associated to a temperature anomaly. A short-term temperature anomaly was identified for 30 rock falls (73.2%), of which 12 cases (29.3%) were also associated to a long-term temperature anomaly. The authors concluded that, at high elevation and in absence of a clear rainfall trigger, temperature and its variations are key factors for rock fall occurrence in the Italian Alps, and that the impact of global warming on the instability of rock slopes was more evident above 3300 m of elevation where permafrost conditions predominate. However, it should be noted that the relationship between rock slope instabilities and temperature anomalies is difficult to prove (Chiarle et al., 2015). In many cases, the temperature at the time of failure is inferred from measurements taken by stations located at elevations and in topographic settings distant and different from those of the landslide failure zones. This jeopardizes any interpretation.

Other investigators have searched relationships linking temporal variations in rainfall amounts to changes in landslide occurrence. Polemio and Petrucci (2010), working in Calabria, southern Italy, found that antecedent rainfall in the month before a landslide event played a key role to initiate rainfall-induced landslides, whereas the role of temperature was negligible. They also observed that despite a decrease in the monthly rainfall in the 20th century, landslide occurrence has not decreased significantly in the same period in their study area. They explained the finding with incompleteness of the earlier part of the landslide catalogue, and with an amplification of the landslide damage due to the increased number of vulnerable elements in the last part of the 20th century. Using the same landslide information and daily rainfall records obtained by 318 rain gauges in Calabria, Gariano et al. (2015a) studied variations in the temporal and geographical variations of rainfall-induced landslides and their impact on the population in the 90-year period 1921–2010. They found that the geographical and the temporal distributions (chiefly the monthly distribution) of landslides changed in the observation period, and that less cumulated event rainfall was necessary to trigger landslides in the recent period 1981–2010 than in the preceding period 1951–1980. The change was attributed to an increased susceptibility to landslides of the territory. Polemio and Lonigro (2015), working in the nearby Puglia region, southern Italy, analyzed monthly rainfall and temperature records, and annual maxima of hourly and daily rainfall measurements, to conclude that the climate variations did not justify the observed increase in landslide (and flood) events between 1918 and 2006.

A few authors have identified seasonal variations in landslide occurrence, which may reveal the influence of a changing climate. Stoffel et al. (2014) analyzed changes in frequency, seasonal distribution, and number of shallow landslides in the Alps, in the 52-year period 1960–2011. They found that, before 2002, the scenario was dominated by shallow landslides triggered by prolonged and locally extreme autumn rainfall events, and after 2002 landslides occurred more frequently in the early spring triggered by moderate rainfall, and autumn events triggered few landslides. The observed variations, more evident in decade 2001–2011, were explained with a change in the seasonal distribution of the precipitation that changed from a bimodal distribution with maxima in the spring and summer, to a unimodal distribution, with increases in winter precipitation and in dry conditions in the spring and summer. The authors also related the observed changes in landslide activity to terrain elevation, and concluded that above 1500 m of elevation the projected decrease in snowpack depth and duration during future winters and springs will affect the frequency and seasonality of landslides. Variations in the seasonal distribution of landslides were also identified in Umbria, central Italy, by Salvati et al. (2006) who explored a catalogue of historical landslide (and flood) events covering the period 1139–2001, and found that before 1900 landslides were most abundant in October and November, and to a lesser extent in March, whereas after 1900 they were more evenly distributed throughout the year, with a maximum in February and a second maximum in December.

2.3. Analysis of landslide paleo-evidences

A few investigators have used "paleo-evidences" to study possible relationships between long-term climate changes and the temporal distribution of landslides (Borgatti and Soldati, 2010, and references therein). Works focused primarily in Europe (14) (Innes, 1983, 1985, 1997; González Díez et al., 1996; Lateltin et al., 1997; Matthews et al., 1997; Margielewski, 1998; Schmidt and Dikau, 2004; Soldati et al., 2004, 2006; Stoffel and Beniston, 2006; Francani and Gattinoni, 2009; Matthews et al., 2009; Borgatti and Soldati, 2010), and in America (Bovis and Jones, 1992; Cruden, 1999; Trauth et al., 2000, 2003; Holm et al., 2004), but studies exist also in Asia (Yin et al., 2014; Sewell et al., 2014), Africa (Thomas, 1999) and Oceania (Crozier, 1997) (Figs. 2, 4, Table 1). The investigated periods are significantly longer (and older) that the periods covered by the recent and historical investigations covered in Section 2.2, and span the age range from the late Quaternary, through the Last Glacial Maximum, to the 20th century (Fig. 4). Various techniques are used to date the landslides (Lang et al., 1999), including dendrochronology (Bovis and Jones, 1992; Lateltin et al., 1997; Paolini et al., 2005; Stoffel et al., 2005; Stoffel and Beniston, 2006; Corominas and Moya, 2000; Stoffel et al., 2010, 2011, to cite a few), radiocarbon dating (Margielewski, 1998; Trauth et al., 2000; Soldati et al., 2004; Matthews et al., 2009; Borgatti and Soldati, 2010), lichenometry (Innes, 1983, 1985), stratigraphic (Schmidt and Dikau, 2004; Borgatti and Soldati, 2010), and sedimentological analysis, and pollen metric (González Díez et al., 1996), or geomorphological and morphometrical analyses (Bovis and Jones, 1992; Holm et al., 2004; Yin et al., 2014). Past landslide occurrences were also used as climate proxies (Matthews et al., 1997; Eden and Page, 1998; Dikau and Schrott, 1999; De Blasio, 2010).

Not surprisingly given the geographical breath and temporal span of the studies, the investigations of paleo-landslide evidences provide contrasting results. Innes (1983) used lichenometry to date debris flow deposits in Scotland, and found that the observed increase in debris flow activity in the previous 500 years was not the result of climate variations, but was caused by human activities (i.e., burning and overgrazing) in the 19th and 20th centuries. The same author, working in SW Norway, did not find indications of the climate change effects or human actions on debris flow activity, in the previous 500 years (Innes, 1985). Bovis and Jones (1992) used dendrochronological data and stratigraphic records to show that movements of large earthflows in British Columbia, Canada, from 1950 to 1980, responded to Holocene climatic variations.

Using luminescence and radiocarbon analysis, Sewell et al. (2015) dated five debris flow fan complexes in Lantau Island, Hong Kong, and identified six main periods of accumulation (Fig. 4). These periods of increased landslide activity and sediment transport were attributed to an intensification of the East Asian monsoon during the early to middle Holocene. Also using radiocarbon dating, Trauth et al. (2000) identified two temporal clusters of landslides in NW Argentina between 35,000 and 25,000 BP and after 5000 BP (Fig. 4), corresponding to the Minchin and Titicaca wet periods when the El Niño Southern Oscillation (ENSO) was active. The authors attributed the increase in the inter-annual variability of landslide occurrence to climatic variations.

Soldati et al. (2004) and Borgatti and Soldati (2010) studied the relationships between climate change and hill slope evolution in different areas in Europe, including the Dolomites and the Eastern Alps, from about 11,000 BP (Last Glacial) to 2100 BP. Analyzing paleo-landslide records obtained from stratigraphy and radiocarbon dating, they recognized two periods of enhanced landslide activity; an earlier period at the Late-glacial-Holocene transition, from about 11,000 to about 8500 year BP, and a later period in the Upper Holocene, from about 5500 to about 2500 year BP. The higher landslide activity was attributed, for the earlier period to an increase in temperature and permafrost melting at high elevations, and for the latter period to human action (mainly deforestation) and to an increase in precipitation. The two periods of enhanced slope instability correlate well with indicators of cold and humid climate, suggesting that a positive moisture balance played a major role on landslide activity.

Schmidt and Dikau (2004) modelled landscape sensitivity to climate change for groundwater-controlled deep-seated landslides in three hill slopes of the Rhine valley near Bonn, Germany, using monthly and daily meteorological records and paleo data obtained from archive proxies for seasonal temperature and rainfall from 1500 to 2000. The results revealed considerable variations in the sensitivity of the landscape to slope instability in relation to different climate scenarios. A relevant conclusion of the work was that, in the study area, the local geomorphological and lithological settings were more relevant than the changes in climate to control the landscape sensitivity to deep-seated landslides, which we take as a proxy for susceptibility.

3. Influence of climate on slope stability and landslide hazard

The influence of climate and its variations on landslides can be classified broadly as: (i) local or regional (or global), (ii) of short- or long-term impact, and (iii) direct or indirect. For four climate variables known to affect landslides (i.e., total rainfall, rainfall intensity, air temperature, weather system), Fig. 5 summarizes the known or expected impact (local or regional, short-term or long term, direct or indirect) of climate change on different landslide types. Fig. 6 shows the

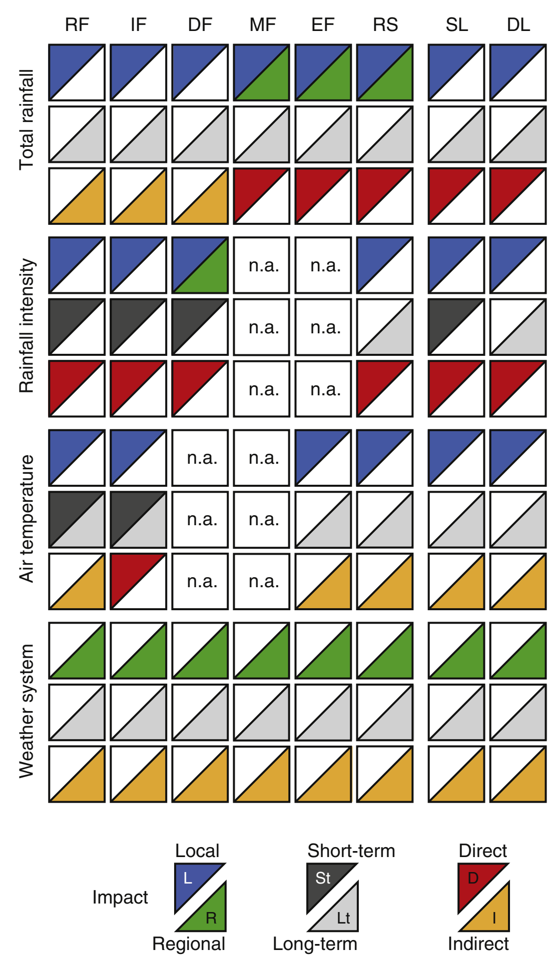

Fig. 5. For four climate variables, known to affect landslides (total rainfall, rainfall intensity, air temperature, weather system, in four groups of rows), and for eight landslide types (RF, rock fall/avalanche; IF, ice fall/avalanche; DF, debris flow; EF, earthflow; MF, mudflow; RS, rock slide; SL, shallow landslides; DS, deep-seated landslides, columns), we show with different colours the geographical (local, blue; regional, green), the temporal (short-term, dark grey; long-term, light grey), and the direct (red) and indirect (orange) expected impact. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

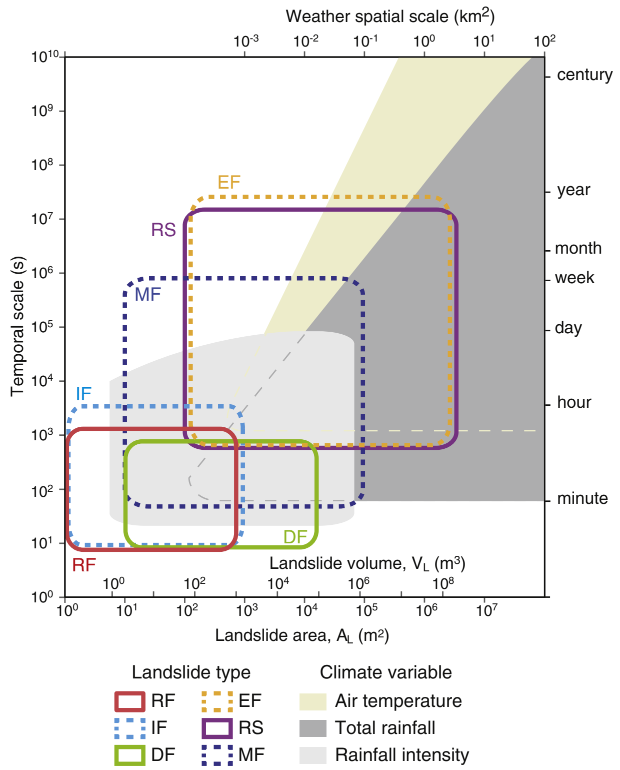

Fig. 6. Schematic representation of the geographical and temporal ranges of variation (on logarithmic axes) of six landslide types (RF, rock fall/avalanche; IF, ice fall/avalanche; DB, debris flow; EF, earth flow; MD, mud flow; RS, rock slide), and three climate variables (air temperature, total rainfall, rainfall intensity). Scale for landslide time (y-axes) shows timeframe over which landslides activate and evolve. Scale for landslide volume obtained using the relationship $V_L = 0.0074 \cdot A_L^{1.450}$ (Guzzetti et al., 2009).

geographical and temporal ranges of six landslide types (rock falls, ice falls, debris flows, earth flows, mud flows, rock slides) and three climate variables (air temperature, total rainfall, rainfall intensity) known to affect slope stability and landslides (Crozier, 2010). We find that climate and landslides (areas and lines in Fig. 6) operate on different and only partially overlapping scales.

Local impacts influence a single slope, a portion of a slope, an individual landslide, or a small catchment (Buma and Dehn, 1998; Collison et al., 2000; Malet et al., 2005; Tommasi et al., 2006; Dixon and Brook, 2007; Tacher and Bonnard, 2007; Jomelli et al., 2009; Chang and Chiang, 2011; Moore et al., 2010; Coe, 2012; Comegna et al., 2013; Rianna et al., 2014; Zollo et al., 2014). Regional influences affect landslide occurrence in areas ranging from a few hundreds to several thousands of square kilometers i.e., a province (Rebetez et al., 1997; Jomelli et al., 2004; Malet et al., 2007; Guthrie et al., 2010; Jakob and Lambert, 2009; Polemio and Petrucci, 2010; Polemio and Lonigro, 2013, 2015; Gassner et al., 2015; Gariano et al., 2015a; Kim et al., 2015; Ciabatta et al., 2016), a state or country, or a broad geographical or physiographical region (Sidle and Dhakal, 2002; Schmidt and Glade, 2003; Nadim et al., 2006; Chiarle et al., 2007; Hultén et al., 2007; Winter et al., 2010; Huggel et al., 2012; Stoffel et al., 2014; Winter and Shearer, 2015; Paranunzio et al., 2016). The regional impact of climate change was also ascertained for engineered slopes. Loveridge and Spink (2010), working in England, highlighted that clay slopes will be at greater risk in the future from increased-magnitude seasonal cycles of moisture changes, leading potentially to loss of roads and railways serviceability e.g., due to track settlement, and greater rates of strain softening. Clarke and Smethurst (2010), also working in England, showed that in volume-sensitive clays climate change leads to more pronounced differences between the cycles of winter soil wetting and summer drying, which cause shrink and swell displacements and damage to engineered slopes.

Short-term climate effects influence landslides in periods ranging from a few years to one or two centuries, whereas long-term effects cover longer periods in the range from a few centuries (Schmidt and Dikau, 2004) to several thousands of years (Trauth et al., 2000; Borgatti and Soldati, 2010; Yin et al., 2014). Direct climate impacts influence parameters that directly control landslide occurrence, like a change in rainfall regime that influences the amount of rainfall that can result in landslides (Chiarle et al., 2007; Guzzetti et al., 2007, 2008; Jakob and Lambert, 2009; Stoffel et al., 2014). Indirect climate effects influence environmental and landscape conditions that, in turn, affect landslides. As an example, a change in rainfall regime can alter land cover types and land use, which have consequences both on single slope stability conditions, and on the type, abundance and frequency of landslides (Sidle and Dhakal, 2002; Glade, 2003; Smith and Glade, 2003; Sidle and Ochiai, 2006; Wasowski et al., 2010).

Climate change also affects the human impact on natural landscapes and socio-economic environments, and this in turn has direct and indirect consequences on slope stability and landslides. As an example, variations in climate may affect directly through meteorological drivers, or indirectly through economical and societal drivers, agricultural and forest practices over very large areas. This is expected to have consequences both at the local scale (i.e., on single slopes or landslides) and at the regional scale on the type, abundance and frequency of landslides. Imaizumi et al. (2008) analyzed the effects of forest age and forest harvesting on the frequency of landslides and debris flows in a catchment in central Japan between 1964 and 2003. They found that trends of new landslides and debris flows corresponded to changes in slope stability explained by root strength decay and recovery.

At the slope (local) scale, the landslide response to climate change varies depending on landslide type and size (depth D_L – in particular, area A_L, volume V_L), and on the initial or current stability conditions of the slopes (Schmidt and Glade, 2003; Glade and Crozier, 2005; Crozier, 2010). For stable slopes, climate variations are expected to influence primarily the landslide preparatory factors (e.g., antecedent rainfall, weathering, land cover, forestation, deforestation), bringing the slopes to marginally stable conditions. For slopes that are already in marginally stable or in critical conditions, climate variations are expected to affect primarily the landslide triggers (e.g., precipitation, water table rise, fractures induced by changes in temperature). We expect the slope response to be different for first-time, shallow failures compared to the reactivation of active, large, deep-seated landslides (Crozier, 2010). This is because small shallow landslides are controlled by rainfall peaks or maxima and by rainfall intensity at short durations, whereas large deep-seated landslides are affected chiefly by monthly and/or seasonal rainfall, and the related groundwater variations (e.g., the position of the water table in the slope) (Sidle and Ochiai, 2006; Crozier, 2010; Dijkstra and Dixon, 2010).

Inspection of the literature revealed that variations in rainfall totals influence mostly rock slides, mud flows and earth flows, at both the local and the regional scale, whereas variations in rainfall intensity affect, mostly directly, rock falls and debris flows/avalanches, in the short-term and at the local scale (Fig. 5). Changes in the air temperature influence directly ice falls and avalanches, and have and indirect impact on rock falls (due to the formation and opening of fractures), and on deep-seated landslides (due to changes in the hydrological cycle) (Fig. 5).

Variations in the weather systems are expected to affect indirectly all landslide types, with regional, long-term effects (Fig. 5). Wood et al. (2016) used an inventory of 2966 landslides in the French and Swiss Alps (described in Wood et al., 2015) and Monte Carlo simulations to study the influence of synoptic weather systems on landslides. They found that landslides were triggered by high precipitation regardless of the type of weather system, but with seasonal variations. Westerly weather patterns resulted in more landslides from autumn to spring, and southern patterns were responsible for more landslides in the summer.

To investigate further the difference between the local and the regional influences of climate change and its variations on landslides, we consider that the local climate influences affect primarily the stability conditions of single slopes or portions of a slope, whereas the regional influences affect landslide hazard over broad areas.

3.1. Changes in the stability of individual slopes

At the local scale, the stability conditions of a slope can be ascertained computing the factor of safety, FS which expresses the ratio between the local resisting (R) and driving (D) forces i.e.,

$$FS = \frac{R}{D} = \frac{\tan(\varphi)}{\tan(\delta)} + \frac{c - \psi \cdot \gamma_w \cdot \tan(\varphi)}{\gamma_s \cdot z_s \cdot \sin(\delta) \cdot \cos(\delta)} \quad (1)$$

where: c is the cohesion of the slope material, γ_s is the soil unit weight, γ_w is the groundwater unit weight, φ is internal friction angle, ψ is the pressure head – governed by Richards (1931) equation – δ is the slope angle of the sliding surface, and z_s is the vertical depth of the sliding surface. In stable conditions the resisting forces exceed the driving forces, $R > D$, and $FS > 1.0$. $FS = 1.0$ represents the metastable condition where the driving and the resisting forces are equal ($R = D$), and $FS < 1.0$ characterises the condition where the driving forces exceed the resisting forces ($R < D$), and the slope fails (Taylor, 1948).

