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Review of approaches for assessing the impact of climate change on landslide hazards

J.A. Coe & J.W. Godt
U.S. Geological Survey, Denver Federal Center, Denver, Colorado, USA

ABSTRACT: As part of an effort to understand the impact of climate change on landslide activity, we identified fourteen technical approaches used to assess the issue, compiled their strengths and weaknesses, and placed them in one of three categories: 1) long-term monitoring of climate change and the accompanying landslide response, 2) retrospective approaches that establish links between climate and landslide activity from historical or prehistoric data, and 3) prospective approaches that establish patterns between historical landslide activity and climate records and then use these patterns with downscaled climate projections to predict future landslide activity. Results from studies to predict the activity of precipitation-triggered shallow landslides and debris flows have the greatest uncertainty because of difficulty in predicting the frequency and magnitude of short-term extreme storms and storm systems. Results from studies that predict landslide activity using air temperature, sea-level rise, or annual/seasonal precipitation are less uncertain because there is less difficulty in predicting these variables. In North America, we suggest that productive advances can be made in the near-term by examining the effects of climate change on coastal landslides, temperature-controlled landslides in high altitude and latitude areas, and deep-seated landslides in areas with expected increases in annual precipitation.

1 INTRODUCTION

Landslide hazards are evaluated over a range of scales depending on the needs of end users. For example, a land developer may be interested in the hazard posed by a single large landslide, whereas the insurance industry may be interested in landslide hazards at a national scale (e.g., Godt et al., this volume). Most landslide hazard assessments are conducted at local to regional scales (e.g., single landslides, highway corridors, large drainage basins or mountain range fronts, see van Westen 2006). Effective management of landslide hazards at local to regional scales requires an understanding of how landslide processes, frequency, and magnitude may be altered by a changing climate. However, two issues impede rapid advances in understanding the impact of climate change on landslide hazards. First, landslide activity is difficult to forecast in a static climate, so forecasting landslide activity in a changing climate is challenging at best. Second, projections of changes in precipitation tend to focus on projection of mean conditions for relatively large areas rather than on the frequency and magnitude of extremes. Such projections poorly correspond with the temporal and spatial scale of landslide occurrence and hazard assessments.

Despite these difficulties, since the release of the First Assessment Report in 1990 by the Intergovernmental Panel on Climate Change (IPCC 1990), the number of scientific publications on landslides and climate change has steadily grown. Additionally, since 2007, there has been at least one specialty conference on landslides and climate change, three special journal issues, and the establishment of multiple special projects on the topic. This pattern of increasing publications and general interest indicates that the topic of landslides and climate change is, and will continue to be, an ongoing challenge for landslide scientists.

Landslide occurrence is sensitive to precipitation over timescales ranging from minutes to years. Seasonal and longer-term variations in rainfall and potential evaporation influence soil moisture and recharge, and thus the near-surface groundwater flow field. This flow field controls the initiation and movement of deep-seated landslides (e.g., Iverson & Reid 1992), typically slope failures a few to several tens of meters thick, generally involving the surficial mantle and underlying bedrock. The occurrence of shallow landslides, typically failures of the poorly consolidated surficial mantle or regolith less than a few meters thick, is sensitive to initial soil moisture conditions and variation in storm-scale precipitation intensity and duration (e.g., Godt et al., 2006). The abundance, frequency, and magnitude of landslides are sensitive to the "extremes" in the hydrological cycle, whether they are extended drought and evapotranspiration that reduces groundwater levels leading to a decrease or cessation of deep-seated landslide movement (e.g., Coe, in press) or exceptionally heavy rainfall that generates shallow landslides (e.g., Sidle 2007).

Clearly, technical approaches that address the impact of climate change on landslide hazards have to address many complex variables. In this paper, we review the strengths and weaknesses of technical approaches that have been used to address the impact of climate change on landslide hazards. Our intent with this work is to provide a resource for landslide researchers interested in the climate change/landslide issue.