In Eq. (1), except for γ_w, all the variables that contribute to the resisting and the driving forces can be affected by changes in the triggering (short-term) or the predisposing (long-term) factors, which can be caused or influenced by climate change (Sidle and Ochiai, 2006). Crozier (2010) considered six climate-related factors and discussed their effects and interactions in controlling the local stability conditions, including: (i) precipitation totals, (ii) rainfall intensity, (iii) air temperature, (iv) wind speed and duration, (v) changes in the weather systems and the related (vi) meteorological variability. Table 2 summarizes the known or expected effects of climate change on landslides, and reveals the complexity of the links and feedbacks between the main factors altered by climate change, and their known, expected or inferred effects on landslides.

An increase in the total precipitation is expected to result in wetter antecedent conditions, which can have multiple negative consequences on slope instability, including (i) less rain required to reach a critical level that can cause a slope to fail, and (ii) higher water table contributing to the reduction of shear strength, to the reduction in soil suction and cohesion, and to an increase in the weight (wet density) of the slope materials, all working to enhance the slope instability (Tacher and Bonnard, 2007). Conversely, a reduction in total precipitation will typically result in more stable conditions. Dryer antecedent conditions will require more rain to attain unstable conditions, and will keep the water table low, contributing to increase shear strength, soil suction and cohesion.

More abundant precipitation will result in increased river discharge that, in turn can result in increased erosion of the river banks, contributing to the removal of basal slope support and to increasing river bank instability. The instability of the river banks may propagate upslope or laterally, initiating new landslides or reactivating old, dormant landslides. River discharge has also effects on lakes and their shores. A higher discharge may result in higher lake levels and higher coastal water tables that, depending on the local conditions, may have contrasting effects, contributing to slope stability or instability. Where higher river discharge and higher water levels have seasonal components, they are expected to result in larger drawdown events, with enhanced drag forces that contribute to the instability of the coastal slopes (Pinyol et al., 2008; Barton, 2015).

An increase in rainfall intensity may result in higher infiltration (where the soil and bedrock allow it) and in an increased subsurface drainage and through flow, which will contribute to the build-up and to maintain perched water tables, the reduction of effective normal stresses and the shear strength, again contributing to slope instability. High rainfall rates are associated to soil piping (Jones, 2010), which is known to be related to soil erosion (Verachtert et al., 2011) and landslides (Uchida et al., 2001). Increased rainfall intensity may increase surface runoff (overland flow) and the related surface erosion processes, which in turn may facilitate debris flow initiation and enlargement (Hungr et al., 2005; Iverson et al., 2011). Conversely, a reduction in rainfall intensity lowers infiltration of water into the ground and reduces

Table 2
Potential slope stability responses to changes in climatic factors (modified after Crozier, 2010).

Change in climatic factor	Process affected	Effects on landslide response
Increased precipitation total	Wetter antecedent conditions Increased weight Higher water table for longer periods Increased river discharge	Less rainfall required to attain critical water content Reduction in soil suction and cohesion Increased shear stress Higher water table and reduction in shear strength Increased bulk density More frequent achievement of critical water content Increased bank erosion and removal of basal slope support Higher lake levels Higher coastal water tables Larger drawdown events and related drag forces
Increased rainfall intensity	Infiltration exceeds subsurface drainage Increased through flow Increased surface runoff	Build of perched water tables Reduction of effective normal stress Reduction in shear strength Increase seepage and drag forces Piping Increased surface erosion
Increase in air temperature	Higher evapotranspiration More abundant vegetation Higher hydraulic conductivity Rapid snowmelt Reduction in interstitial ice and permafrost	Reduction in antecedent water conditions More rainfall required to trigger landslides Higher evapotranspiration Reduced infiltration rate Higher root cohesion Higher infiltration Buildup of water tables, reduction of effective normal stress Higher runoff and infiltration Reduction in shear strength, reduction in cohesion in jointed rock masses Reduction in rock mass strength
Change in wind speed and duration	Enhanced evapotranspiration Enhanced root levering by trees Increased wave action on shorelines	Reduction in soil moisture Enhanced cracking, reduction of cohesion and soil strength Reduction of root cohesion Loosening and dislodging joint blocks Removal of slope lateral support
Change in weather systems	Areas previously unaffected (affected) subject to higher (lower) rainfall	Adjustment of slopes to changed weather conditions
Larger meteorological variability	More (less) frequent wetting and drying cycles	Increased fissuring Widening of joint systems Reduction of cohesion and rock mass friction

surface runoff, preventing excessive overland flow from entering cracks in the soil around the heads of landslides, and thus favouring stable conditions. An increase in rainfall intensity may also result in a change in the type of slope failures, with shallow failures (i.e., soil slips, debris flows, soil slides, rock falls) becoming more abundant (Chang and Chiang, 2011; Saez et al., 2013; Turkington et al., 2016) and deep-seated landslides becoming less active and less abundant in response to a higher rainfall rate (Comegna et al., 2013; Rianna et al., 2014).

Changes in rainfall intensity will require a re-evaluation of engineered slopes (Loveridge and Spink, 2010). Where rainfall intensity increases, the critical value of permeability increases, and the conditions of slopes at risk may change. Surface and sub-surface drainage systems designed for lower rainfall intensities may prove insufficient, and the excess water may take undesired and potentially dangerous paths, contributing in various ways to slope instability (e.g., surface and sub-surface erosion, build-up of the water table, piping).

The increase in air temperature can have contrasting consequences on slope stability. A higher air temperature will expand evapotranspiration on vegetated slopes (Senatore et al., 2011), producing positive effects on slope stability though a reduction of the antecedent water conditions (Collison et al., 2000; Comegna et al., 2013). Because of the increased evapotranspiration, a larger amount of rainfall is required to attain unstable conditions. Where snow fall occurs, a higher air temperature will favor snowmelt, and particularly rapid snowmelt (Cardinali et al., 2000), contributing to increasing surface runoff (that can foster soil erosion) and infiltration of water into the ground, to the build-up of pore water pressure, and to the reduction of the shear strength of the materials in the slopes. A warmer climate may increase the likelihood of rain-on-snow events (Guthrie et al., 2010), an often neglected component of hydrological slope-stability analysis. Harr (1981), working in western Oregon, USA, showed that 85% of all slope failures between 1958 and 1977 were related to rain-on-snow events, and that rain-on-snow produced a more rapid hydrological response of the watersheds. Guthrie et al. (2010) analyzed 626 debris flows in Vancouver Island, British Columbia, in the winter 2006–2007 and found that half of the debris flows were caused by rain-on-snow events.

In mountain regions and at high elevations, an increase in air temperature may result in the thawing of permafrost and in the reduction of interstitial ice in the rocks, which may result in a reduction in the shear strength of soil and rock masses, and of ice-filled rock discontinuities, at shallow depth, increasing the frequency of rock slope failures (Huggel et al., 2010, 2012, 2013; Stoffel et al., 2014; Chiarle et al., 2015; Ravanel and Deline, 2015; Paranunzio et al., 2016). Permafrost thaw in talus slopes may increase the frequency and magnitude of debris flows (Rist and Phillips, 2005). Glacier retreat due to increasing temperature may also result in more slope failures, since slopes are steepened or unloaded (Evans and Clague, 1994; Chiarle et al., 2007; Stoffel and Huggel, 2012). In places, a higher air temperature may also stimulate the grow of vegetation, which contributes to slope stability through the protection effects of trees and shrubs on precipitation, chiefly intense rainfall (Glade, 2003; Sidle and Ochiai, 2006), increased evapotranspiration, a reduced rate of infiltration, and a higher cohesion due to the strengthening effects of the roots in the ground (Sidle and Ochiai, 2006; Wu, 2013).

Changes in temperature and precipitation regimes may produce more frequent freezing-thawing or wetting-drying cycles, which may induce greater dry ravel and dry creep on steep, disturbed or partially vegetated hill slopes. Conversely, fewer cycles may reduce dry ravel and dry creep (Sidle and Ochiai, 2006; Imaizumi et al., 2015).

A change of speed and duration of wind may alter evapotranspiration and consequently soil moisture, thus affecting slope stability (Crozier, 2010). Increasing wind speed may increase the root levering by trees, resulting in cracks, loosening and dislodging rock blocks, favouring the initiation of rock falls and shallow debris landslides (Sidle and Ochiai, 2006). Wind has local effects of precipitation rates and snow melt. Guthrie et al. (2010) showed that wind caused increased concentrations of rainfall associated to landslide occurrence, and had an effect on snow-melting, substantially increasing the rate of melt in exposed (e.g., clear-cut) areas in Vancouver Island. Along the high costs of oceans, seas and large lakes, increasing wind speed and duration may change the characteristics of the waves in the water bodies (i.e., their height, length, frequency), contributing to augmenting the impact and the frequency of the damaging events (Katz and Mushkin, 2013). This will result in an increased instability of the costal slopes and in an acceleration of coastal landsliding (Barton, 2015).

Weather systems are expected to change in response to climate change, with wide-ranging impacts from the local to the continental scales (IPCC, 2014; Hatzianastassiou et al., 2016a, 2016b, and references therein). This may have contrasting effects on landslides (Crozier, 2010; Wood et al., 2016). Geographical areas previously unaffected by meteorological conditions prone to landslides (e.g., characterized by prolonged or intense rainfall, rapid snowmelt) may be altered, and they will have to respond and adjust to the new weather and meteorological conditions. In many areas, this may lead to more abundant and more frequent landslides. Contrariwise, areas where the meteorological conditions will become less prone to landslides may shift towards more stable slope conditions, and to experience less landslides.

3.2. Changes in landslide hazard

At the regional scale, we discuss the impact of climate and its variation on the distribution, abundance, frequency, and types of landslides, considering the influence of climate on landslide hazard. In a broad sense, ascertaining landslide hazard requires the joint assessment (or prediction) of "where" landslides will occur, "when" or how frequently they will occur, and "how large" or destructive they will be. Here, we use a probabilistic model for landslide hazard assessment (Guzzetti et al., 2005a), in which landslide hazard H_L is given by the joint probability of landslide size $p(A_L)$, of landslide occurrence in a given period $p(N_L)$, and of landslide spatial occurrence, S. The later (S) is known in the literature as landslide susceptibility (Guzzetti, 2006). In mathematical terms (Guzzetti et al., 2005a),

$$H_L = p(A_L) \times p(N_L) \times S. \tag{2}$$

We now treat separately the possible effects of climate and its variations on the three components of landslide hazard H_L, given in Eq. (2).

3.2.1. Changes in the probability of landslide size

For the probability of landslide area, $p(A_L)$ (Malamud et al., 2004), the information available indicates that the statistics (frequency, probability) of landslide area is not expected to vary significantly in a multi-decadal period (Guzzetti et al., 2005a, 2006; Galli et al., 2008). The expectation holds if the mechanical properties of the slope materials (and particularly cohesion) do not change in the considered period. Stark and Guzzetti (2009) have shown that the probability density function (*pdf*) of landslide area depends on the mechanical properties (i.e., cohesion, friction angle) of the slope materials. Thus, a change in the properties of the materials is expected to modify the shape of the $p(A_L)$, affecting the size of landslides that initiate. Brunetti et al. (2009) have argued that the type of failures conditions the *pdf* of landslide volume $p(V_L)$, which is known to be related to $p(A_L)$ (Guzzetti et al., 2009; Larsen and Montgomery, 2012). At this stage, no clear evidence exists on the amount of the possible changes in landslide hazard due to variations in the probability of landslide size. In some areas, human actions may also affect the statistics of landslide sizes (Van Den Eeckhaut et al., 2007), further complicating the evaluation of the climate-driven effects on the size component of landslide hazard.

3.2.2. Changes in the temporal probability of landslide occurrence

Investigating the temporal probability of landslides is a difficult and uncertain task (Crovelli, 2000; Coe et al., 2000; Rossi et al., 2010; Witt et al., 2010). Landslide frequency depends largely on the frequency of the triggers, including seismic, climatic/meteorological, and human-induced triggers, which are not simple (or are impossible) to determine. We maintain that in most areas, the frequency of seismic triggers will not change in the period considered by climate change modelling (i.e., decades to a century). However, the frequency of landslide events may change where large earthquakes occur. Lin et al. (2006) have shown that in Taiwan, after the 21 September 1999, Ms. 7.3 Chi-Chi earthquake, the rainfall conditions necessary for triggering landslides were less severe than before the earthquake. Forest fires are also expected to change the frequency of subsequent landslide events in the burnt areas. Cannon et al. (2001, 2011) and Moody et al. (2013) have shown that the rainfall amounts necessary to initiate shallow landslides in an area decrease after a wildfire, and that the effect is transient. Other natural hazards, including volcanic eruptions and the related seismic activity may also alter the frequency of landslides locally, and transiently.

Meteorological conditions will change in response to climate change (IPCC, 2014), with different and contrasting effects on landslide hazard. Domroes and Schaefer (2008) studied the occurrences of rainstorms from 1976 to 2000 in eastern China, a region controlled by a monsoon-type climate, and found an increasing trend of rainstorm occurrences related to an increase of mean annual and summer cumulated rainfall, particularly in the southern, subtropical part of the study area. Caloiero et al. (2008) studied the monthly frequency of short-duration rainfall events in Calabria, southern Italy, in the two periods 1921–1960 and 1961–2000, and found the events more frequent in November in the old period 1921–1960 and in October in the recent period, with a possible impact on the frequency of the landslide events, as found by Vennari et al. (2014) and Gariano et al. (2015a). Brunetti et al. (2012) examined variations in the cumulated annual rainfall in the same study area, from 1916 to 2006 and observed a marked decrease in the cumulated annual rainfall, particularly on the east side of the region linked to a general negative trend in the monthly total precipitation in the autumn-winter period. The changes may have an impact on the frequency of the landslide events. In Calabria, the temporal distribution of rainfall-induced landslides changed from 1921 to 2010. In the most recent period 1980–2010, landslides occurred mainly in winter and were triggered, on average, by a cumulated event rainfall lower than in the immediately preceding period 1951–1980 (Gariano et al., 2015a). Huggel et al. (2012) and Stoffel et al. (2014) showed that the frequency of occurrence of landslides has changed in the Alps, and Stoffel et al. (2014) outlined a change in the annual distribution of landslides (with more events in the early spring and fewer events in the autumn), and in the related triggering rainfall conditions (with landslides triggered chiefly by moderate rainfall events).

3.2.3. Changes in the spatial probability of landslide occurrence

For landslide hazard modelling, the landslide spatial occurrence S, is typically considered "invariant" (Guzzetti et al., 1999; Guzzetti et al., 2005a). As such, susceptibility should not be affected by climate variations. However, susceptibility depends on multiple local and regional terrain and environmental conditions, some of which are not expected to change in the time frame of a typical hazard assessment (i.e., a few to several decades) in response to climate drivers (e.g., topography, morphology, hydrology and lithology), whereas other factors (e.g., land use, land cover) are known or predicted to change in the same time frame (Falcucci et al., 2007; Santini and Valentini, 2011), as a direct or indirect effect of climate changes.

The idea that landslide susceptibility is "invariant" in time, at least in the range useful to hazard assessment (i.e., from decades to centuries) was challenged recently. Reichenbach et al. (2014), working in NE Sicily, southern Italy, found that landslide susceptibility had changed from 1954 to 2009 in response to land cover variations. Similar findings were obtained by Imaizumi et al. (2008). Samia et al. (2016), working in Umbria, central Italy, identified a short-term legacy (hereditary) effect of existing landslides on new landslides, with exiting landslides causing a greater susceptibility for follow-up landslides over a period of about ten years. Where (or if) susceptibility changes irrespectively of external drivers e.g., as a result of a landslide legacy effect, the evaluation of the climate-driven impact on susceptibility becomes even more complicated, and uncertain.

3.2.4. Additional hazard considerations

The definition of landslide hazard given in Eq. (2) assumes that the probabilities of landslide size, of temporal occurrence, and of spatial occurrence of landslides are independent (Guzzetti et al., 2005a). The legitimacy of this approach is difficult to prove in a landscape subject to a changing climate. The little available information suggests that the probability of landslide area $p(A_L)$ is as a first-approximation independent from the local physiographical setting (Malamud et al., 2004; Guzzetti et al., 2008), and from the rate of the events. Thus, we can expect that $p(A_L)$ is independent from susceptibility, S and from $p(N_L)$, in the time-frame of a climate projection (e.g., a century). Susceptibility models are typically constructed without considering the driving forces (e.g., meteorological, seismic) that control the rate of landslide occurrence. As a result, S is considered independent from the rate of the triggers.

4. Discussion

We focus the discussion on three main topics i.e., (i) advantages and limitations of the different approaches adopted in the literature to evaluate the effects of climate and its variations on landslides, including modelling problems related to the exploitation of GCMs and their climate projections for landslide-climate studies, (ii) expected changes in landslide activity, abundance and type in response to the projected climate changes, and on (iii) recommendations for the design and adoption of landslide adaptation and risk reduction strategies in the framework of a warming climate.

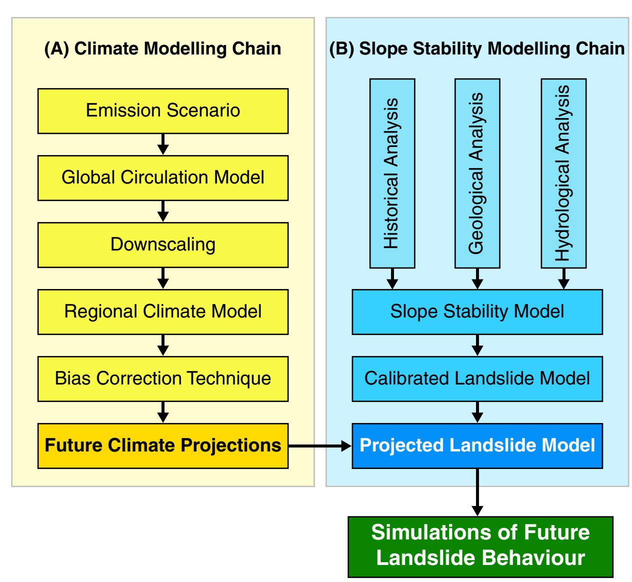

Fig. 7. Schematic landslide-climate modelling logical framework. (A) Climate modelling chain (modified after Rianna et al., 2014). (B) Slope stability modelling chain. See text for explanation.

4.1. Advantages and drawbacks of existing approaches

The different approaches used to evaluate the past, present, and future impacts of climate and its variations on landslides have inherent advantages and significant limitations that should be considered.

4.1.1. Evaluation of slope stability conditions using downscaled climate projections

Using climate projections obtained from downscaled GCMs for the evaluation of the future stability conditions of single slopes or landslides, or of large geographical areas or regional landscapes, relays on a modelling framework that consists of a climate and a slope stability component (Fig. 7). The climate component (Fig. 7A) exploits a chain of models to produce outputs from downscaled GCMs suited for landslide modelling, which represent the transient input for the slope stability modelling component (Fig. 7B). The prime advantage of using downscaled GCM outputs for slope stability modelling lays in the possibility of using the synthetic climate records of rainfall (and temperature) produced by the downscaled GCMs into existing and consolidated slope stability engineering, geomorphological, and hydrological modelling frameworks, and their associated software tools. Where synthetic rainfall and temperature records are available for the past (for calibration) and the future (for projections), it is straightforward – albeit often time-consuming and computationally intensive – to evaluate the effects of the climate variables on the slopes under investigation, and to construct scenarios that provide information on the expected/projected trend of the stability conditions.

For single slopes or landslides, the future average rate of movement, and the total displacement in a period can be predicted (Comegna et al., 2013; Rianna et al., 2014), allowing to determine if a landslide is expected to accelerate or decelerate, depending on the considered climate scenarios. In the case of populations of landslides, or multiple slopes in a catchment or landscape, a regional approach is required, and the downscaled climate variables are used as input to physically-based distributed models (Chang and Chiang, 2011), spatially distributed hydrological models (Ciabatta et al., 2016), or empirical threshold-based models (Jakob and Lambert, 2009), to evaluate the expected increase or decrease in the proportion of unstable areas, or in the probability of exceeding landslide occurrence thresholds.

The main drawback in the use of downscaled climate variables from GCMs for landslide-climate analyses lays in the uncertainty inherent to the downscaled climate projections (Crozier, 2010; Melchiorre and Frattini, 2012; Villani et al., 2015; Ciabatta et al., 2016). Early investigators who used initial versions of the GCMs and the downscaling techniques recognized the problem (Buma and Dehn, 1998, 2000; Dehn and Buma, 1999; Dehn, 1999; Dehn et al., 2000). Almost two decades of work have improved the GCMs and the downscaling approaches and techniques, but the problem of the significant epistemic (due to lack of knowledge) and aleatory (due to inherent natural variability) uncertainty remains. In a recent analysis of statistical downscaling methods and weather generators for site-specific landslide-climate modelling, Villani et al. (2015) recognized that the performances of the climate modelling chains (Fig. 7A) remain inadequate for the assessment of the effects of climate change on geo-hydrological hazards, at the slope scale. For regional-scale studies, the results are strongly dependent on the selection of the GCM, the downscaling methods, the weather generators (Ciabatta et al., 2016), and the adopted reference scenarios. The problem is not limited to landslides, and was studied extensively for floods, another climate-related hazard. Fowler et al. (2007); Kay et al. (2009), and Camici et al. (2014) concur that the selection of reasonable future scenarios, reliable GCMs, and effective downscaling techniques can produce larger uncertainty than the characterization of the physical variables controlling the hydrological processes.

For landslide-climate modelling, the selection of reasonable emission scenarios, reliable GCMs, and effective downscaling techniques is more relevant than the characterization and parametrization of the physical process that control the stability conditions of a single natural or engineered slope (Zollo et al., 2014; Ciabatta et al., 2016). Inadequate choices in the climate part (Fig. 7A) of the landslide-climate modelling framework may lead to an underestimation or overestimation of the landslide activity or abundance, without any real physical reason (Fowler et al., 2007).

In flood-climate modelling, different solutions were proposed to limit the propagation of the uncertainties inherent to the downscaled climate variables into the hydrological models, including e.g., using sophisticated non-stationary statistical approaches (Seidou et al., 2012a, 2012b) or bias-correction methods (Teutschbein and Seibert, 2012; Ahmed et al., 2013). However, Bloschl and Montanari (2010) have challenged the idea of using sophisticated modelling approaches, and argued that advanced attempt to minimize errors using complex multi-parameter models may increase the model uncertainty. For landslide-climate modelling, a way forward consists in the construction of "ensembles" of projections (Chang and Chiang, 2011; Melchiorre and Frattini, 2012; Zollo et al., 2014; Villani et al., 2015), always considering that climate projections are not, and cannot be used as forecasts (Bloschl and Montanari, 2010), and that the uncertainty in the models and their outputs needs always to be assessed and, where possible, reduced.

Fatichi et al. (2016) argued that a better knowledge of the relative contribution of anthropogenic forcing (scenario uncertainty), climate modelling (epistemic uncertainty), and internal climate variability (stochastic uncertainty) – the three main sources of uncertainty in climate-related studies – is essential to evaluate if the uncertainty can be reduced, or not. At the local scale, internal climate variability and model uncertainty are the dominant sources of uncertainty in projections of mean and extreme precipitation for short lead-times (a few decades), and for century-distant projections. Internal climate variability is independent of models and emission scenarios, and becomes less relevant for longer projections, because of stronger climate change signals. At the regional to global scales, scenario uncertainty is the primary source of uncertainty for air temperature projections. At these scales, projected changes in mean air temperature (and other climate variables) can be better constrained developing more accurate emission scenarios.

The second component of the landslide-climate modelling framework (Fig. 7B) consists of more or less sophisticated slope stability models commonly adopted in engineering geology, slope hydrology, or geomorphology to evaluate the stability conditions of natural or engineered slopes, or catchments. Selection of the stability model depends on the number and type of the landslides (e.g., deep-seated, shallow), the type and amount of information available to characterize the slope or landslide, and the extent of the study area (i.e., a single slope or landslide, a catchment, a large geographical region).

When the scope of the investigation is to determine the stability conditions of a single slope, the infinite-slope stability model is adopted chiefly for its simplicity of use and implementation in computer codes, even if it may fail to capture crucial details. All the processes and factors known to control or condition slope stability, including rainfall infiltration, rapid snowmelt, surface runoff, build-up of the water table(s), subsurface hydrology, evapotranspiration, the mechanical and hydrological effects of vegetation, and even the effects of engineering works (e.g., retaining structures, drainages) can be considered. More sophisticated 2D and 3D stress-stain modelling approaches can also be adopted, but are justified only where sufficient information (geological, mechanical, hydrological) is available, and where the problem is particularly relevant (e.g., in urban areas).

When the goal of the study is determining the stability conditions of entire catchments, large geographical areas or many slopes and populations of landslides, spatially-distributed modelling approaches are used, including physically-based (Chang and Chiang, 2011), statistical, or empirical threshold-based (Jakob and Lambert, 2009) models. Modern physically-based modelling approaches (Baum et al., 2008; Simoni et al., 2008; Milledge et al., 2014; Anagnostopoulos et al., 2015; Bellugi et al., 2015, 2016; Alvioli and Baum, 2016) extend spatially the local slope stability models, and are very promising for catchment-scale landslide-climate modelling. Their main limitations consist in (i) the large amount and detail of the distributed, surface, and sub-surface information required to properly inform the models, and (ii) the computer resources needed to run the models. The latter may not represent a severe problem anymore, as parallel versions of existing and new computer codes are becoming available (Anagnostopoulos et al., 2015; Alvioli and Baum, 2016). However, the quantity of thematic (e.g., topographic, geological, hydrological) information needed for catchment-scale, spatially-distributed, physically-based stability modelling remains (and is expected to remain) a challenge.

At the catchment and regional/physiographic scales, an alternative approach consists in exploiting hydrological (Ciabatta et al., 2016) or threshold-based, empirical approaches (Jakob and Lambert, 2009). These approaches exploit catalogues of rainfall (Guzzetti et al., 2007; Guzzetti et al., 2008) or hydrological (Reichenbach et al., 1998) events that have resulted in landslides, and attempt to identify temporal variations, including e.g., seasonal variations in the occurrence of landslides (Peruccacci et al., 2012; Vennari et al., 2014; Gariano et al., 2015b). Problems with the approach include (i) the completeness or representativeness of the empirical information (Guzzetti et al., 2007; Guzzetti et al., 2008), (ii) the methods used for the identification of the thresholds (Brunetti et al., 2010; Peruccacci et al., 2012), (iii) the difficulty in establishing thresholds for a single landslide type, and (iv) the fact that multiple factors influenced by climate variations – including meteorological, environmental, and human-induced factors – directly or indirectly control landslide occurrence, and that it may be difficult (or impossible) to separate the effects and role of the different factors.

When predicting changes in the stability conditions of entire catchments or large geographical areas, an additional problem is that climate variations may change, directly or indirectly, the prevalent landslide type. Landslide-climate models constructed and calibrated for a specific predominant landslide type (e.g., deep-seated, slow moving slides) may not work where, in response to climate variations, the predominant landslide type will change (e.g., to shallow, fast-moving soil slides). In this case, the model will provide misleading projections of the landslide activity and abundance.

The applicability of the landslide-climate modelling framework to engineered slopes is useful for local risk assessments, for planning maintenance, and to decide if the planned or existing mitigation measures will prove effective and resilient to the projected climate changes, under different emission scenarios. When a climate modelling chain is calibrated in a specific site or geographical area, it can be used at different neighbouring sites or areas, allowing for comparisons. However, the possibility to export the modelling results depends on the representativeness of the model, which is difficult to decide.

4.1.2. Analysis of landslide and climate records

Joint analysis of past climate and landslide records aims at establishing empirical relationships (or the lack of a relationship e.g., Flageollet et al., 1999; Rossi et al., 2010; Chiarle et al., 2015) amongst time series of triggers (e.g., rainfall, temperature, snowmelt) and of landslide occurrences. A historical landslide time series can be regarded as a Marked Point Process i.e., a random element whose values are "point patterns" on a mathematical set (Last and Brandt, 1995), and analyzed in conjunction with a corresponding rainfall record to search for correlations between landslide events and the rainfall record (Rossi et al., 2010; Witt et al., 2010; Gariano et al., 2015a). The advantage of the approach consists in its (apparent) simplicity. In many areas, meteorological or climate records are now available for several decades, and locally for centuries. Compiling catalogues of recent and historical landslide events may be tedious and time consuming (although digital technologies are making the task simpler and faster), but it is not difficult, technologically demanding, or expensive.

Global catalogues of landslides exist (Petley, 2012; Kirschbaum, 2014; Guha-Sapir et al., 2015; Munich RE, 2016), but they focus primarily on major catastrophic events, and are known to be incomplete for small, non-catastrophic events, limiting their use for landslide-climate studies. Several national and regional landslide catalogues and databases are also available (e.g., Guzzetti et al., 1994; Guzzetti and Tonelli, 2004; Devoli et al., 2007; Damm and Klose, 2014; Zêzere et al., 2014; Taylor et al., 2015), and their number, quality and completeness continue to increase. Although more work needs to be done to compile and organize information on landslide events and their consequences (Van Den Eeckhaut and Hervás, 2012), systematic analysis of the existing catalogues opens to the possibility for innovative landslide-climate studies.

The major limitation of the approach lays in the well-known inherent incompleteness of non-instrumental historical records of natural events, including landslides (Guzzetti, 2000; Benito et al., 2004). The incompleteness of a landslide time series depends on many factors, including the types of information sources, the techniques used to search the sources, and the geographical, environmental, historical, and societal characteristics of the study area. Regardless of the causes, incompleteness introduces a bias in the time series. What is worse is that the level of incompleteness (i.e., the amount of the missing information) is generally unknown, and it varies along the time series, being usually larger in the older parts of the record. This limits the possibility to analyze landslide time series with standard statistical methods that assume that the record is complete, and free of biases.

To be able to analyze statistically landslide time series, the series needs to contain a reasonable number of events, and to cover a significant period (multiple decades). For practical purposes, landslide time series are typically constructed for large geographical areas, favouring space for time. However, if the study of a large area increases the number of records, it may also introduce a larger climate and environmental variability. Lastly, when interpreting the results of correlations, it should always be clear that "correlation does not imply causation" (Spearman, 1904; Aldrich, 1995; Spiegelman, 2010).

4.1.3. Analysis of paleo landslide evidences

The approach is used typically to investigate long periods, spanning thousands of years (Fig. 4, Table 1), and has several known challenges (Crozier, 2010). First, accurate dating of a landslide is not trivial. It depends on the age of the landside, that controls the type and accuracy of the dating method (Lang et al., 1999), the type and size of the landslide, and the location and the materials involved by the landslide. A second challenge lays in the reconstruction of a sufficiently long and accurate record of landslide paleo-evidences, which depends on the number of datable landslides and on the size of the study area. A larger area may have more datable landslides, at the expense of a possible larger climate and environmental variability that conditions the significance of the results, producing a higher aleatory uncertainty. A third challenge is in the difficulty (and often the impossibility) to identify the exact landslide triggers, and to separate landslides caused by meteorological triggers or climate drivers, from landslides caused by the indirect effects of climate variations (e.g., land cover or land use changes, forest harvesting and other human actions, Innes, 1983, 1985; Glade, 1998, 2003; van Beek, 2002; Imaizumi et al., 2008; Lonigro et al., 2015), from other landslides caused by non-meteorological/climatic triggers (e.g., earthquakes). Lastly, there exists a clear limitation inherent to working with processes, variables and data characterized by a large natural (aleatory) variability and epistemic uncertainty.

4.2. Expected changes in landslide activity, abundance and type

A few attempts exist at global landslide hazard or risk assessments. Nadim et al. (2006, 2013) proposed a global hotspot landslide hazard zonation map, and Petley (2012) showed the global distribution of 2620 non-seismically triggered fatal landslides between 2004 and

2010. The two maps show common clusters of moderate to very high hazard areas and fatal landslide sites, chiefly in the main mountain ranges, including the Himalayas, the Alps, and the American Cordillera. In both maps, Asia is the most landslide-prone continent.

In the global landslide hazard map (Fig. 7 of Nadim et al., 2006) areas of moderate to very high landslide hazard are identified in Central and Western America, the Caucasus, the Middle-East, the Himalayas, Southeast Asia, Italy, and Japan. Conversely, Europe (except for the Alps, Apennines and the Dinarides), Africa (except part of the East Africa's Rift Valley) and Oceania (except New Zealand), are considered having a negligible to very low level of hazard. In his Fig. 5, Petley (2012) showed large numbers of fatal landslides in the Himalayas, China, Southeast Asia, Central America, and northwestern South America. Fatal landslides are reported in Africa and Europe, in areas considered at negligible to very low landslide hazard by Nadim et al. (2006, 2013), whereas they appear under-represented in south America, possibly due to lack of information.

Not surprisingly, the geographical pattern of the fatal landslides, and of the hazardous landslide areas, depends largely on relief, precipitation, and the distribution and abundance of the population. Precipitation (directly) and the distribution and abundance of the population (indirectly) are affected by climate and its variations, and may influence the geographical pattern of landslide hazard and of fatal landslides.

Globally, the average surface temperature is projected to increase in many regions under all emission scenarios (IPCC, 2014) (Fig. 8A). The increase is the highest under the worst-case RCP8.5 scenario (in terms of projected CO_2 emissions), and it is projected to be more significant in the northern hemisphere, but also distinct in northern Africa, southern Africa, and central South America. Changes in the surface temperature are expected to influence precipitation, with mean precipitation projected to increase significantly (more significantly under the RCP8.5 scenario) at high latitudes, in mid-latitude wet regions, and in parts of the equatorial regions and of the northern tropical areas of Africa and the Arabic peninsula (Fig. 8A, B). In many areas, it is anticipated that extreme precipitation events will become more intense and frequent. Conversely, the mean precipitation is likely to decrease (more significantly under the RCP8.5 scenario) in mid-latitude and subtropical dry regions, in Central America, in the Mediterranean area, and in the southern regions of Africa and South America (Fig. 8B).

The projected increase in surface temperature is expected to result in more intense and frequent rainfall events. In particular, "extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will *very likely* become more intense and more frequent" (IPCC, 2014). In addition, there is a "*high confidence* that changes in heavy precipitation will affect landslides in some regions" (Seneviratne et al., 2012). Where the frequency and/or the intensity of the rainstorms will increase, shallow landslides, including rock falls, debris flows and debris avalanches, and also ice falls and snow avalanches in high mountain areas, are also expected to increase (Stoffel et al., 2014). These areas include the Alps, the Himalayas and most of the American Cordillera, but also the Atlas Mountains in northwestern Africa, mountains and hills in southwestern Africa, the East Africa's Rift Valley and the Arabian Peninsula, the Carpathians in Eastern Europe, the Appalachians in eastern North America (Fig. 9). According to Seneviratne et al. (2012), there is "*low confidence* regarding future locations and timing of large rock avalanches, as these depend on local geological conditions and other non-climatic factors". Given the high vulnerability of individuals and communities to shallow landslides – which often are very to extremely rapid (Cruden and Varnes, 1996) – we expect that in these areas landslide risk to the population will increase in absence of adequate mitigation measures or adaptation strategies (Sidle and Burt, 2012), including e.g., local or regional landslide early warning systems (Stähli et al., 2015).

In the same general areas, the degree of activity and the occurrences of new deep-seated landslides are expected to decrease (Malet et al., 2005; Coe, 2012; Comegna et al., 2013; Rianna et al., 2014) (Fig. 9). Extremely to moderately slow deep-seated landslides (including e.g., earthflows, mudflows, complex and compound slides) generally

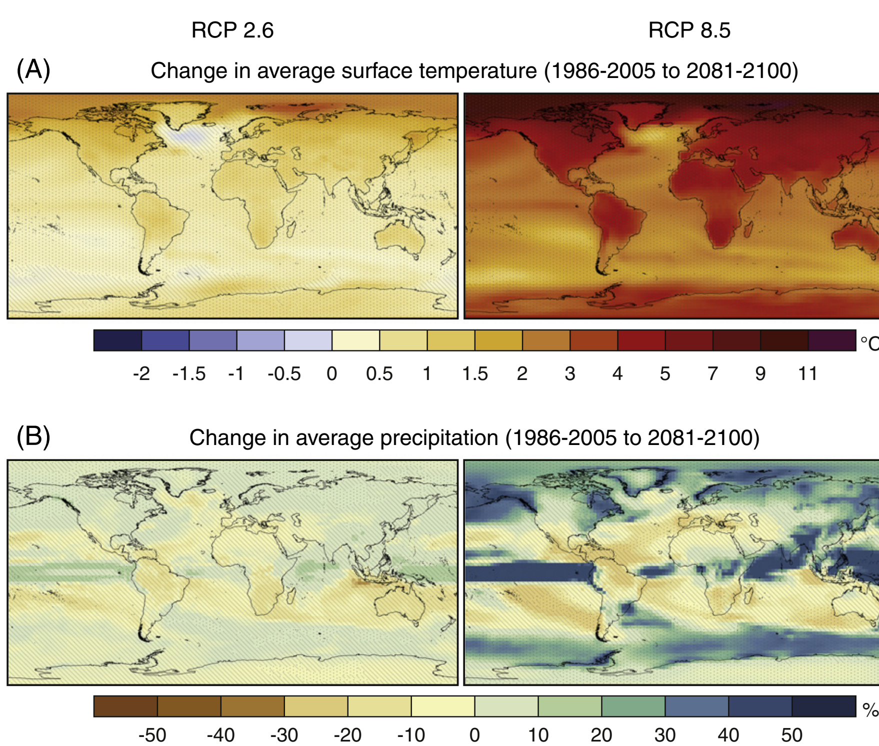

Fig. 8. Maps show projected climate variations in (A) average annual surface temperature (°C), and (B) average annual precipitation (percentage), based on multi-model mean projections for 2081–2100, relative to 1986–2005, under the RCP2.6 (left) and the RCP8.5 (right) scenarios. Dotted pattern shows regions where the projected change is large compared to natural internal variability, and where at least 90% of models agree on the sign of change. Oblique line pattern shows regions where projected change is less than one standard deviation of natural internal variability. Modified after IPCC (2014).