2 REVIEW OF TECHNICAL APPROACHES

We have identified fourteen technical approaches that have been used to address the impact of climate change on landslide hazards (Table 1). We divided the approaches into three categories: 1) long-term monitoring of changes in climate variables such as rainfall rates and temperature, and the accompanying geomorphic response at study sites (see monitoring approach 1, Table 1); 2) approaches to establish links between past climate and landslide occurrence (see retrospective approaches 2–9, Table 1); and 3) approaches to establish changes in landslide frequency or magnitude in the future using established patterns of historical activity and climate projections (prospective approaches 10–14, Table 1). Approaches in all three of these categories are at least partly reliant on an assumption of stationarity of climate if they use historical observations or statistically downscaled projections based on historical observations between global climate and regional climate. Stationarity (e.g., Milly et al., 2008) is the concept that natural systems (e.g., climate and landslides) fluctuate within an unchanging envelope of variability (i.e., mean values are stationary through time). Climate change is projected to alter the extremes and means of temperature and precipitation beyond the range of historical variability (e.g., IPCC 2007), which will eventually render the stationarity assumption invalid. Studies that use dynamical downscaling techniques, which use physical equations in numerical models to convert global climate patterns into regional/local projections, do not assume stationarity of climate.

Each of the approaches in Table 1 has strengths and weaknesses. Most of the strengths and weaknesses that we identified are related to input and output data, rather than to the methodology of the approaches themselves. An obvious strength of the monitoring approach is that it provides robust data that form a basis for interpretive models of slope processes ranging from melting of permafrost and rock weathering to massive slope failures. Results from approach 1 can potentially provide information to all landslide studies related to climate change. Unfortunately, the main problem with the monitoring approach is not scientific, but political. In the current era of budget tightening, financial support for long-term monitoring efforts is unusual, perhaps because long-term monitoring does not provide information that decision makers can act upon in the near term. Long-term monitoring efforts require lasting commitments from funding agencies and scientists.

Retrospective approaches rely on historical observations or Quaternary deposits and proxy climate records (approaches 2–9, Table 1). This reliance is both a strength and weakness. Empirical observations provide a sound basis for interpretation and conclusions. However, observations, deposits, and records are nearly always incomplete, therefore distinguishing among possible triggers and any climate influence, as well as reconstruction of the timing of landslides can be difficult. These issues become more prominent as past-time increases. Dating techniques applicable to pre-historic landslides are generally of insufficient temporal accuracy (+/– 5 years at best, e.g., Lang et al., 1999) to correlate landslide occurrence with seasonal or annual precipitation, although approaches that use dendrochronology and varve dating (approaches 5 and 7, Table 1) can provide dates accurate to < 1 year. Pre-historic reconstructions of past climate rely on proxy records and tend to identify warm/dry periods from cool/wet periods, but are generally poor at isolating/identifying the short-term extreme precipitation or temperature events that often trigger shallow slides, rockfalls, and debris flows (e.g., Schmidt & Dikau 2004).

Prospective approaches rely on relations between climate and landslides established from historical records, followed by the use of these relations with downscaled projections of air temperature and precipitation to predict future landslide activity (approaches 10–14, Table 1). Projected changes in air temperature are more consistent than projected changes in precipitation (e.g., Randall et al., 2007, Meehl et al., 2007). Unlike temperature, which is largely determined by insolation and the configuration of oceans and continents, precipitation is strongly influenced by the vertical movement of air, which is dependent on multiple processes that are difficult to predict (Randall et al., 2007). Therefore, our opinion is that approaches that rely on projected air temperatures (approaches 10 and 14) produce results with less uncertainty than approaches based on projections of precipitation (approaches 11–13). Approaches 10 and 14 have been used in coastal areas to assess the impact of rising sea level on coastal bluff stability and in alpine- and high-latitude areas where melting of ice and permafrost is a major factor in the stability

Table 1. List of technical approaches used assess the impact of climate change on landslide hazards.