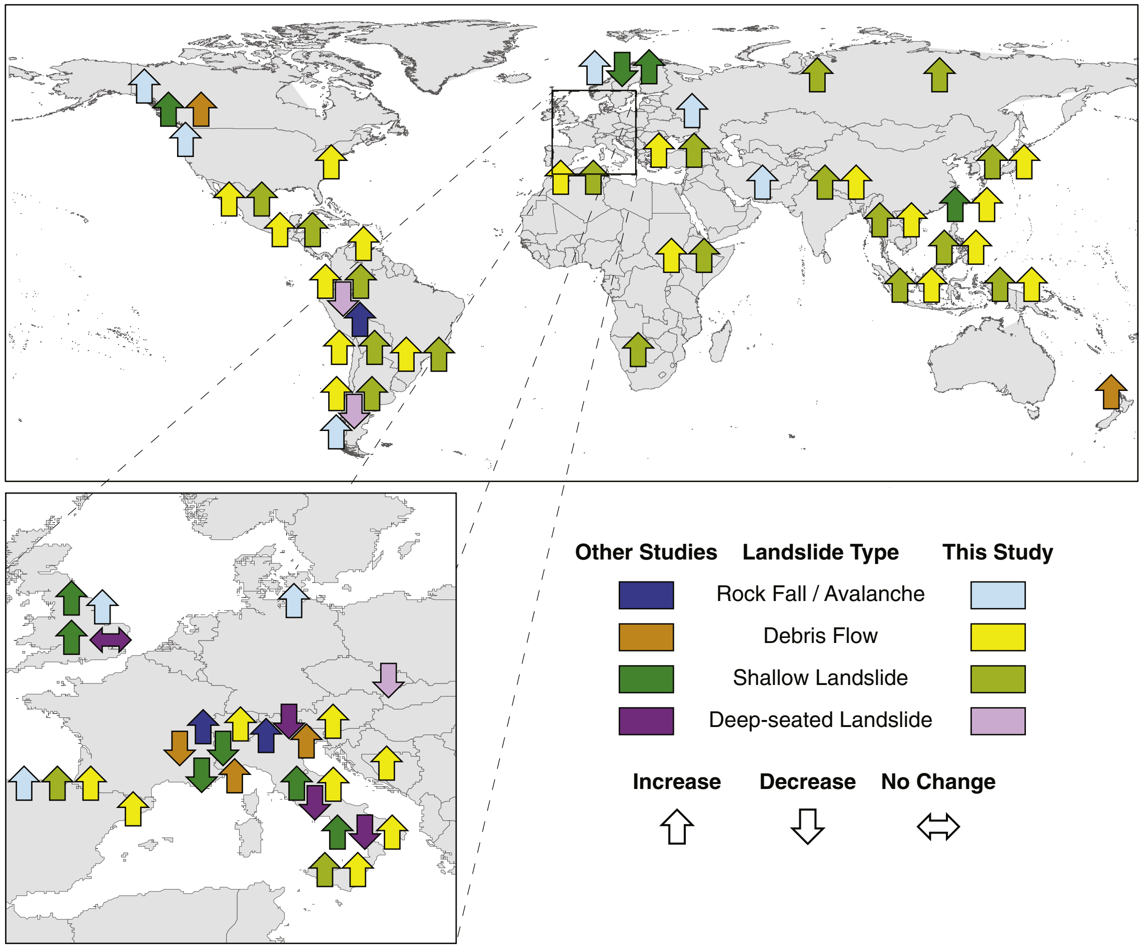

Fig. 9. Map shows general areas of expected variations in the abundance or activity of four landslide types, driven by the projected climate change. Dark colours are projections from the literature and light colours are projections from this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

do not pose a serious threat to human life. Hence, their predicted reduced activity will not decrease landslide risk to the population significantly, but it is expected to contribute to reducing landslide impact and the related economic damage.

The projected increase in air temperature is also expected to affect the stability of rock slopes at high latitudes (particularly in the northern hemisphere, Fig. 8A) and at high elevations, where permafrost exists and may be reduced by the increased temperature (Huggel et al., 2012, 2013; Stoffel et al., 2014; Chiarle et al., 2015; Ravanel and Deline, 2015; Paranunzio et al., 2016). According to IPCC, there is a "*high confidence* that changes in temperature, glacial retreat, and/or permafrost degradation will affect slope instabilities in high mountains, and *medium confidence* that temperature-related changes will influence bedrock stability" (Seneviratne et al., 2012). In high mountain areas, not only small-sized rock falls and ice falls, but also large rock slides and rock avalanches may become more abundant (Fig. 9), and instability conditions initiated locally by variations in the air temperature can evolve independently of the climate drivers (Huggel et al., 2012, 2013), extending the temporal legacy of the climate drivers. At high latitudes, particularly in the taiga and tundra areas in the northern hemisphere, permafrost melting can initiate ground instability processes even in low gradient terrain, producing incised gullies that transform rapidly into wide badland areas.

Finally, variations in the air temperature are expected to change the geographical location of areas affected by snowfall, the frequency of snowfall events, the depth of the snow pack, and the time required for the snow to melt. They will also change the frequency of rain-on-snow events. Rapid snowmelt and rain-on-snow events are known triggers of landslides, that will change in frequency and efficacy where the air temperature changes. There is "*medium confidence* that high-mountain debris flows will begin earlier in the year because of earlier snowmelt, and that continued mountain permafrost degradation and glacier retreat will further decrease the stability of rock slopes" (Seneviratne et al., 2012).

Annual mean precipitation is projected to increase at the high latitudes and in the equatorial Pacific, under the RCP8.5 scenario (Fig. 8B) (IPCC, 2014). In these areas, and particularly in mountainous and hilly terrains, deep-seated landslides, rock slides, earthflows, and mudflows are expected to occur more frequently, or to increase their seasonal activity (Jakob and Lambert, 2009; Chang and Chiang, 2011). In North America, the annual precipitation is expected to increase in the north and to decrease in the south, with opposite consequences on climate-related landslide occurrences (Jakob and Lambert, 2009; Coe, 2012). Here, an increase in the frequency of shallow landslides and debris flows (Jakob and Lambert, 2009), and a reduction in the activity of rainfall triggered deep-seated landslides, or a deceleration in their displacements (Coe, 2012), are expected (Fig. 9).

In places, including e.g., the southern European Alps, the mean annual precipitation is projected to remain constant, but concentrated in a fewer number of rainy days, resulting in more intense rainfall events (IPCC, 2014). We anticipate that this will result in more frequent shallow landslides (Saez et al., 2013; Stoffel et al., 2014), and in less frequent deep-seated failures (Malet et al., 2005; Comegna et al., 2013; Rianna et al., 2014) (Fig. 9). In these areas, a variation in the number of the rainy days may change the precipitation regime, resulting in a variation in the temporal distribution of rainfall-induced landslides and debris flows. Nikolopoulos et al. (2015) found a strong N—S separation in the seasonal distribution of debris flows in Trentino–Alto Adige, eastern Italian Alps. In the northern part of their study area, characterized by abundant snowfall and less rainfall, debris flows occur mostly in summer, whereas in the southern and rainier part of the study area most of the events occur in autumn. This spatial and temporal distribution of debris flows may change due to variations in the seasonality of the rainy days. In the same areas, the climate models predict a higher air temperature, which will favor evapotranspiration, reducing the amount of water in the sub-surface, and increasing slope stability.

It should also be considered that in many areas, global warming will have an impact on land use and land cover, on agricultural and forestry practices, and on the economy. These changes may also change the activity and the rate of occurrence of landslides, and hence landslide hazard and risk (van Beek, 2002; Wasowski et al., 2010; Lonigro et al., 2015). There is currently "*low confidence* in projections of an anthropogenic effect on phenomena such as shallow landslides in temperate and tropical regions, because these are strongly influenced by human activities such as poor land use practices, deforestation, and overgrazing" (Seneviratne et al., 2012). In the central Apennines of Italy, and in similar areas in the Mediterranean region, the expected increase in rainfall intensity, coupled with a general lack of maintenance of old debris flow controlling structures, may increase the frequency of large debris flow events with catastrophic consequences in areas that are currently considered at low to moderate landslide risk (Fig. 9). In regions of SE Asia – and elsewhere – where in response to climate and economic drivers, forests are cut (e.g., to obtain wood or agricultural land) or the forest cover is converted (e.g., from native vegetation to oil palms), landslide activity and the frequency of landslide occurrences are expected to increase of an amount that is difficult to predict, and even to model. In these cases, land cover change has a greater influence on landslides than climate change (Sidle et al., 2006). Finally, in fast urbanizing areas, and particularly where demographic, societal and economic stresses are expected high or rising, we should expect an increase in the number of failures, of both natural and engineered slopes.

4.3. Recommendations for adaptation and risk reduction strategies

A number of countries have designed, and some are implementing climate adaptation strategies. A thorough review of the strategies is beyond the scope of this work, but an unsystematic analysis of the strategies and of the related preparatory and accompanying documents, revealed that only a few countries have considered landslides in their strategies (Table 3), typically in association with other hazards (e.g., flood, erosion, subsidence, drought). Swart et al. (2009) in a comparison of climate adaptation strategies in European countries concluded that landslides are an increasing risk in Europe. Yet, adaptation strategies in Europe (and elsewhere) are not clear or specific on the actions required to limit landslides and to reduce landslide risk.

Table 3
Partial list of countries that consider landslides (natural or human induced) in their climate change adaptation strategies, or in related preparatory and accompanying reports.

Country	Continent	Year	Reference
Finland	EU	2005	Finland's Ministry of Agriculture and Forestry (2005)
France	EU	2007	Observatoire national sur les effets du réchauffement climatique (2007)
Denmark	EU	2008	Danish Government (2008)
Germany	EU	2008	German Federal Government (2008)
Seychelles	AF	2009	Seychelles National Climate Change Committee (2009)
Belgium	EU	2010	Belgian National Climate Commission (2010)
Japan	AS	2010	Government of Japan (2010)
Kenya	AF	2010	Government of Kenya (2010)
Malta	EU	2010	Government of Malta, Climate Change Committee for Adaptation (2010)
Switzerland	EU	2012	Götz et al. (2012)
Tanzania	AF	2012	United Republic of Tanzania (2012)
United Kingdom	EU	2012	UK Government (2012)
Mexico	AM	2013	Federal Government of Mexico (2013)
Canada	AM	2014	Lemmen et al. (2008); Warren and Lemmen (2014)
Italy	EU	2014	Castellari et al. (2014a, 2014b)
Australia	OC	2015	Australian Government (2015)

It is accepted that effective risk reduction requires a mix of mitigation efforts and adaptation strategies acting at different temporal and geographical scales, and adopting an ensemble of structural and non-structural measures. Structural ("hard") measures imply the construction of physical defenses (e.g., walls, piles, drainages, retaining basins), which are designed considering the type and size (magnitude) of the expected hazard (e.g., a landslide) and a reference return period for the design (expected) hazardous event. Most commonly, the return period, or the expected frequency of the event, are determined assuming a stationary time series of events (i.e., a landslide record) or of triggers (i.e., a record of rainfall or snowmelt events). In the framework of a changing climate, the stationary hypothesis may not be valid (Milly et al., 2008), and other approaches are needed for the design of engineered structures (Pauling and Pauleth, 2007; Cheng and AghaKouchak, 2014). We recommend that the design of structural measures adopts a pragmatic, problem solving approach, profiting from experience (historical records), existing and new information (monitoring), and modern modelling and computational means (Montanari and Koutsoyiannis, 2014). It is equally important that the uncertainties inherent in the historical records, monitoring data, and modelling tools are considered.

Existing single (e.g., a retaining wall, a check dam, a drainage) or multiple (e.g., a system of retaining barriers or a set of drainages in a slope, a set of check dams in a catchment) defensive structures may require modifications to adapt to the new, predicted climate conditions. For single landslides and for marginally stable engineered slopes (Loveridge and Spink, 2010), surface and deep drainages may prove insufficient or may become ineffective, resulting in unpredicted instability conditions. Defensive structures may have been designed for a specific type of failure (e.g., a slow moving deep-seated landslide) and as a result of a change in climate, a different type of landslide may be triggered (e.g., a very rapid soil slip – debris flow). In this case, the presence of structural defensive measures gives a false sense of safety (Sidle and Chigira, 2004). We recommend that all structural slope defensive measures are checked to evaluate their efficacy in the new or predicted climate conditions.

In the central Apennines of Italy, between 1930 and 1960, complex systems of check dams were installed and catchments were reforested to reduce torrential phenomena and debris flow events. The combined effect of the containment capacity of the check dams and the lowered erosion capacity of rainfall produced by the forest cover, has reduced the frequency and intensity of the debris flow events (Guzzetti and Cardinali, 1991). Today, the check dams are filled by large quantities of materials, and most of the forests are not, or are poorly maintained. An increase in rainfall intensity, or in the number of intense rainfall events, may reactivate the debris flows causing the collapse of single or multiple check dams, with potentially catastrophic domino effects that can mobilize volumes of material larger than historically recorded. Lack of maintenance of the forest worsen the situation, increasing the potential magnitude of the debris flows. The long-term, basin-scale effort conducted between 1930 and 1960 to mitigate the debris flow hazard is in jeopardy due to the predicted climate changes in this area. The efficacy of the entire defensive system provided by the sets of check dams and the forest should be evaluated considering the projected climate conditions, and their meteorological and environmental consequences. Similar situations are found in other parts of the Apennines, in the Italian Alps, and elsewhere in the Mediterranean area and in Japan.

Non-structural ("soft") measures exploit practices and policies on information, dissemination, and education, avoiding physical constructions. A number of soft measures can prove cost-effective against landslide risk, including sustainable land management, and forest harvesting. However, long-term land planning frequently does not consider climate change and the related environmental and societal consequences. In Italy, River Basin Authorities have prepared basin-scale, landslide (and flood) hazard and risk assessment and management plans (PAI, an Italian acronym for River Basin Management Plan) largely ignoring the effects of the predicted climate and environmental changes. This limits the future effectiveness of the plans that may even be counterproductive. In places, the plans ignore or underestimate the risk posed by specific landslide types and particularly the types that are expected to increase in response to the predicted climate changes (e.g., very to extremely rapid soil slips and debris flows). In these areas, mitigation actions and adaptation strategies based on the existing risk assessments may be misleading, inadequate, or incorrect. The problem is not limited to the Italian PAI, and we recommend that wherever existing plans should be re-evaluated, and new plans should consider the expected direct and indirect effects of climate and environmental changes.

Landslide monitoring and early warning systems (Stähli et al., 2015) are a different type of effective non-structural defensive measure that can greatly reduce landslide risk, and particularly the risk to the population. However, existing systems often rely on information and models (i.e., rainfall, discharge, soil-moisture, displacement or velocity thresholds) that typically do not consider the predicted future climate or environmental changes. For systems based on rainfall thresholds, it is unclear how to scale or transfer a threshold established in a climate zone to a different and distant climate zone (Guzzetti et al., 2007, 2008). We recommend that empirical rainfall thresholds for possible landslide occurrence used for early warning are based on rainfall information measured by the same (or a similar) network of rain gauges used to prepare the landslide forecasts, and rely on landslide information and rainfall measurements taken in the same (or similar) climate and environmental conditions. Similar recommendations apply to other types of measurements and thresholds.

The ability of the existing networks of meteo-hydrological sensors to measure variables relevant to landslide early warning may be reduced where the effects of climate change will be more rapid. In places, the networks (i) have an insufficient density of stations at elevated areas, and in small and remote catchments (Borga et al., 2008), (ii) do not measure accurately high intensity rainfall, a primary trigger of soil slips and debris flows (Borga et al., 2014), (iii) may be blind to snowfall and subsequent snowmelt or rain-on-snow events (other triggers of landslides) particularly at lower elevations, and typically (iv) do not measure soil moisture and pore water in the ground, which are useful to know for shallow landslide modelling and early warning. Some of these limitations may be (partially) addressed by modern weather radar systems (Borga et al., 2008, 2014; Peleg et al., 2013; Marra et al., 2014; Penna et al., 2014) and ensembles of limited area numerical weather prediction models (Collier, 2007; Alfieri et al., 2014; Borga et al., 2014), where they are available. We recommend that the on-setting and predicted meteorological variations due to climate change are considered in the design and the operation of landslide early warning systems, and that the systems are adjusted periodically considering the changing climate.

Overall, considering that global warming will increase the frequency of the intense rainfall events, and will modify – and in several case, extend – the areas subject to rapid-moving shallow landslides triggered by intense rainfall, a particularly lethal type of landslide (Guzzetti et al., 2005b), we anticipate that the number of people exposed to landslide risk will increase. However, when considering the direct impact of landslide on the population (Fell and Hartford, 1997; Guzzetti, 2000; Gariano et al., 2015a), one must consider that landslide risk results from multiple factors with contrasting effects and feedbacks, including the type, abundance, distribution and frequency of the landslides, and

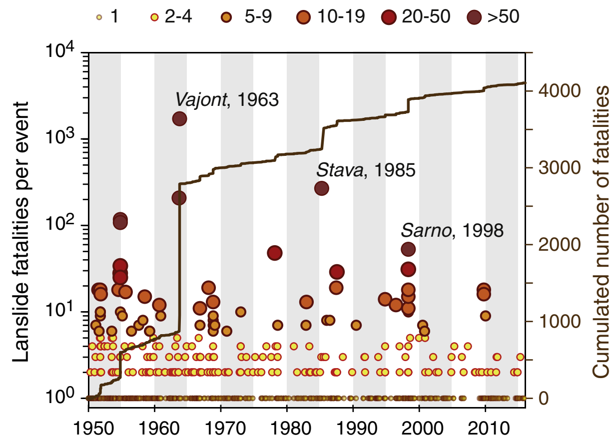

Fig. 10. Temporal distribution of fatal landslides in Italy between 1950 and 2015 with an indication of the magnitude of the events, measured by the number of fatalities (dead and missing persons), shown in six classes. The place and year of the three largest events is given.
Source: http://polaris.irpi.cnr.it.

the abundance and distribution of the population. Both types of factors are influenced by climate and its variations.

Fig. 10 shows the distribution and magnitude of fatal landslides in Italy from 1950 to 2015, a period in which 661 fatal landslides have caused 4105 fatalities, including 1910 estimated fatalities caused by the Vajont landslide (9 October 1963), the most destructive slope failure in Europe in historic time. In the same period, the population has increased from 47 million (1950) to 59 million (2015), the climate has changed, with a reduced number of wet days balanced by an increase in the intensity of the rainfall events (Brunetti et al., 2001), and more than half of the Italian territory has changed land use, with an acceleration of the changes in the last decades (Falcucci et al., 2007). Inspection of Fig. 10 reveals that whereas the frequency of the low magnitude events (with one or two fatalities) has remained unchanged, the magnitude of the most destructive events has decreased in the observation period. This is the result of a mix of natural (including climate conditions) and societal causes. We argue that the reduced magnitude of the most destructive events is due largely to the increased availability of information, and to improved monitoring and warning systems.

5. Conclusions

"Warming of the climate system is unequivocal" (IPCC, 2014), and climate change can affect landslides and the stability of natural and engineered slopes (Seneviratne et al., 2012). The majority (80%) of the papers that we have examined found causal relationships between landslides and climate change. Climate and landslides operate at different geographical and temporal scales (Fig. 6), and reconciling the different scales is difficult, and remains uncertain. The type, extent, magnitude, and direction of the changes in the stability conditions of the slopes, and on the location, abundance and frequency of the landslides, are not completely clear. The effects of the warming climate on landslide risk, and particularly the risk to the population, also remain difficult to quantify.

Our analysis of the literature, and our understanding of how climate factors condition slope stability and landslide hazard, allows for the following considerations and recommendations.

There is a clear geographical bias in the existing landslide-climate studies (Fig. 2). Large parts of the world remain poorly investigated, or not investigated at all, and particularly in the regions where the impact of the changing climate on landslides and slope stability is expected to be more severe, or widespread. Even in countries for which studies are abundant, the studies are distributed unevenly and in a few hotspot areas e.g., the Ubaye Valley and the Barcelonnette area in France, or the Dolomites in Italy. We recommend that more landslide-climate studies are completed, and particularly where a few studies exist i.e., in Asia, South America, and Africa.

The current landslide-climate modelling capabilities, based on a complex framework that exploits downscaled climate variables in more or less sophisticated (physically-based/empirical) slope stability models (Fig. 7), remain limited. Each component of the landslide-climate modelling chain can – and should – be improved, but significant epistemic and aleatory uncertainties are expected to persist (Crozier, 2010; Melchiorre and Frattini, 2012; Fatichi et al., 2016). The uncertainties will percolate through the modelling chain affecting the landslide-climate projections. Some of the uncertainties are larger than others, or have a greater role in determining the landslide-climate predictions, or scenarios (Coe and Godt, 2012). Adopting a pragmatic approach (Bloschl and Montanari, 2010), we maintain that uncertainties must be (i) determined and quantified, as much as possible, (ii) considered, when using the projections, and (iii) communicated, to decision makers and the public.

The slope stability models used to predict the effects of climate change on landslides (Fig. 7) at different geographical scales ignore that climate records are typically not stationary (Milly et al., 2008), the time dependence of the landslide events (Rossi et al., 2010; Witt et al., 2010), and the effects of specific triggers and their magnitude on future landslides. Models further assume that susceptibility is time invariant, and ignore the hereditary effects of old landslides on new landslides (Samia et al., 2016). These limitations may jeopardize the landslide predictions. We recommend to construct new slope stability models capable of cope with non-stationary climate and landslide records, and of considering the time dependence of the events. We also recommend that temporal variations in landslide susceptibility driven by climate and environmental changes are investigated (Reichenbach et al., 2014) to determine their sign and magnitude, and their effects on the landslide projections.

Although the trends foreseen by modern climate modelling are unambiguous (IPCC, 2014), the details of the projections vary depending on the severity of the emission scenarios. A number of authors have recognized that selection of reasonable scenarios, together with reliable GCMs and effective downscaling techniques, affects significantly the landslide-climate projections (Dehn et al., 2000; Melchiorre and Frattini, 2012; Villani et al., 2015), and is more relevant than the selection of the slope stability model and its parametrization (Zollo et al., 2014). For landslide-climate studies, we recommend to select a range of emissions scenarios and to construct ensembles of projections (Zollo et al., 2014; Villani et al., 2015), although this may be time consuming and resource intensive. We also recommend to use with caution results obtained adopting catastrophic scenarios. Catastrophic scenarios will have larger impacts on all climate variables, making the landslide-climate projections more uncertain, and may produce unrealistic overestimations or underestimations of the landslide activity, or abundance (Fowler et al., 2007). We further suggest working in areas with long-term past climate records, which should be used to calibrate the downscaled GCM projections.

Most of the physically-based landslide-climate modelling efforts have focused on individual landslides (Crozier, 2010; Coe and Godt, 2012; Comegna et al., 2013). Empirical and/or statistical approaches have also focused on relatively small geographical areas encompassing a few tens to a few thousand square kilometers (Jakob and Lambert, 2009; Jomelli et al., 2009) (Table 1). We argue that there is a need for more, and better regional to global assessments of the projected impacts of climate change on landslide activity, abundance, and types. With this respect, our Fig. 9 should be regarded as preliminary, and a first attempt to tackle the problem.

Regardless of the drivers and the specific trigger, where a new landslide occurs the soil and rock in the slope degrade from peak to residual strength conditions. This is typically an unrecoverable effect in the range from years to decades, characteristic of landslide-climate analyses. Where, in direct or indirect response to climate variations, new landslides form or dormant landslides are reactivated, the mechanical properties of the slope materials degrade, and additional failures are possible in absence of additional climate drivers.

Climate modelling predicts different climate variables. The significance of the projections varies geographically, and depends on the type of variables, with predictions of temperature more dependable than predictions of precipitation. For precipitation, the uncertainty associated to downscaled projections for short and intense rainfall is much larger than for prolonged rainfall. We expect that the landslide-climate studies are affected by the significance of the climate variables used, and that projections based on temperature are more dependable than those based on precipitation. Thus, we expect that landslide-climate studies in high-mountain environments (where temperature plays a major role) will produce reliable results, and that projections of the behavior of deep-seated landslide activity (related to long rainfall periods) will be more dependable than projections for shallow landslides. Given the uncertainty associated to the forecast of high intensity and short duration precipitation, for shallow landslides triggered by short and intense rainfall events we anticipate that only regional landslide-climate studies will provide significant results.

Determining if and where landslide risk, and particularly risk to the population is excepted to increase (or decrease) in direct or indirect response to changes in the climate drivers remains a difficult and uncertain task that needs more investigations. However, given the fact that in some areas global warming is expected to increase the intensity of rainfall events and the frequency of intense events, which are a primary trigger of shallow, rapid-moving landslides, and that rapid landslides (e.g., soil slips, debris flows, rock falls, minor rock slides) are a primary cause of landslide fatalities (Guzzetti et al., 2005b; Petley, 2012), we expect that in these areas the total number of people exposed to landslide risk will increase, in response to the available climate projections (Fig. 8).

Lastly, we stress that global warming has direct and indirect impacts on multiple natural (e.g., environmental, water availability), and human induced (e.g., land use/cover, agriculture and forest practices, energy resources, urbanization, demography, economics) factors, which in turn can condition (directly and indirectly) landslide activity and abundance, and the frequency of landslide events. The natural and human induced drivers have complex interactions and feedbacks, which are difficult to investigate and quantify even in a “stable” climate. The direction and magnitude of the drivers, and of their effects, may outweigh the known or predicted changes in landslide activity due to climate change (Sidle and Dhakal, 2002). In many areas the shifting climate drivers will act on landscapes (and slopes in the landscapes) that were long modified by human actions. This all adds to the uncertainty in the evaluation of the impacts of climate change on landslides and the stability of natural and engineered slopes.

Acknowledgements

We are grateful to Luciano Picarelli, Luca Comegna, Paola Mercogliano, Guido Rianna, and Paolo Tommasi for fruitful discussions, to Reto Knutti and Jan Sedlacek for providing the information on the IPCC climate projections shown in Fig. 8, and to Paola Salvati for data on fatal landslides in Italy shown in Fig. 10. The manuscript greatly benefited from the constructive comments of Roy Sidle and a second anonymous referee.

Appendix

Variables and acronyms used in text.

Variable	Description	Unit
A_L	Landslide area	m^2
D_L	Landslide depth	m
FS	Factor of safety	–
L_L	Landslide length	m
L_w	Landslide width	m
V_L	Landslide volume	m^3
R	Resisting forces	N
D	Driving forces	N
S	Susceptibility	–
$p(A_L)$	Probability density of landslide area, A_L	m^{-2}
$p(N_L)$	Probability of landslide occurrence in a period	–
$p(V_L)$	Probability density of landslide volume, V_L	m^{-3}
c	Cohesion	Pa
φ	Friction angle	°
z_s	Vertical depth of the sliding surface	m
ψ	Pressure head	m
δ	Slope angle	°
γ_s	Soil unit weight	N/m^3
γ_w	Water unit weight	N/m^3

Acronym	Description
pdf	Probability density function
AD	Anno Domini
BP	Before Present
CAPE	Convective Available Potential Energy
CMCC	Centro Euro-Mediterraneo sui Cambiamenti Climatici
COSMO-CLM	COnsortium for SMall scale MOdeling - Climate Limited-area Modelling
ENSO	El Niño Southern Oscillation
GCM	Global Circulation Model
IPCC	Intergovernmental Panel on Climate Change
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
TESLEC	Temporal Stability and activity of Landslides in Europe
UKCIPS	United Kingdom Climate Impacts Program

References

Ahmed, K.Z., Wang, G., Silander, J., Wilson, A.M., Allen, J.M., Horton, R., Anyah, R., 2013. Statistical downscaling and bias correction of climate model outputs for climate change impact assessment in the U.S. northeast. Glob. Planet. Chang. 100, 320–332. http://dx.doi.org/10.1016/j.gloplacha.2012.11.003.

Aldrich, J., 1995. Correlations genuine and spurious in Pearson and Yule. Stat. Sci. 10 (4), 364–376.

Alfieri, L., Pappenberger, F., Wetterhall, F., 2014. The extreme runoff index for flood early warning in Europe. Nat. Hazards Earth Syst. Sci. 14, 1505–1515. http://dx.doi.org/10.5194/nhess-14-1505-2014.

Allen, S.K., Cox, S.C., Owens, I.F., 2011. Rock-avalanches and other landslides in the central Southern Alps of New Zealand: a regional assessment of possible climate change impacts. Landslides 8 (1), 33–48. http://dx.doi.org/10.1007/s10346-010-0222-z.

Alvioli, M., Baum, R.L., 2016. Parallelization of the TRIGRS model for rainfall-induced landslides using the message passing interface. Environ. Modell. Software 81 (C), 122–135. http://dx.doi.org/10.1016/j.envsoft.2016.04.002.

Anagnostopoulos, G.G., Fatichi, S., Burlando, P., 2015. An advanced process-based distributed model for the investigation of rainfall-induced landslides: the effect of process representation and boundary conditions. Water Resour. Res. 51 (9), 7501–7523. http://dx.doi.org/10.1002/2015WR016909.

Arambepola, N.S.M.I., Basnayake, S., Bhasin, R.K., Kjestad, O., 2013. Approaches for promoting landslide early warning in a changing climate scenario. In: Sassa, K., Rouhban, B., Briceno, S., McSaveney, M., He, B. (Eds.), Landslides: Global Risk Preparedness. Springer-Verlag, Berlin, Heidelberg, pp. 179–188 http://dx.doi.org/10.1007/978-3-642-22087-6_12.

Australian Government, 2015. National Climate Resilience and Adaptation Strategy 80 pp.

Baills, A., Vandromme, R., Desramaut, N., Sedan-Miegemolle, O., Grandjean, G., 2013. Changing patterns in climate-driven landslide hazard: an alpine test site. In: Margottini, C., Canuti, P., Sassa, K. (Eds.), Landslide Science and Practice: Global Environmental Change 4. Springer-Verlag, Berlin Heidelberg, pp. 93–98. http://dx.doi.org/10.1007/978-3-642-31337-0.

Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L., 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA 688 pp.

Barton, M., 2015. Climate change, sea level rise and coastal landslides. In: Lollino, G., Manconi, A., Clague, J.J., Shan, W., Chiarle, M. (Eds.), Engineering Geology for Society and Territory. Climate Change and Engineering Geology 1, pp. 415–418. http://dx.doi.org/10.1007/978-3-319-09300-0_84.

Baum, R.L., Savage, W.Z., Godt, J.W., 2008. TRIGRS - A Fortran Program for Transient Rainfall Infiltration and Grid-based Regional Slope-stability Analysis. Version 2.0. U.S. Geological Survey Open-File Report 2008-1159 75 pp.

Belgian National Climate Commission, 2010. Belgian National Climate Adaptation Strategy, Edited by National Climate Commission. National Climate Commission 54 pp.

Bellugi, D., Milledge, D.G., Dietrich, W.E., McKean, J.A., Perron, J.T., Sudderth, E.B., Kazian, B., 2015. A spectral clustering search algorithm for predicting shallow landslide size and location. J. Geophys. Res. 120, 300–324. http://dx.doi.org/10.1002/(ISSN)2169-9011.

Bellugi, D., Milledge, D.G., Dietrich, W.E., Perron, J.T., McKean, J.A., 2016. Predicting shallow landslide size and location across a natural landscape: application of a spectral clustering search algorithm. J. Geophys. Res. 120, 2552–2585. http://dx.doi.org/10.1002/(ISSN)2169-9011.

Beniston, M., 2003. Climatic change in mountain regions. A review of possible impacts. Clim. Chang. 59, 5–31. http://dx.doi.org/10.1023/A:1024458411589.

Benito, G., Lang, M., Barriendos i Vallvé, M., Llasat, M.C., Francés, F., Ouarda, T.B.M.J., Thorndycraft, V., Enzel, Y., Bardossy, A., Coeur, D., Bobée, B., 2004. Use of systematic, palaeoflood and historical data for the improvement of flood risk estimation. Review of scientific methods. Nat. Hazards 31 (3), 623–643. http://dx.doi.org/10.1023/B:NHAZ.0000024895.48463.eb.

Bloschl, G., Montanari, A., 2010. Climate change impacts - throwing the dice? Hydrol. Process. 24, 374–381. http://dx.doi.org/10.1002/hyp.7574.

Bonnard, C., Tacher, L., Beniston, M., 2008. Prediction of landslide movements caused by climate change: modelling the behaviour of a mean elevation large slide in the Alps and assessing its uncertainties. In: Chen, Z., Zhang, J.M., Li, Z.K., Wu, F.Q., Ho, K. (Eds.), Landslides and Engineering Slopes: From the Past to the Future, pp. 217–227 http://dx.doi.org/10.1201/9780203885284-c13.

Borga, M., Gaume, E., Creutin, J.D., Marchi, L., 2008. Surveying flash floods: gauging the ungauged extremes. Hydrol. Process. 22 (18), 3883–3885. http://dx.doi.org/10.1002/hyp.7111.

Borga, M., Stoffel, M., Marchi, L., Marra, F., Jakob, M., 2014. Hydrogeomorphic response to extreme rainfall in headwater systems: Flash floods and debris flows. J. Hydrol. 518 (PB), 194–205. http://dx.doi.org/10.1016/j.jhydrol.2014.05.022.

Borgatti, L., Soldati, M., 2010. Landslides as a geomorphological proxy for climate change: a record from the Dolomites (northern Italy). Geomorphology 120, 56–64. http://dx.doi.org/10.1016/j.geomorph.2009.09.015.

Bovis, M.J., Jones, P., 1992. Holocene history of earthflow mass movements in southcentral British Columbia: the influence of hydroclimatic changes. Can. J. Earth Sci. 29, 1746–1754. http://dx.doi.org/10.1139/e92-137.

Brunetti, M., Colacino, M., Maugeri, M., Nanni, T., 2001. Trends in the daily intensity of precipitation in Italy from 1951 to 1996. Int. J. Climatol. 21, 299–316. http://dx.doi.org/10.1002/joc.613.

Brunetti, M.T., Guzzetti, F., Rossi, M., 2009. Probability distributions of landslide volumes. Nonlinear Process. Geophys. 16, 179–188. http://dx.doi.org/10.5194/npg-16-179-2009.

Brunetti, M.T., Peruccacci, S., Rossi, M., Luciani, S., Valigi, D., Guzzetti, F., 2010. Rainfall thresholds for the possible occurrence of landslides in Italy. Nat. Hazards Earth Syst. Sci. 10, 447–458. http://dx.doi.org/10.1007/s10346-015-0630-1.

Bracegirdle, A., Menkiti, C.O., Clark, A.R., 2007. Climate change impacts on landslide mechanisms and hazard in southern UK. In: McInnes, R., Jakeways, J., Fairbank, H., Mathie, E. (Eds.), Landslides and Climate Change: Challenges and Solutions, Proceedings of the International Conference on Landslides and Climate Change. Taylor & Francis, Ventnor, Isle of Wight, UK, pp. 259–267 21–24 May 2007.

Brunetti, M., Caloiero, T., Coscarelli, R., Gullà, G., Nanni, T., Simolo, C., 2012. Precipitation variability and change in the Calabria region (Italy) from a high resolution daily dataset. Int. J. Climatol. 32, 57–73. http://dx.doi.org/10.1002/joc.2233.

Buma, J., 2000. Finding the most suitable slope stability model for the assessment of the impact of climate change on a landslide in southeast France. Earth Surf. Process. Landf. 25, 565–582. http://dx.doi.org/10.1002/1096-9837(200006)25.

Buma, J., Dehn, M., 1998. A method for predicting the impact of climate change on slope stability. Environ. Geol. 35 (2–3), 190–196. http://dx.doi.org/10.1007/s002540050305.

Buma, J., Dehn, M., 2000. Impact of climate change on a landslide in South East France, simulated using different GCM scenarios and downscaling methods for local precipitation. Clim. Res. 15, 69–81. http://dx.doi.org/10.3354/cr015069.

Caloiero, T., Coscarelli, R., Ferrari, E., 2008. Trend analysis of short rainfalls annual maxima in Calabria. In: Ferrari, E., Versace, P. (Eds.), Variability in Space and Time of Extreme Rainfalls, Floods and Droughts. Bios, Cosenza, Italy, pp. 103–111.

Camici, S., Brocca, L., Melone, F., Moramarco, T., 2014. Impact of climate change on flood frequency using different climate models and downscaling approaches. J. Hydrol. Eng. 19 (8). http://dx.doi.org/10.1061/(ASCE)HE.1943-5584.0000959.

Cannon, S.H., Kirkham, R.M., Parise, M., 2001. Wildfire-related debris-flow initiation processes, Storm King Mountain, Colorado. Geomorphology 39, 171–188. http://dx.doi.org/10.1016/S0169-555X(00)00108-2.

Cannon, S.H., Boldt, E.M., Kean, J.W., Laber, J., Staley, D.M., 2011. Rainfall intensity – duration thresholds for postfire debris-flow emergency-response planning. Nat. Hazards 59, 209–236. http://dx.doi.org/10.1007/s11069-011-9747-2.

Cardinali, M., Ardizzone, F., Galli, M., Guzzetti, F., Reichenbach, P., 2000. Landslides triggered by rapid snow melting: the December 1996–January 1997 event in Central Italy. Proceedings of the EGS Plinius Conference. Editoriale Bios, Cosenza, Maratea, Italy, pp. 439–448.

Castellari, S., Venturini, S., Ballarin Denti, A., Bigano, A., Bindi, M., Bosello, F., Carrera, L., Chiriaco, M.V., Danovaro, R., Desiato, F., Filpa, A., Gatto, M., Gaudioso, D., Giovanardi, O., Giupponi, C., Gualdi, S., Guzzetti, F., Luise, A., Marino, G., Mysiak, J., Montanari, A., Ricchiuti, A., Rudari, R., Sabbioni, C., Sciortino, M., Sinisi, L., Valentini, R., Viaroli, P., Vurro, M., Marco, Z., 2014a. Elementi per una Strategia Nazionale di Adattamento ai Cambiamenti Climatici. Ministero dell'Ambiente e della Tutela del Territorio e del Mare 245 pp.

Castellari, S., Venturini, S., Ballarin Denti, A., Bigano, A., Bindi, M., Bosello, F., Carrera, L., Chiriaco, M.V., Danovaro, R., Desiato, F., Filpa, A., Gaudioso, D., Giovanardi, O., Giupponi, C., Gualdi, S., Guzzetti, F., Lapi, M., Luise, A., Mysiak, J., Gatto, M., Montanari, A., Ricchiuti, A., Rudari, R., Sabbioni, C., Sciortino, M., Sinisi, L., Valentini, R., Viaroli, P., Vurro, M., Marco, Z., 2014b. Rapporto sullo stato delle conoscenze scientifiche su impatti, vulnerabilità ed adattamento ai cambiamenti climatici in Italia. Ministero dell'Ambiente e della Tutela del Territorio e del Mare 878 pp.

Chang, S.-H., Chiang, K.-T., 2011. The potential impact of climate change on typhoon-triggered landslides in Taiwan, 2010–2099. Geomorphology 133, 143–151. http://dx.doi.org/10.1016/j.geomorph.2010.12.028.

Cheng, L., AghaKouchak, A., 2014. Nonstationary precipitation intensity-duration-frequency curves for infrastructure design in a changing climate. Sci. Rep. 4, 7093. http://dx.doi.org/10.1038/srep07093.

Chiarle, M., Iannotti, S., Mortara, G., Deline, P., 2007. Recent debris flow occurrences associated with glaciers in the Alps. Glob. Planet. Chang. 56, 123–136. http://dx.doi.org/10.1016/j.gloplacha.2006.07.003.

Chiarle, M., Coviello, V., Arattano, M., Silvestri, P., Nigrelli, G., 2015. High elevation rock falls and their climatic control: a case study in the Conca di Cervinia (NW Italian Alps). In: Lollino, G., Manconi, A., Clague, J.J., Shan, W., Chiarle, M. (Eds.), Engineering Geology for Society and Territory. Climate Change and Engineering Geology 1, pp. 423–443. http://dx.doi.org/10.1007/978-3-319-09300-0_84.