Approach	Strengths	Weaknesses	Example*
1. Establish long-term study sites where impacts of climate change can be measured and observed	Provides observational data on changes in landslide response due to climate change.	Requires long-term commitment from funding agencies and patience of scientists involved. Many study sites are needed to assess impacts to broad geographic regions.	Jaedicke et al., 2008
2. Evaluate changes in sediment supply, debutressing of slopes, and/or hydrology in source areas to predict future activity	Results tend to provide binary answers, i.e., there will be an increase or decrease in sediment supply. Implications are that future events will be transport limited or supply limited.	Inability to predict characteristics of specific triggering events.	Evans & Clague 1994
3. Compare the impact of changes due to historical land-use and population growth to impacts from changes in historical climate	Provides defensible results on the relative influence that climate, population, and land use will have on slope stability.	Based exclusively on historical observations that may or may not apply to the future.	Petley 2010
4. Map and date fan sediments (related to wildfire and not related to wildfire)	Possible to identify temporal clusters of debris flows linked to warmer/drier (periods of drought) or cooler/wetter past climatic conditions.	Provides a minimum record of debris flow activity. Requires distinguishing debris flow from non-debris flow deposits, a proxy climate record, and capability to date deposits. Inability to date extreme, short-term climatic events with high accuracy.	Pierce & Meyer 2008, Matthews et al., 2009
5. Map and date pond and lake sediments related to landslides	Possible to identify temporal clusters of landslides. Dating of varves can provide ages accurate to ≤ 1 year.	Provides a minimum record of landslide activity. Requires distinguishing climatically induced landsides from landslides caused by other processes (e.g., earthquake and land-use activities), a proxy climate record, and capability to accurately date deposits. Inability to date extreme, short-term climatic events with high accuracy.	Trauth et al., 2000
6. Map and date landslides	Possible to identify temporal clusters of landslides.	Provides a minimum record of landslide activity. Requires distinguishing climatically induced landsides from landslides caused by other processes (e.g., earthquake and land-use activities), a proxy climate record, and capability to accurately date deposits or scars. Inability to date extreme, short-term climatic events with high accuracy.	Soldati et al., 2004
7. Analyze tree rings (dendrochronology) from hillslopes or fan surfaces (related to wildfire and not related to wildfire)	Possible to identify extreme climatic events and temporal clusters of debris flows.	Provides a minimum record of landslide activity; period of analysis is limited to lifetime of trees.	Bigio et al., 2010, Stoffel & Beniston 2006
8. Analyze long record of historical debris flows with respect to precipitation, snowmelt, and/or elevation.	Identifies changes in debris flow frequency and magnitude in period of record.	Ideally requires a long period of record (≥ 30 years) with rainfall and debris flow occurrence data.	Jomelli et al., 2007

(*Continued*)

Table 1. (*Continued*).

9. Use proxy derived past climate data with hydrologic and slope stability models to predict past periods of slope instability.	Allows for scenario modeling; capability to incorporate historical landslide records.	Limited by large uncertainty in proxy climate data; analysis of general warm/dry, cool/wet trends only; generally not possible to resolve short-term extreme events.	Schmidt & Dikau 2004
10. Analyze occurrence of recent high latitude or high altitude landslides with respect to temperature or elevation data, some authors also evaluate the occurrence of future triggering warm spells using downscaled General Circulation Model (GCM)/Regional Climate Model (RCM) projections.	Results are based on air temperatures. Downscaled projections of air temperature are more consistent than projections of precipitation.	Temperature related triggers for rockfalls in historical inventories can be difficult to distinguish from other triggers (e.g., earthquakes, weathering and erosion). Temperature related triggering thresholds will probably have dynamic and/or limited temporal and spatial applicability as ice and permafrost degrade and disappear in a warming climate.	Huggel et al., 2010
11. Assess future shallow landslide or debris flow activity using downscaled results from GCMs/RCMs in combination with hydrologic, moisture balance, and/or slope stability models.	Hydrologic and slope stability models are capable of producing useful predictions given accurate downscaled projections. Allows for scenario modeling.	Results are highly dependent on the accuracy of the magnitude and frequency of short-term and extreme storms and storm tracks in downscaled climate projections. Projections of these storms currently contain a great deal of uncertainty.	Collison et al., 2000
12. Assess future deep-seated landslide activity using downscaled results from GCMs/RCMs in combination with hydrologic, moisture balance, and/or slope stability models.	Hydrologic and slope stability models are capable of producing useful predictions given the incorporation of evapotranspiration and accurate downscaled projections. Allows for scenario modeling. Projections of seasonal and annual precipitation and temperature (which control deep-seated landslides) contain less uncertainty than projections of extreme storms.	Results are dependent on the accuracy of seasonal and annual precipitation in downscaled climate projections.	Dehn & Buma 1999
13. Assess future shallow landslide or debris flow frequency using downscaled results from GCMs/RCMs in combination with existing precipitation thresholds.	Precipitation thresholds have proven reliability as predictors of local landslide activity. Allows for scenario modeling.	Results are highly dependent on the accuracy of the magnitude and frequency of short-term and extreme storms in downscaled climate projections. Projections of these storms currently contain a great deal of uncertainty. Results are applicable to limited geographic areas where thresholds have been developed.	Jakob & Lambert 2009
14. Assess future coastal bluff failures using wave height, sea level, and/or precipitation thresholds established from historical records in combination with projections of sea-level rise and precipitation.	Results are based partly on changes in sea level. Projections of changes in sea level contain less uncertainty than projections of precipitation. Allows for scenario modeling.	Results are dependent on the accuracy of long-term changes in temperature, precipitation, and sea level in climate projections.	Collins et al., 2007