Ciabatta, L., Camici, S., Brocca, L., Ponziani, F., Stelluti, F., Berni, N., Moramarco, T., 2016. Assessing the impact of climate-change scenarios on landslide occurrence in Umbria Region, Italy. J. Hydrol. http://dx.doi.org/10.1016/j.jhydrol.2016.02.007.

Clarke, D., Smethurst, J.A., 2010. Effects of climate change on cycles of wetting and drying in engineered clay slopes in England. Q. J. Eng. Geol. Hydrogeol. 43, 473–486. http://dx.doi.org/10.1144/1470-9236/08-106.

Coe, J.A., 2012. Regional moisture balance control of landslide motion: implications for landslide forecasting in a changing climate. Geology 40 (4), 323–326. http://dx.doi.org/10.1130/G32897.1.

Coe, J.A., Godt, J.W., 2012. Review of approaches for assessing the impact of climate change on landslide hazards. In: Eberhardt, E., Froese, C., Turner, A.K., Leroueil, S. (Eds.), Landslides and Engineered Slopes, Protecting Society Through Improved Understanding: Proceedings 11th International and 2nd North American Symposium on Landslides and Engineered Slopes, Banff, Canada 1. Taylor & Francis Group, London, pp. 371–377 3–8 June.

Coe, J.A., Michael, J.A., Crovelli, R.A., Savage, W.Z., 2000. Preliminary Map Showing Landslide Densities, Mean Recurrence Intervals, and Exceedance Probabilities as Determined from Historic Records, Seattle, Washington, U.S. Geological Survey Open-File Report 00–303. US Geological Survey, Reston, VA.

Collier, C.G., 2007. Flash flood forecasting: what are the limits of predictability? Q. J. R. Meteorol. Soc. 133 (622), 3–23. http://dx.doi.org/10.1002/qj.29.

Collison, A., Wade, S., Griffiths, J., Dehn, M., 2000. Modelling the impact of predicted climate change on landslide frequency and magnitude in SE England. Eng. Geol. 5, 205–218. http://dx.doi.org/10.1016/s0013-7952(99)00121-0.

Comegna, L., Picarelli, L., Bucchignani, E., Mercogliano, P., 2013. Potential effects of incoming climate changes on the behaviour of slow active landslides in clay. Landslides 10 (4), 373–391. http://dx.doi.org/10.1007/s10346-012-0339-3.

Corominas, J., Moya, J., 2000. Contribution of dendrochronology to the determination of magnitude–frequency relationships for landslides. Geomorphology 124 (3–4), 137–149. http://dx.doi.org/10.1016/j.geomorph.2010.09.001.

Crovelli, R.A., 2000. Probability Models for Estimation of Number and Costs of Landslides. U.S. Geological Survey Open File Report 00–249. US Geological Survey, Reston, VA 24 pp.

Crozier, M.J., 1997. The climate landslide couple: a Southern Hemisphere perspective. Paleoclimate Research 19 12. European Science Foundation Special Issue, pp. 329–350.

Crozier, M.J., 2010. Deciphering the effect of climate change on landslide activity: a review. Geomorphology 124, 260–267. http://dx.doi.org/10.1016/j.geomorph.2010.04.009.

Cruden, D.M., 1999. Rapid mass movement and climate: a North American perspective. Palaoklimaforschung-Palaeoclimate Research. 19, pp. 371–378.

Cruden, D.M., Varnes, D.J., 1996. Landslide types and processes. In: Turner, A.K., Schuster, R.L. (Eds.), Landslides, Investigation and Mitigation, Special Report 247. Transportation Research Board, Washington D.C., pp. 36–75 ISSN: 0360-859X, ISBN: 030906208X.

Damm, B., Klose, M., 2014. Landslide database for the Federal Republic of Germany: a tool for analysis of mass movement processes. In: Sassa, K., Canuti, P., Yin, Y. (Eds.), Landslide Science for a Safer Geoenvironment 2. Springer International Publishing Switzerland, pp. 787–792.

Danish Government, 2008. Danish Strategy for Adaptation to a Changing Climate 52 pp.

De Blasio, F.V., 2010. Indications on the past climate of Mars based on the examination of ancient landslides: some basic considerations. Nuovo Cimento Soc. Ital. Fis. 125 (11), 1395–1400. http://dx.doi.org/10.1393/ncb/i2010-10932-1.

Dehn, M., 1999. Application of an analog downscaling technique to the assessment of future landslide activity - a case study in the Italian Alps. Clim. Res. 13, 103–113. http://dx.doi.org/10.3354/cr013103.

Dehn, M., Buma, J., 1999. Modelling future landslide activity based on general circulation models. Geomorphology 30 (1), 175–187. http://dx.doi.org/10.1016/s0169-555x(99)00053-7.

Dehn, M., Bürger, G., Buma, J., Gasparetto, P., 2000. Impact of climate change on slope stability using expanded downscaling. Eng. Geol. 55 (3), 193–204. http://dx.doi.org/10.1016/s0013-7952(99)00123-4.

Déqué, M., Dreveton, C., Braun, A., Cariolle, D., 1994. The ARPEGE-IFS atmosphere model: a contribution to the French community climate modeling. Clim. Dyn. 10, 249–266. http://dx.doi.org/10.1007/s003820050047.

Devoli, G., Strauch, W., Chavez, G., Hoeg, K., 2007. A landslide database for Nicaragua: a tool for landslide-hazard management. Landslides 4 (2), 163–176.

Dhakal, A.S., Sidle, R.C., 2004. Distributed simulations of landslides for different rainfall conditions. Hydrol. Process. 18 (4), 757–776. http://dx.doi.org/10.1002/hyp.1365.

Diffenbaugh, N.S., Field, C., 2013. Changes in ecologically critical terrestrial climate conditions. Science 341 (6145), 486–492. http://dx.doi.org/10.1126/science.1237123.

Dijkstra, T.A., Dixon, N., 2010. Climate change and slope stability: Challenges and approaches. Q. J. Eng. Geol. Hydrogeol. 43 (4), 371–385. http://dx.doi.org/10.1144/1470-9236/09-036.

Dikau, R., Schrott, L., 1999. The temporal stability and activity of landslides in Europe with respect to climatic change (TESLEC): main objectives and results. Geomorphology 30, 1–12. http://dx.doi.org/10.1016/s0169-555x(99)00040-9.

Dixon, N., Brook, E., 2007. Impact of predicted climate change on landslide reactivation: case study of Mam Tor, UK. Landslides 4, 137–147. http://dx.doi.org/10.1007/s10346-006-0071-y.

Domroes, M., Schaefer, D., 2008. Recent climate change affecting rainstorm occurrences: a case study in East China. Clim. Past 4, 303–309. http://dx.doi.org/10.5194/cp-4-303-2008.

Dutto, F., Mortara, G., 1992. Rischi connessi con la dinamica glaciale nelle Alpi Italiane. Geogr. Fis. Din. Quat. 15, 85–99 (in Italian).

Eden, D.N., Page, M.J., 1998. Palaeoclimatic implications of a storm erosion record from late Holocene lake sediments, North Island, New Zealand. Palaeogeogr. Palaeoc. 139, 37–58. http://dx.doi.org/10.1016/S0031-0182(97)00136-3.

Evans, S.G., Clague, J.J., 1994. Recent climatic changes and catastrophic geomorphic processes in mountain environments. Geomorphology 10, 107–128. http://dx.doi.org/10.1016/0169-555X(94)90011-6.

Falcucci, A., Maiorano, L., Boitani, L., 2007. Changes in land-use/land cover patterns in Italy and their implications for biodiversity conservation. Landsc. Ecol. 22, 617–631. http://dx.doi.org/10.1007/s10980-006-9056-4.

Fan, J.C., Yang, C.H., Chang, S.C., Huang, H.Y., Guo, J.J., 2013. Effects of climate change on the potential of the landslides in the basin of Kaoping stream. J. Chin. Soil Water Conserv. 44 (4), 335–350.

Fatichi, S., Ivanov, V.Y., Paschalis, A., Peleg, N., Molnar, P., Rimkus, S., Kim, J., Burlando, P., Caporali, E., 2016. Uncertainty partition challenges the predictability of vital details of climate change. Earth's Future. 4. http://dx.doi.org/10.1002/2015EF000336.

Federal Government of Mexico, 2013. National Climate Change Strategy, 10-20-40 Vision 60 pp.

Fell, R., Hartford, D., 1997. Landslide risk management. In: Cruden, D., Fell, R. (Eds.), Landslide Risk Assessment. Balkema, Rotterdam, pp. 51–109.

Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., 2014. In: White, L.L. (Ed.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA 1132 pp.

Finland's Ministry of Agriculture and Forestry of Finland, 2005,. In: Marttila, E., Granholm, H., Laanikari, J., Yrjola, T., Aalto, A., Heikinheimo, P., Honkatuki, J., Jarvinen, H., Liski, J., Merivirta, R., Paunio, M. (Eds.), Finland's National Strategy for Adaptation to Climate Change. Ministry of Agriculture and Forestry. ISBN: 952-453-231-X 281 pp.

Fischer, L., Huggel, C., Kääb, A., Haeberli, W., 2013. Slope failures and erosion rates on a glacierized high-mountain face under climatic changes. Earth Surf. Process. Landf. 38, 836–846. http://dx.doi.org/10.1002/esp.3355.

Flageollet, J.-C., Maquaire, O., Martin, B., Weber, D., 1999. Landslides and climatic conditions in the Barcelonnette and Vars basins (Southern French Alps, France). Geomorphology 30, 65–78. http://dx.doi.org/10.1016/S0169-555X(99)00045-8.

Fowler, H.J., Blenkisop, S., Tebaldi, C., 2007. Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. Int. J. Climatol. 27, 1547–1578. http://dx.doi.org/10.1002/joc.1556.

Francani, V., Gattinoni, P., 2009. Relationship between climate change and landslide hazard in alpine areas interested by thawing permafrost. In: Oka, F., Kimoto, S., Murakami, A. (Eds.), Prediction and Simulation Methods for Geohazard Mitigation. Taylor & Francis Group, London. ISBN: 978-0-415-80482-0, pp. 97–102.

Galli, M., Ardizzone, F., Cardinali, M., Guzzetti, F., Reichenbach, P., 2008. Comparing landslide inventory maps. Geomorphology 94 (3–4), 268–289. http://dx.doi.org/10.1016/j.geomorph.2006.09.023.

Gariano, S.L., Petrucci, O., Guzzetti, F., 2015a. Changes in the occurrence of rainfall-induced landslides in Calabria, southern Italy, in the 20th century. Nat. Hazards Earth Syst. Sci. 15, 2313–2330. http://dx.doi.org/10.5194/nhess-15-2313-2015.

Gariano, S.L., Brunetti, M.T., Iovine, G., Melillo, M., Peruccacci, S., Terranova, O., Vennari, C., Guzzetti, F., 2015b. Calibration and validation of rainfall thresholds for shallow landslide forecasting in Sicily, Southern Italy. Geomorphology 228, 653–665. http://dx.doi.org/10.1016/j.geomorph.2014.10.019.

Gassner, C., Promper, C., Begueria, S., Glade, T., 2015. Climate change impact for spatial landslide susceptibility. In: Lollino, G., Manconi, A., Clague, J., Shan, W., Chiarle, M. (Eds.), Engineering Geology for Society and TerritoryClimate Change and Engineering Geology 1. Springer International Publishing, pp. 429–433.

Geertsema, M., 2013. Quick clay landslides, landscape evolution, climate change: a perspective from British Columbia. In: Margottini, C., Canuti, P., Sassa, K. (Eds.), Landslide Science and PracticeGlobal Environmental Change 4. Springer, Berlin Heidelberg, pp. 9–16.

Geertsema, M., Egginton, V.N., Schwab, J.V., Clague, J.J., 2007. Landslides and historic climate in northern British Columbia. In: McInnes, R., Jakeways, J., Fairbank, H., Mathie, E.

(Eds.), Landslides and Climate Change: Challenges and SolutionsProceedings of the International Conference on Landslides and Climate Change. Taylor & Francis, Ventnor, pp. 131–141.

German Federal Government, 2008. German Strategy for Adaptation to Climate Change 73 pp.

Glade, T., 1998. Establishing the frequency and magnitude of landslide-triggering rainstorm events in New Zealand. Environ. Geol. 35 (2–3), 160–174. http://dx.doi.org/10.1007/s002540050302.

Glade, T., 2003. Landslide occurrence as a response to land use change: a review of evidence from New Zealand. Catena 51 (3–4), 297–314. http://dx.doi.org/10.1016/s0341-8162(02)00170-4.

Glade, T., Crozier, M.J., 2005. The nature of landslide hazard impact. In: Glade, T., Anderson, M.G., Crozier, M.J. (Eds.), Landslide Hazard and Risk. Wiley, Chichester, pp. 43–74.

González Díez, A., Salas, L., Díaz de Terán, J.R., Cendrero, A., 1996. Late Quaternary climate changes and mass movement frequency and magnitude in the Cantabrian region, Spain. Geomorphology 15 (3–4), 291–309. http://dx.doi.org/10.1016/0169-555X(95)00076-H.

Götz, A., Burkhardt, A., Manser, R., Marendaz, E., Willi, H.P., 2012. Adaptation aux changements climatiques en Suisse – objectifs, défis et champs d'action (in French).

Government of Japan, Ministry of Environment, Committee on Approaches to Climate Change Adaptation, 2010n. Approaches to Climate Change Adaptation, Japan 80 pp.

Government of Kenya, 2010. National Climate Change Response Strategy 120 pp.

Government of Malta, Climate Change Committee for Adaptation, 2010o. National Climate Change Adaptation Strategy, Malta 165 pp.

Guha-Sapir, D., Hoyois, P., Below, R., 2015. Annual Disaster Statistical Review 2014: The Numbers and Trends. CRED, Bruxelles 54 pp.

Guthrie, R.H., Mitchell, S.J., Lanquaye-Opoku, N., Evans, S.G., 2010. Extreme weather and landslide initiation in coastal British Columbia. Q. J. Eng. Geol. Hydrogeol. 43, 417–428. http://dx.doi.org/10.1144/1470-9236/08-119.

Guzzetti, F., 2000. Landslide fatalities and the evaluation of landslide risk in Italy. Eng. Geol. 58 (2), 89–107. http://dx.doi.org/10.1016/S0013-7952(00)00047-8.

Guzzetti, F., 2006. Landslide Hazard and Risk Assessment. Ph.D. Thesis. Mathematisch-Naturwissenschaftlichen Fakultät der Rheinischen Friedrich-Wilhelms-Universität University of Bonn, Bonn, Germany 389 pp. http://hss.ulb.uni-bonn.de/2006/0817/0817.htm.

Guzzetti, F., Cardinali, M., 1991. Debris-flow phenomena in the Central Apennines of Italy. Terra Nova 3, 619–627. http://dx.doi.org/10.1111/j.1365-3121.1991.tb00204.x.

Guzzetti, F., Tonelli, G., 2004. Information system on hydrological and geomorphological catastrophes in Italy (SICI): a tool for managing landslide and flood hazards. Nat. Hazards Earth Syst. Sci. 4, 213–232. http://dx.doi.org/10.5194/nhess-4-213-2004.

Guzzetti, F., Cardinali, M., Reichenbach, P., 1994. The AVI Project. A bibliographical and archive inventory of landslides and floods in Italy. Environ. Manag. 18 (4), 623–633. http://dx.doi.org/10.1007/BF02400865.

Guzzetti, F., Carrara, A., Cardinali, M., Reichenbach, P., 1999. Landslide hazard evaluation: a review ofcurrent techniques and their application in a multi-scale study. Central Italy. Geomorphology 31 (1–4), 181–216.

Guzzetti, F., Reichenbach, P., Cardinali, M., Galli, M., Ardizzone, F., 2005a. Probabilistic landslide hazard assessment at the basin scale. Geomorphology 72 (1–4), 272–299. http://dx.doi.org/10.1016/j.geomorph.2005.06.002.

Guzzetti, F., Stark, C.P., Salvati, P., 2005b. Evaluation of flood and landslide risk to the population of Italy. Environ. Manag. 36 (1), 15–36. http://dx.doi.org/10.1007/s00267-003-0257-1.

Guzzetti, F., Galli, M., Reichenbach, P., Ardizzone, F., Cardinali, M., 2006. Landslide hazard assessment in the Collazzone area, Umbria, central Italy. Nat. Hazards Earth Syst. Sci. 6, 115–131. http://dx.doi.org/10.5194/nhess-6-115-2006.

Guzzetti, F., Peruccacci, S., Rossi, M., Stark, C.P., 2007. Rainfall thresholds for the initiation of landslides in central and southern Europe. Meteorog. Atmos. Phys. 98 (3), 239–267. http://dx.doi.org/10.1007/s00703-007-0262-7.

Guzzetti, F., Peruccacci, S., Rossi, M., Stark, C.P., 2008. The rainfall intensity–duration control of shallow landslides and debris flows: an update. Landslides 5 (1), 3–17. http://dx.doi.org/10.1007/s10346-007-0112-1.

Guzzetti, F., Ardizzone, F., Cardinali, M., Rossi, M., Valigi, D., 2009. Landslide volumes and landslide mobilization rates in Umbria, central Italy. Earth Planet. Sci. Lett. 279 (3–4), 222–229. http://dx.doi.org/10.1016/j.epsl.2009.01.005.

Harr, R.D., 1981. Some characteristics and consequences of snowmelt during rainfall in western Oregon. J. Hydrol. 53, 277–304. http://dx.doi.org/10.1016/0022-1694(81)90006-8.

Hatzianastassiou, N., Papadimas, C.D., Lolis, C.J., Bartzokas, A., Levizzani, V., Pnevmatikosa, J.D., Katsoulisa, B.D., 2016a. Spatial and temporal variability of precipitation over the Mediterranean Basin based on 32-year satellite Global Precipitation Climatology Project data, part I: evaluation and climatological patterns. Int. J. Climatol. http://dx.doi.org/10.1002/joc.4666.

Hatzianastassiou, N., Papadimas, C.D., Lolis, C.J., Bartzokas, A., Levizzani, V., Pnevmatikosa, J.D., Katsoulisa, B.D., 2016b. Spatial and temporal variability of precipitation over the Mediterranean Basin based on 32-year satellite Global Precipitation Climatology Project data. Part-II: inter-annual variability and trends. Int. J. Climatol. http://dx.doi.org/10.1002/joc.4665.

Holm, K., Bovis, M., Jakob, M., 2004. The landslide response of alpine basins to post-Little Ice Age glacial thinning and retreat in southwestern British Columbia. Geomorphology 57 (3–4), 201–216.

Houghton, J.T., Jenkins, G.J., Ephramus, J.J., 1990. Climate Change: The IPCC Scientific Assessment. Cambridge University Press, Cambridge 410 pp.

Houghton, J.T., Callander, B.A., Varney, S.K., 1992. Climate change 1992. The Supplementary Report to the IPCC Scientific Assessment. Cambridge University Press, Cambridge 218 pp.

Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A., 2001. Climate Change 2001. The Scientific Basis. Cambridge University Press 881 pp.

Huggel, C., Salzman, N., Allen, S., Caplan-Auerbach, J., Fischer, L., Haeberli, W., Larsen, C., Schneider, D., Wessels, R., 2010. Recent and future warm extreme events and high-mountain slope stability. Phil. Trans. R. Soc. A 368, 2435–2459. http://dx.doi.org/10.1098/rsta.2010.0078.

Huggel, S., Clague, J.J., Korup, O., 2012. Is climate change responsible for changing landslide activity in high mountains? Earth Surf. Process. Landf. 37, 77–91. http://dx.doi.org/10.1002/esp.2223.