* Multiple references are available for most approaches. Because of page length limitations, we only list one representative reference for each approach. Exceptions to this statement are approaches 4 and 7, where we list two references, the first related to wildfire, and the second not related to wildfire.

of slopes. Similarly, results from studies that focus on predicting deep-seated landslide activity triggered by long-term precipitation appear to have less uncertainty than results from studies that predict shallow landslides and debris flows from short-term precipitation. This situation results from greater uncertainty in projections of short-term precipitation that drives shallow landslide initiation. Projections of changes in seasonal and annual precipitation, which commonly control deep-seated landslides, are less uncertain than projections of short-term extreme precipitation (Randall et al., 2007).

3 CONCLUDING DISCUSSION

Our review of the technical approaches listed in Table 1 leads to us to pose two questions. First, what approaches are most effective for evaluating relations between landslide activity and climate change given our current understanding and available data? And second, in what geographic areas would results likely be of sufficient accuracy and specificity to be of use in assessing changes in landslide hazard?

Retrospective approaches that link pre-historic landslides to past climate variability will continue to be limited to general statements about temporal clusters of landslide occurrence. With good reason, many retrospective studies have focused on debris fans. Tributary fans that have not been eroded by mainstem rivers offer unique opportunities for climate change studies because they contain complete depositional records of debris flow and flood events through time. What is needed for fan stratigraphy to have a greater impact in climate-change studies are improved techniques for sampling, mapping, and dating, and better models of how deposits are distributed on fan surfaces through time.

For the prospective approaches, limited spatial and temporal resolution of precipitation projections will continue to hamper landslide assessments in the near future (e.g., Crozier 2010). In particular, there is inconsistency in downscaled predictions of changes in the magnitude and frequency of extreme storms and weather systems (e.g., Mass et al., 2011) such as Atmospheric Rivers (Ralph & Dettinger 2011). These short-term phenomena are often the trigger for shallow landslides and debris flows, therefore, characterizing the impact of climate change on these types of landslides will remain difficult. The uncertainty of long-term (e.g., seasonal to annual) downscaled projections is less than for short-term extreme storm predictions, and estimates of changes in long-term precipitation and temperature patterns are readily available.

Given these constraints, approaches that use projections of seasonal or annual precipitation, or temperature values, would produce results with less uncertainty than approaches that rely on projections of short-term, extreme precipitation. Thus, studies to predict the impact of climate change on deep-seated landslide activity, and landslides in high altitude or latitude areas related to melting of glaciers and permafrost, will probably produce results most useful for landslide hazard assessments in the near term.

In North America, annual precipitation is expected to increase in the north and decrease in the south (Fig. 1). The boundary between negative and positive changes in annual precipitation (i.e., the line of no change, or the zero line) is located in the United States (Fig. 1). Research into landslides in areas north of this line would be most likely to produce beneficial results in the near term. Possible approaches that would be applicable to this work are 9 and 12, with 14 being applicable along coastlines.

With increasing temperatures, a greater portion of total precipitation is expected to fall in extreme precipitation events (e.g., Karl et al., 2008). As the understanding of the magnitude and frequency of these events at specific locations advances, and the uncertainty in downscaled precipitation projections is reduced, our confidence in studies of changes in the hazard associated with shallow landslides and debris flows will increase.