Huggel, C., Gruber, S., Korup, O., 2013. Landslide hazards and climate change in high mountains. In: Shroder, J., James, L.A., Harden, C.P., Clague, J.J. (Eds.), Treatise on GeomorphologyGeomorphology of Human Disturbances, Climate Change, and Natural Hazards 13. Academic Press, San Diego CA, USA, pp. 288–301.

Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphey, J.M., Hassell, D., Boorman, P., McDonald, R., Hill, S., 2002. Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report. Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich 120 pp.

Hultén, C., Andersson-Sköld, Y., Ottosson, E., Johansson, Å., Edstam., T., 2007. Case studies of landslide risk due to climate change in Sweden. In: McInnes, R., Jakeways, J., Fairbank, H., E., M. (Eds.), Landslides and Climate Change: Challenges and Solutions, Proceedings of the International Conference on Landslides and Climate Change. Taylor & Francis, Ventnor, Isle of Wight, UK, pp. 149–157 21–24 May 2007.

Hungr, O., McDougall, S., Bovis, M., 2005. Entrainment of material by debris flows. In: M., J., Hungr, O. (Eds.), Debris-flow Hazards and Related Phenomena. Springer, Berlin, pp. 135–158.

Hungr, O., Leroueil, S., Picarelli, L., 2013. The Varnes classification of landslide types, an update. Landslides 11 (2), 167–194. http://dx.doi.org/10.1007/s10346-013-0436-y.

Imaizumi, F., Sidle, R.C., Kamei, R., 2008. Effects of forest harvesting on the occurrence of landslides and debris flows in steep terrain of central Japan. Earth Surf. Process. Landf. 33, 827–840. http://dx.doi.org/10.1002/esp.1574.

Imaizumi, F., Sidle, R.C., Togari-Ohta, A., Shimamura, M., 2015. Temporal and spatial variation of infilling processes in a landslide scar in a steep mountainous region, Japan. Earth Surf. Process. Landf. 40 (5), 642–653. http://dx.doi.org/10.1002/esp.3659.

Innes, J.L., 1983. Lichenometric dating of debris-flow deposits in the Scottish Highlands. Earth Surf. Process. Landf. 8, 579–588. http://dx.doi.org/10.1002/esp.3290080609.

Innes, J.L., 1985. Lichenometric dating of debris-flow deposits on alpine colluvial fans in southwest Norway. Earth Surf. Process. Landf. 10, 519–524. http://dx.doi.org/10.1002/esp.3290100510.

Innes, J.L., 1997. Historical debris-flow activity and climate in Scotland. In: Matthews, J.A., Brunsden, D., Frenzel, B., Gläser, B., Weiss, M.M. (Eds.), Rapid Mass Movement as a Source of Climatic Evidence for the Holocene. Paläoklimaforschung-Paleoclimate Res 19, pp. 233–240.

IPCC – Intergovernmental Panel on Climate Change, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Geneva, Switzerland 151 pp.

Iverson, R.M., Reid, M.E., Logan, M., LaHusen, R.G., Godt, J.W., Griswold, J.P., 2011. Positive feedback and momentum growth during debris-flow entrainment of wet bed sediment. Nat. Geosci. 4 (2), 116–121. http://dx.doi.org/10.1038/NGEO1040.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O., Bouwer, L., Braun, A., Colette, A., Déqué, M., Georgievski, G., et al., 2014. EURO-CORDEX: new high-resolution climate change projections for European impact research. Reg. Environ. Chang. 14, 563–578. http://dx.doi.org/10.1007/s10113-013-0499-2.

Jakob, M., Lambert, S., 2009. Climate change effects on landslides along the southwest coast of British Columbia. Geomorphology 107, 275–284. http://dx.doi.org/10.1016/j.geomorph.2008.12.009.

Johns, T.C., Carnell, R.E., Crossley, J.F., Gregory, J.M., Mitchell, J.F.B., Senior, C.A., Tett, S.F.B., Wood, R.A., 1997. The Second Hadley Centre coupled ocean-atmosphere GCM: model description, spinup and validation. Clim. Dyn. 13, 103–134.

Jomelli, V., Pech, V.P., Chochillon, C., Brunstein, D., 2004. Geomorphic variations of debris flows and recent climatic change in the French Alps. Clim. Chang. 64, 77–102. http://dx.doi.org/10.1023/B:CLIM.0000024700.35154.44.

Jomelli, V., Brunstein, D., Grancher, D., Pech, P., 2007. Is the response of hill slope debris flows to recent climate change univocal? A case study in the Massif des Ecrins (French Alps). Clim. Chang. 85, 119–137. http://dx.doi.org/10.1007/s10584-006-9209-0.

Jomelli, V., Brunstein, D., Déqué, M., Vrac, M., Grancher, D., 2009. Impacts of future climatic change (2070–2099) on the potential occurrence of debris flows: a case study in the Massif des Ecrins (French Alps). Clim. Chang. 97, 171–191. http://dx.doi.org/10.1007/s10584-009-9616-0.

Jones, J.A.A., 2010. Soil piping and catchment response. Hydrol. Process. 24 (12), 1548–1566. http://dx.doi.org/10.1002/hyp.7634.

Katz, O., Mushkin, A., 2013. Characteristics of sea-cliff erosion induced by a strong winter storm in the eastern Mediterranean. Quat. Res. 80 (1), 20–32. http://dx.doi.org/10.1016/j.yqres.2013.04.004.

Kay, A.L., Davies, H.N., Bell, V.A., Jones, R.G., 2009. Comparison of uncertainty sources for climate change impacts: flood frequency in England. Clim. Chang. 92 (1–2), 41–63. http://dx.doi.org/10.1007/s10584-008-9471-4.

Kim, K.G., Lee, D.K., Park, C., Kil, S., Son, Y., Park, J.H., 2015. Evaluating landslide hazards using RCP 4.5 and 8.5 scenarios. Environ. Earth Sci. 73, 1385–1400. http://dx.doi.org/10.1007/s12665-014-3775-7.

Kirschbaum, D., 2014. Global catalog of rainfall-triggered landslides for spatial and temporal hazard characterization. In: Sassa, K., Canuti, P., Yin, Y. (Eds.), Landslide Science for a Safer Geoenvironment 2. Springer International Publishing Switzerland, pp. 809–814.

Lang, A., Moya, J., Corominas, J., Schrott, L., Dikau, R., 1999. Classic and new dating methods for assessing the temporal occurrence of mass movements. Geomorphology 30, 33–52. http://dx.doi.org/10.1016/s0169-555x(99)00043-4.

Larsen, I.J., Montgomery, D.R., 2012. Landslide erosion coupled to tectonics and river incision. Nat. Geosci. 5 (7), 468–473. http://dx.doi.org/10.1038/ngeo1479.

Last, G., Brandt, A., 1995. Marked Point Processes on the Real Line. The Dynamic Approach. Probability and its Applications. Springer, New York.

Lateltin, O., Beer, C., Raetzo, H., Caron, C., 1997. Landslides in Flysch terranes of Switzerland: Causal factors and climate change. Eclogae Geol. Helv. 90, 401–406.

Lee, M.-J., Song, W.-K., Won, J.-S., Park, I., Lee, S., 2014. Spatial and temporal change in landslide hazard by future climate change scenarios using probabilistic-based frequency ratio model. Geocarto International 29 (6), 639–662. http://dx.doi.org/10.1080/10106049.2013.826739.

Lemmen, D.S., Warren, F.J., Lacroix, J., Bush, E., 2008. From Impacts to Adaptation: Canada in a Changing Climate 2007. Government of Canada, Ottawa, ON 448 pp.

Lin, C.W., Liu, S.H., Lee, S.Y., Liu, C.C., 2006. Impacts of the Chi-Chi earthquake on sub- sequent rainfall-induced landslides in central Taiwan. Eng. Geol. 86, 87–101. http://dx.doi.org/10.1016/j.enggeo.2006.02.010.

Lonigro, T., Gentile, F., Polemio, M., 2015. The influence of climate variability and land use variations on the occurrence of landslide events (Subappennino Dauno, Southern Italy). Rend. Online Soc. Geol. Ital. 35, 192–195. http://dx.doi.org/10.3301/ROL.2015.98.

LoPresti, A., Charland, A., Woodard, D., Randerson, J., Diffenbaugh, N.S., Davis, S.J., 2015. Rate and velocity of climate change caused by cumulative carbon emissions. Environ. Res. Lett. 10, 095001. http://dx.doi.org/10.1088/1748-9326/10/9/095001.

Loveridge, F.A., Spink, T.W., O'Brien, A.S., Briggs, K.M., Butcher, D., 2010. The impact of climate and climate change on infrastructure slopes, with particular reference to southern England. Q. J. Eng. Geol. Hydrogeol. 43, 461–471. http://dx.doi.org/10.1144/1470-9236/09-050.

Malamud, B.D., Turcotte, D.L., Guzzetti, F., Reichenbach, P., 2004. Landslide inventories and their statistical properties. Earth Surf. Process. Landf. 29 (6), 687–711. http://dx.doi.org/10.1002/esp.1064.

Malet, J.-P., van Asch, T.H.W.J., van Beek, R., Maquaire, O., 2005. Forecasting the behaviours of complex landslides with a spatially distributed hydrological model. Nat. Hazards Earth Syst. Sci. 5 (1), 71–85. http://dx.doi.org/10.5194/nhess-5-71-2005.

Malet, J.-P., Remaître, A., Maquaire, O., Durand, Y., Etchevers, P., Guyomarch, G., Déqué, M., van Beek, L.P.H., 2007. Assessing the influence of climate change on the activity of landslides in the Ubaye Valley. In: McInnes, R., Jakeways, J., Fairbank, H., E., M. (Eds.), Landslides and Climate Change: Challenges and Solutions, Proceedings of the International Conference on Landslides and Climate Change. Taylor & Francis, Ventnor, Isle of Wight, UK, pp. 195–205 21–24 May 2007.

Margielewski, W., 1998. Landslide phases in the Polish Outer Carpathians and their relation to the climatic changes in the Late Glacial and the Holocene. Quatern. Stud. Pol. 15, 37–53.

Marra, F., Nikolopoulos, E.I., Creutin, J.D., Borga, M., Creutin, J.D., 2014. Radar rainfall estimation for the identification of debris-flow occurrence thresholds. J. Hydrol. 519, 1607–1619. http://dx.doi.org/10.1016/j.jhydrol.2014.09.039.

Matthews, J.A., Brunsden, D., Frenzel, B., Gläser, B., Weiss, M.M., 1997. Rapid mass movement as a source of climatic evidence for the Holocene. Paläoklimaforschung-Paleoclimate Res. 19 444 pp.

Matthews, J.A., Dahl, S.O., Dresser, P.Q., Berrisford, M.S., Lie, O., Nesje, A., Owen, G., 2009. Radiocarbon chronology of Holocene colluvial (debris-flow) events at Sletthamm, Jotunheimen, southern Norway: a window on the changing frequency of extreme climatic events and their landscape impact. The Holocene 19 (8), 1107–1129. http://dx.doi.org/10.1177/0959683609344674.

McInnes, R., Jakeways, J., Fairbank, H., Mathie, E. (Eds.), 2007. Landslides and Climate Change: Challenges and Solutions, Proceedings of the International Conference on Landslides and Climate Change. Taylor & Francis, Ventnor http://dx.doi.org/10.1201/noe0415443180.

Meinshausen, M., Smith, S.J., Calvin, K., Daniel, J.S., Lamarque, M.L.J.-F., Matsumoto, K., Montzka, S.A., Raper, S.C.B., Thomson, A., Velders, G.J.M., van Vuuren, D.P.P., 2011. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Clim. Chang. 109, 213–241.

Melchiorre, C., Frattini, P., 2012. Modelling probability of rainfall-induced shallow landslides in a changing climate, Otta, Central Norway. Clim. Chang. 113, 413–436. http://dx.doi.org/10.1007/s10584-011-0325-0.

Milledge, D.G., Bellugi, D., McKean, J.A., Densmore, A.L., Dietrich, W.E., 2014. A multidimensional stability model for predicting shallow landslide size and shape across landscapes. J. Geoph. Res. 119, 2481–2504. http://dx.doi.org/10.1002/(ISSN)2169-9011.

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., Stouffer, R.J., 2008. Stationarity is dead: whither water management? Science 319, 573–574. http://dx.doi.org/10.1126/science.1151915.

Montanari, A., Koutsoyiannis, D., 2014. Modeling and mitigating natural hazards: stationarity is immortal! Water Resour. Res. 50 (12), 9748–9756. http://dx.doi.org/10.1002/2014WR016092.

Moody, J.A., Shakesby, R.A., Robichaud, P.R., Cannon, S.H., Martin, D.A., 2013. Current research issues related to post-wildfire runoff and erosion processes. Earth Sci. Rev. 122 (C), 10–37. http://dx.doi.org/10.1016/j.earscirev.2013.03.004, 2013.

Moore, R., Carey, J.M., McInnes, R.G., 2010. Landslide behaviour and climate change: predictable consequences for the Ventnor Undercliff, Isle of Wight. Q. J. Eng. Geol. Hydrogeol. 43, 447–4606. http://dx.doi.org/10.1144/1470-9236/08-086.

Munich RE, 2016. Natural catastrophes 2015: analyses, assessments, positions. Topics Geo. Munich Reinsurance Company, Munchen 65 pp.

Nadim, F., Kjekstad, O., Peduzzi, P., Herold, C., Jaedicke, C., 2006. Global landslide and avalanche hotspots. Landslides 3 (2), 159–173. http://dx.doi.org/10.1007/s10346-006-0036-1.

Nadim, F., Jaedicke, C., Smebye, H., Kalsnes, B., 2013. Assessment of global landslide hazard hotspots. In: Sassa, K., Rouhban, B., Briceno, S., McSaveney, M., He, B. (Eds.), Landslides: Global Risk Preparedness. Springer-Verlag, pp. 59–71 http://dx.doi.org/10.1007/978-3-642-22087-6_4.

Nikolopoulos, E.I., Borga, M., Marra, F., Crema, S., Marchi, L., 2015. Debris flows in the Eastern Italian Alps: seasonality and atmospheric circulation patterns. Nat. Hazards Earth Syst. Sci. 15, 647–656. http://dx.doi.org/10.5194/nhess-15-647-2015.

Observatoire national sur les effets du réchauffement climatique, 2007m. Stratégie nationale d'adaptation au changement climatique. La documentation Française (96 pp.) (in French).

Palomba, M., Giardino, M., Ratto, S., Pogliotti, P., 2015. Analysis of factor controlling landslide susceptibility in the Aosta Valley (NW Italy): relationship to climatic and environmental changes. In: Lollino, G., Manconi, A., Clague, J., Shan, W., Chiarle, M. (Eds.), Engineering Geology for Society and TerritoryClimate Change and Engineering Geology 1. Springer International Publishing, pp. 435–438.

Paolini, L., Villalba, R., Grau, H.R., 2005. Precipitation variability and landslide occurrence in a subtropical mountain ecosystem of NW Argentina. Dendrochronologia 22, 175–180. http://dx.doi.org/10.1016/j.dendro.2005.06.001.

Paranunzio, R., Laio, F., Nigrelli, G., Chiarle, M., 2015. A method to reveal climatic variables triggering slope failures at high elevation. Nat. Hazards 76, 1039–1061. http://dx.doi.org/10.1007/s11069-014-1532-6.

Paranunzio, R., Laio, F., Chiarle, M., Nigrelli, G., Guzzetti, F., 2016. Climate anomalies associated to the occurrence of rockfalls at high-elevation in the Italian Alps. Nat. Hazard Earth Sys. Sci. Discuss. http://dx.doi.org/10.5194/nhess-2016-100.

Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E., 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK 976 pp.

Pauling, A., Pauleth, H., 2007. On the variability of return periods of European winter precipitation extremes over the last three centuries. Clim. Past 3, 65–76. http://dx.doi.org/10.5194/cp-3-65-2007.

Peleg, N., Ben-Asher, M., Morin, E., 2013. Radar subpixel-scale rainfall variability and uncertainty: lessons learned from observations of a dense rain-gauge network. Hydrol. Earth Syst. Sci. 17, 2195–2208. http://dx.doi.org/10.5194/hess-17-2195-2013.

Penna, D., Borga, M., Aronica, G.T., Brigandì, G., Tarolli, P., 2014. The influence of grid resolution on the prediction of natural and road-related shallow landslides. Hydrol. Earth Syst. Sci. 18, 2127–2139. http://dx.doi.org/10.5194/hess-18-2127-2014.

Peruccacci, S., Brunetti, M.T., Luciani, S., Vennari, C., Guzzetti, F., 2012. Lithological and seasonal control on rainfall thresholds for the possible initiation of landslides in central Italy. Geomorphology 139–140, 79–90. http://dx.doi.org/10.1016/j.geomorph.2011.10.005.

Petley, D., 2012. Global patterns of loss of life from landslides. Geology 40 (10), 927–930. http://dx.doi.org/10.1130/G33217.1.

Pinyol, N.M., Alonso, E.E., Olivella, S., 2008. Rapid drawdown in slopes and embankments. Water Resour. Res. 44 (5). http://dx.doi.org/10.1029/2007WR006525.

Polemio, M., Lonigro, T., 2013. Climate variability and landslide occurrence in Apulia (Southern Italy). In: Margottini, C., Canuti, P., Sassa, K. (Eds.), Landslide Science and PracticeGlobal Environmental Change 4. Springer, Berlin Heidelberg, pp. 37–41.

Polemio, M., Lonigro, T., 2015. Trends in climate, short-duration rainfall, and damaging hydrogeological events (Apulia, Southern Italy). Nat. Hazards 75, 515–540. http://dx.doi.org/10.1007/s11069-014-1333-y.

Polemio, M., Petrucci, O., 2010. Occurrence of landslide events and the role of climate in the twentieth century in Calabria, southern Italy. Q. J. Eng. Geol. Hydrogeol. 43, 403–415. http://dx.doi.org/10.1144/1470-9236/09-006.

Ponziani, F., Pandolfo, C., Stelluti, M., Berni, N., Brocca, L., Moramarco, T., 2012. Assessment of rainfall thresholds and soil moisture modeling for operational hydrogeological risk prevention in the Umbria region (central Italy). Landslides 9, 229–237.

Ravanel, L., Deline, P., 2011. Climate influence on rockfalls in high-Alpine steep rockwalls: The north side of the Aiguilles de Chamonix (Mont Blanc massif) since the end of the 'Little Ice Age'. The Holocene 21 (2), 357–365. http://dx.doi.org/10.1177/0959683610374887.

Ravanel, L., Deline, P., 2015. Rockfall hazard in the Mont Blanc massif increased by the current atmospheric warming. In: Lollino, G., Manconi, A., Clague, J., Shan, W., Chiarle, M. (Eds.), Engineering Geology for Society and TerritoryClimate Change and Engineering Geology 1. Springer International Publishing, pp. 425–428.

Rebetez, M., Lugon, R., Baeriswyl, P.-A., 1997. Climatic change and debris flows in high mountain regions: the case study of the Ritigraben torrent (Swiss Alps). Clim. Chang. 36, 371–389. http://dx.doi.org/10.1023/A:1005356130392.

Reichenbach, P., Cardinali, M., De Vita, P., Guzzetti, F., 1998. Regional hydrological thresholds for landslides and floods in the Tiber River Basin (central Italy). Environ. Manag. 35 (2–3), 146–159. http://dx.doi.org/10.1007/s002540050301.

Reichenbach, P., Busca, C., Mondini, A.C., Rossi, M., 2014. The influence of land use change on landslide susceptibility zonation: the Briga catchment test site (Messina, Italy). Environ. Manag. 54, 1372–1384. http://dx.doi.org/10.1007/s00267-014-0357-0.

Riahi, K., Rao, S., Krey, V., Cho, V., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., Rafaj, P., 2011. RCP 8.5 — a scenario of comparatively high greenhouse gas emissions. Clim. Chang. 109, 33–57. http://dx.doi.org/10.1007/s10584-011-0149-y.

Rianna, G., Zollo, A.L., Tommasi, P., Paciucci, M., Comegna, L., Mercogliano, P., 2014. Evaluation of the effects of climate changes on landslide activity of Orvieto clayey slope. Procedia Earth Plan. Sci. 9, 54–63. http://dx.doi.org/10.1016/j.proeps.2014.06.017.

Richards, L., 1931. Capillary conduction of liquids through porous mediums. Physics 1, 318–333. http://dx.doi.org/10.1063/1.1745010.

Rist, A., Phillips, M., 2005. First results of investigations on hydrothermal processes within the active layer above alpine permafrost in steep terrain. Norwegian Journal of Geography 59 (2), 177–183. http://dx.doi.org/10.1080/00291950510020574.

Rockel, B., Will, A., Hense, A., 2008. The regional climate model COSMO-CLM (CCLM). Meteorol. Z. 17 (4), 347–348.

Roeckner, E., Oberhuber, J.M., Bacher, A., Christoph, M., Kirchner, I., 1996. ENSO variability and atmospheric response in a global coupled atmosphere-ocean GCM. Clim. Dyn. 12, 737–754.

Rossi, M., Witt, A., Guzzetti, F., Malamud, B.D., Peruccacci, S., 2010. Analysis of historical landslide time series in the Emilia-Romagna region, northern Italy. Earth Surf. Process. Landf. 35, 1123–1137. http://dx.doi.org/10.1002/esp.1858.

Saez, J.L., Corona, C., Stoffel, M., Berger, F., 2013. Climate change increases frequency of shallow spring landslides in the French Alps. Geology 41 (5), 619–622. http://dx.doi.org/10.1130/G34098.1.

Salvati, P., Bianchi, C., Guzzetti, F., 2006. Catalogo delle Frane e delle Inondazioni Storiche in Umbria. CNR IRPI e Fondazione Cassa di Risparmio di Perugia ISBN-10 88-95172-00-0, ISBN-13 978-88-95172-00-2, (278 pp.) (in Italian).

Samia, J., Temme, A., Bregt, A., Wallinga, J., Guzzetti, F., Ardizzone, F., Rossi, M., 2016. Do landslides follow landslides? Insights in path dependency from a multi-temporal landslide inventory. Landslides accepted for publication.

Santini, M., Valentini, R., 2011. Predicting hot-spots of land use changes in Italy by ensemble forecasting. Reg. Environ. Chang. 11, 483–502. http://dx.doi.org/10.1007/s10113-010-0157-x.

Schmidt, J., Dikau, R., 2004. Modeling historical climate variability and slope stability. Geomorphology 60, 433–447. http://dx.doi.org/10.1016/j.geomorph.2003.11.001.

Schmidt, J., Glade, T., 2003. Linking global circulation model outputs to regional geomorphic models: a case study of landslide activity in New Zealand. Clim. Res. 25, 135–150. http://dx.doi.org/10.3354/cr025135.

Scoccimarro, E., Gualdi, S., Bellucci, A., Sanna, A., Fogli, P.G., Manzini, E., Vichi, M., Oddo, P., Navarra, A., 2011. Effects of tropical cyclones on ocean heat transport in a high resolution coupled general circulation model. J. Clim. 24, 4368–4384.

Seidou, O., Ramsay, A., Nistor, I., 2012a. Climate change impacts on extreme floods I: combining imperfect deterministic simulations and non-stationary frequency analysis. Nat. Hazards 61, 647–659. http://dx.doi.org/10.1007/s11069-011-0052-x.

Seidou, O., Ramsay, A., Nistor, I., 2012b. Climate change impacts on extreme floods II: improving flood future peaks simulation using non-stationary frequency analysis. Nat. Hazards 60, 715–726. http://dx.doi.org/10.1007/s11069-011-0047-7.

Senatore, A., Mendicino, G., Smiatek, G., Kunstmann, H., 2011. Regional climate change projections and hydrological impact analysis for a Mediterranean basin in Southern Italy. J. Hydrol. 399, 70–92. http://dx.doi.org/10.1016/j.jhydrol.2010.12.035.

Seneviratne, S.I., Nicholls, N., Easterling, D., Goodess, C.M., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C., Zhang, X., 2012. Changes in climate extremes and their impacts on the natural physical environment. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., Midgley, P.M. (Eds.), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 109–230.

Sewell, R.J., Parry, S., Millis, S.W., Wang, N., Rieser, U., DeWit, R., 2015. Dating of debris flow fan complexes from Lantau Island, Hong Kong, China: the potential relationship between landslide activity and climate change. Geomorphology 248, 205–227.

Seychelles National Climate Change Committee, 2009. Seychelles National Climate Change Strategy 96 pp.

Shou, K.J., Yang, C.M., 2015. Predictive analysis of landslide susceptibility under climate change conditions - a study on the Chingshui River Watershed of Taiwan. Eng. Geol. 192, 46–62. http://dx.doi.org/10.1016/j.enggeo.2015.03.012.

Sidle, R.C., Burt, T.P., 2012. Temperate forests and rangelands. In: Slaymaker, O., Spencer, T., Embleton-Hamann, C. (Eds.), Geomorphology and Global Environmental Change. Cambridge University Press, pp. 321–343.

Sidle, R.C., Chigira, M., 2004. Landslides and debris flows strike Kyushu, Japan. EOS Trans. Am. Geophys. Union 85 (15), 141–151.

Sidle, R.C., Dhakal, A.S., 2002. Potential effects of environmental change on landslide hazards in forest environments. In: Sidle, R.C. (Ed.), Environmental Change and Geomorphic Hazards in ForestsIUFRO Research Series 9. CABI Publishing, Wallingford, Oxen, UK, pp. 123–165. http://dx.doi.org/10.1079/9780851995984.0123.

Sidle, R.C., Ochiai, H., 2006. Landslides: processes, prediction, and land use. Water Resour. Monogr. Ser. 18. AGU, Washington DC. http://dx.doi.org/10.1029/WM018 312 pp.

Sidle, R.C., Ziegler, A.D., Negishi, J.N., Nik, A.R., Siew, R., Turkelboom, F., 2006. Erosion processes in steep terrain—truths, myths, and uncertainties related to forest management in Southeast Asia. For. Ecol. Manag. 224 (1–2), 199–225. http://dx.doi.org/10.1016/j.foreco.2005.12.019.

Sidorova, T., Belaya, N., Pero, V., 2001. Distribution of slushflows in northern Europe and their potential change due to global warming. Ann. Glaciol. 32 (1), 237–240. http://dx.doi.org/10.3189/172756401781819742.

Simoni, S., Zanotti, F., Bertoldi, G., Rigon, R., 2008. Modelling the probability of occurrence of shallow landslides and channelized debris flows using GEOtop-FS. Hydrol. Process. 22 (4), 532–545. http://dx.doi.org/10.1002/hyp.6886.

Soldati, M., Corsini, A., Pasuto, A., 2004. Landslides and climate change in the Italian Dolomites since the Late glacial. Catena 55, 141–161. http://dx.doi.org/10.1016/S0341-8162(03)00113-9.

Soldati, M., Borgatti, L., Cavallin, A., De Amicis, M., Frigerio, S., Giardino, M., Mortasa, G., Pellegrini, G.B., Ravazzi, C., Surian, N., Tellini, C., Alberto, W., Albanese, D., Chelli, A., Corsini, A., Marchetti, M., Palomba, M., Panizza, M., 2006. Geomorphological evolution of slopes and climate changes in Northern Italy during the Late Quaternary: spatial and temporal distribution of landslides and landscape sensitivity implications. Geogr. Fis. Din. Quater. 29 (2), 165–183.

Spearman, C., 1904. The proof and measurement of association between two things. Am. J. Psychol. 15 (1), 72–101.

Spiegelman, D., 2010. Commentary: some remarks on the seminal 1904 paper of Charles Spearman "the proof and measurement of association between two things". Int. J. Epidemiol. 39 (5), 1156–1159. http://dx.doi.org/10.1093/ije/dyq201.

Stähli, M., Sättele, M., Huggel, C., McArdell, B.W., Lehmann, P., Van Herwijnen, A., Berne, A., Schleiss, M., Ferrari, A., Kos, A., Or, D., Springman, S.M., 2015. Monitoring and prediction in early warning systems for rapid mass movements. Nat. Hazards Earth Syst. Sci. 15 (4), 905–917. http://dx.doi.org/10.5194/nhess-15-905-2015.

Stark, C.P., Guzzetti, F., 2009. Landslide rupture and the probability distribution of mobilized debris volumes. J. Geophys. Res. 114, F00A02. http://dx.doi.org/10.1029/2008JF001008.

Stoffel, M., Beniston, M., 2006. On the incidence of debris flows from the early Little Ice Age to a future greenhouse climate: a case study from the Swiss Alps. Geophys. Res. Lett. 33, L16404. http://dx.doi.org/10.1029/2006GL026805.

Stoffel, M., Huggel, C., 2012. Effects of climate change on mass movements in mountain environments. Prog. Phys. Geogr. 36 (3), 421–439. http://dx.doi.org/10.1177/0309133312441010.

Stoffel, M., Lievré, I., Conus, D., Grichting, M.A., Raetzo, H., Gartner, H.W., Monbaron, M., 2005. 400 Years of debris–flow activity and triggering weather conditions: Ritigraben, Valais, Switzerland. Artic Antarctic Alpine Research 37 (3), 387–395.

Stoffel, M., Bollschweiler, M., Butler, D.R., Luckman, B., 2010. Tree rings and natural hazards. A state-of-the-art. Springer http://dx.doi.org/10.1007/978-90-481-8736-2_11.

Stoffel, M., Bollschweiler, M., Beniston, M., 2011. Rainfall characteristics for periglacial debris flows in the Swiss Alps: past incidences–potential future evolutions. Clim. Chang. 105, 263–280. http://dx.doi.org/10.1007/s10584-011-0036-6.

Stoffel, M., Tiranti, D., Huggel, C., 2014. Climate change impacts on mass movements - case studies from the European Alps. Sci. Total Environ. 493, 1255–1266. http://dx.doi.org/10.1016/j.scitotenv.2014.02.102.

Swart, R., Biesbroek, R., Binnerup, S., Carter, T.R., Cowan, C., Henrichs, T., Loquen, S., Mela, H., Morecroft, M., Reese, M., Rey, D., 2009. Europe adapts to climate change. Comparing National Adaptation Strategies ISBN 978-952-11-3451-7, (283 pp.).

Tacher, L., Bonnard, C., 2007. Hydromechanical modelling of a large landslide considering climate change conditions. In: McInnes, R., Jakeways, J., Fairbank, H., Mathie, E. (Eds.), Landslides and Climate Change: Challenges and SolutionsProceedings of the International Conference on Landslides and Climate Change. Taylor & Francis, Ventnor, pp. 131–141.

Taylor, D.W., 1948. Fundamentals of Soil Mechanics. Wiley, New York 711 pp.

Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2011. An overview of CMIP5 and the Experiment Design. Bull. Am. Meteorol. Soc. 93, 485–498. http://dx.doi.org/10.1175/BAMS-D-11-00094.1.

Taylor, F.E., Malamud, B.D., Freeborough, K., Demeritt, D., 2015. Enriching Great Britain's National Landslide Database by searching newspaper archives. Geomorphology 249, 1–17. http://dx.doi.org/10.1016/j.geomorph.2015.05.019.

Teutschbein, C., Seibert, J., 2012. Bias correction of regional climate model simulations for hydrological climate-change impact studies: review and evaluation of different methods. J. Hydrol. 456–457, 12–29. http://dx.doi.org/10.1016/j.jhydrol.2012.05.052.

Thomas, M.F., 1999. Evidence for high energy landforming events of the central African plateau: eastern province, Zambia. Z. Geomorphologie N.F. 43 (3), 273–297.

Tommasi, P., Pellegrini, P., Boldini, D., Ribacchi, R., 2006. Influence of rainfall regime on hydraulic conditions and movement rates in the overconsolidated clayey slope of the Orvieto hill (Central Italy). Can. Geotech. J. 43, 70–86. http://dx.doi.org/10.1139/cgj-2012-0121.

Trauth, M.H., Alonso, R.A., Haselton, K.R., Hermanns, R.L., Strecker, M.R., 2000. Climate change and mass movements in the NW Argentine Andes. Earth Planet. Sci. Lett. 179 (2), 243–256. http://dx.doi.org/10.1016/S0012-821X(00)00127-8.

Trauth, M.H., Bookhagen, B., Marwan, N., Strecker, M.R., 2003. Multiple landslide clusters record Quaternary climate changes in the northwestern Argentine Andes. Palaeogeogr. Palaeoclimatol. Palaeoecol. 194 (1–3), 109–121. http://dx.doi.org/10.1016/S0031-0182(03)00273-6.

Turkington, T., Ettema, J., van Westen, C., Breinl, K., 2014. Empirical atmospheric thresholds for debris flows and flash floods in the southern French Alps. Nat. Hazards Earth Syst. Sci. 14, 1517–1530. http://dx.doi.org/10.5194/nhess-14-1517-2014.

Turkington, T., Remaître, A., Ettema, J., Hussin, H., van Westen, C., 2016. Assessing debris flow activity in a changing climate. Clim. Chang. http://dx.doi.org/10.1007/s10584-016-1657-6.

Uchida, T., Kosugi, K., Mizuyama, T., 2001. Effects of pipeflow on hydrological process and its relation to landslide: a review of pipeflow studies in forested headwater catchments. Hydrol. Process. 15 (11), 2151–2174. http://dx.doi.org/10.1002/hyp.281.

UK Government, 2012. UK Climate Change Risk Assessment: Government Report. The Stationery Office 48 pp.

United Republic of Tanzania, 2012. National Climate Change Strategy 112 pp.

van Beek, L.P.H., 2002. Assessment of the Influence of Changes in Land Use and Climate on Landslide Activity in a Mediterranean Environment. Netherlands Geo-Graphical Studies NGS 294, Utrecht 360 pp.

Van Den Eeckhaut, M., Hervás, J., 2012. State of the art of national landslide databases in Europe and their potential for assessing landslide susceptibility, hazard and risk. Geomorphology 139–140, 545–558. http://dx.doi.org/10.1016/j.geomorph.2011.12.006.

Van Den Eeckhaut, M., Poesen, J.A., Govers, G., Verstraeten, G., Demoulin, A., 2007. Characteristics of the size distribution of recent and historical landslides in a populated hilly region. Earth Planet. Sci. Lett. 256 (3–4), 588–603. http://dx.doi.org/10.1016/j.epsl.2007.01.040.

Vennari, C., Gariano, S.L., Antronico, L., Brunetti, M.T., Iovine, G.G.R., Peruccacci, S., Terranova, O.G., Guzzetti, F., 2014. Rainfall thresholds for shallow landslide occurrence in Calabria, southern Italy. Nat. Hazards Earth Syst. Sci. 14 (2), 317–330. http://dx.doi.org/10.5194/nhess-14-317-2014.

Verachtert, E., Maetens, W., Van Den Eeckhaut, M., Poesen, J.A., Deckers, J., 2011. Soil loss rates due to piping erosion. Earth Surf. Process. Landf. 36 (13), 1715–1725. http://dx.doi.org/10.1002/esp.2186.

Villani, V., Rianna, G., Mercogliano, P., Zollo, A.L., 2015. Statistical approaches versus weather generator to downscale RCM outputs to slope scale for stability assessment: a comparison of performances. Electron. J. Geotech. Eng. 20, 1495–1515.

Warren, F.J., Lemmen, D.S., 2014. Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation. Government of Canada, Ottawa 286 pp.

Wasowski, J., Lamanna, C., Casarano, D., 2010. Influence of land-use change and precipitation patterns on landslide activity in the Daunia Apennines, Italy. Q. J. Eng. Geol. Hydrogeol. 43, 387–401. http://dx.doi.org/10.1144/1470-9236/08-101.

Wilby, R.L., Wigley, T.M.L., 1997. Downscaling general circulation model output: a review of methods and limitations. Prog. Phys. Geogr. 21, 530–548. http://dx.doi.org/10.1177/030913339702100403.

Winter, M.G., Shearer, B., 2015. Climate change and landslide hazard and risk in Scotland. In: Lollino, G., Manconi, A., Clague, J., Shan, W., Chiarle, M. (Eds.), Engineering Geology for Society and TerritoryClimate Change and Engineering Geology 1. Springer International Publishing, pp. 411–414.

Winter, M.G., Dent, J., Macgregor, F., Dempsey, P., Motion, A., Shackman, L., 2010. Debris flow, rainfall and climate change in Scotland. Q. J. Eng. Geol. Hydrogeol. 43, 429–446. http://dx.doi.org/10.1144/1470-9236/08-108.

Witt, A., Malamud, B.D., Rossi, M., Guzzetti, F., Peruccacci, S., 2010. Temporal correlations and clustering of landslides. Earth Surf. Process. Landf. 35 (10), 1138–1156. http://dx.doi.org/10.1002/esp.1998.

Wood, J.L., Harrison, S., Reinhardt, L., 2015. Landslide inventories for climate impacts research in the European Alps. Geomorphology 228, 398–408. http://dx.doi.org/10.1016/j.geomorph.2014.09.005.

Wood, J.L., Harrison, S., Turkington, T., Reinhardt, L., 2016. Landslides and synoptic weather trends in the European Alps. Clim. Chang. 136, 297–308. http://dx.doi.org/10.1007/s10584-016-1623-3.

Wu, T.H., 2013. Root reinforcement of soil: review of analytical models, test results, and applications to design. Can. Geotech. J. 50 (3), 259–274. http://dx.doi.org/10.1139/cgj-2012-0160.

Wu, X., Chen, X., Zhan, F.B., Hong, S., 2015. Global research trends in landslides during 1991–2014: a bibliometric analysis. Landslides 1–12 http://dx.doi.org/10.1007/s10346-015-0624-z.

Yin, Z., Qin, X., Yin, Y., Zhao, W., Wei, G., 2014. Landslide developmental characteristics and response to climate change since the last glacial in the upper reaches of the Yellow river, NE Tibetan plateau. Acta Geol. Sin. (English edition) 88 (2), 635–646. http://dx.doi.org/10.1111/1755-6724.12219.

Yukimoto, S., Noda, A., Uchiyama, T., Kusunoki, S., Kitoh, A., 2006. Climate changes of the twentieth through twenty-first centuries simulated by the MRI-CGCM2.3. Pap. Meteorol. Geophys. 56, 9–24.

Zêzere, J.L., Pereira, S., Tavares, A.O., Bateira, C., Trigo, R.M., Quaresma, I., Santos, P.P., Santos, M., Verde, J., 2014. DISASTER: a GIS database on hydro-geomorphologic disasters in Portugal. Nat. Hazards 72 (2), 503–532. http://dx.doi.org/10.1007/s11069-013-1018-y.

Zimmermann, M., Haeberli, W., 1992. Climatic change and debris flow activity in high mountain areas - A case study in the Swiss Alps. Catena Suppl. 22, 59–72.

Zollo, A.L., Rianna, G., Mercogliano, P., Tommasi, P., Comegna, L., 2014. Validation of a simulation chain to assess climate change impact on precipitation induced landslides. In: K. Sassa, K., Canuti, P., Yin, Y. (Eds.), Landslide Science for a Safer Geoenvironment 1. Springer International Publishing, pp. 287–292.