Several efforts are necessary to prompt and facilitate landslide research related to climate change. First, continued development of climate models and downscaling techniques should improve projections of the magnitude and frequency of extreme precipitation events. Second, physical modeling would be helpful to estimate the period of time that landslide hazards related to melting of permafrost will be a concern. In a warming climate,

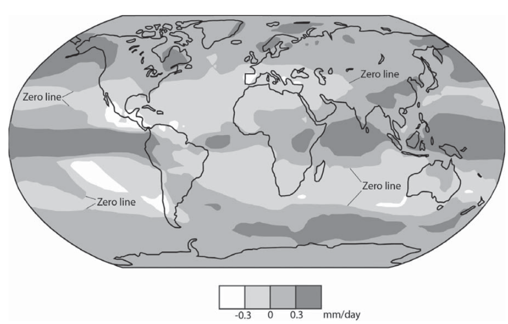

Figure 1. Change in annual mean precipitation (expressed in mm/day) from an ensemble of General Circulation Models using the A1B emissions scenario for the period 2080–2099 relative to 1980–1999. Zero line is the line of no change. Adapted from Meehl et al., 2007.

ice and permafrost will have a finite lifetime. Third, continued efforts should be made to better understand changes in the types and distribution of vegetation to improve estimates of evapotranspiration and predictions of wildfire and the potential for subsequent debris flows. Fourth, continued efforts should be made to better differentiate the impact of population growth and land use from climate-change effects. Lastly, continued improvement is needed in making downscaled climate projection data readily available. Readily available data should lead to the development and application of creative new landslide modeling approaches.

REFERENCES

Bigio, E., Swetnam, T.W. & Baisan, C.H. 2010. A comparison and integration of tree-ring and alluvial records of fire history at the Missionary Ridge Fire, Durango, Colorado, USA. *The Holocene* 20 (7): 1047–1061.

Coe, J.A. In press. Regional moisture balance control of landslide motion: implications for landslide forecasting in a changing climate. *Geology*.

Collins, B.D., Kayen, R. & Sitar, N. 2007. Process-based empirical prediction of landslides in weakly lithified coastal cliffs, San Francisco, California, USA. In R. McInnes, J. Jakeways, H. Fairbank, & E. Mathie (eds.), *Landslides and Climate Change—Challenges and Solutions*: 175–184. London: Taylor & Francis.

Collison, A., Wade, S., Griffths, J. & Dehn, M. 2000. Modelling the impact of predicted climate change on landslide frequency and magnitude in SE England. *Engineering Geology* 55: 205–218.

Crozier, M.J. 2010. Deciphering the effect of climate change on landslide activity: a review. *Geomorphology* 124: 260–267.

Dehn, M. & Buma, J. 1999. Modelling future landslide activity based on general circulation models. *Geomorphology* 30: 175–187.

Evans, S.G. & Clague, J.J. 1994. Recent climate changes and catastrophic geomorphic processes in mountain environments. *Geomorphology* 10: 107–128.

Godt, J.W., Baum, R.L. & Chleborad, A.F. 2006. Rainfall characteristics for shallow landslides in Seattle, Washington, USA. *Earth Surface Processes and Landforms* 31: 97–110.

Godt, J.W., Coe, J.A., Baum, R.L., Highland, L.M., Keaton, J.R. & Roth, J.R. Jr. 2011. Prototype landslide hazard maps of the conterminous United States, *this volume*.

Huggel, C., Slazmann, 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. *Philosophical Transactions of the Royal Society A* 368: 2435–2459.

IPCC. 1990. *Climate change—The IPCC Scientific Assessment*. Houghton J.T., Jenkins, G.J. & Ephraums, J.J. (eds.). Cambridge: Cambridge University Press, p. 365.

IPCC. 2007. *Climate Change 2007: The Physical Science Basis, Contribution of the Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., & Miller, H.L. (eds.). Cambridge: Cambridge University Press, p. 996.

Iverson, R.M. & Reid, M.E., 1992. Gravity-driven groundwater flow and slope failure potential 1. Elastic effective stress model. *Water Resources Research*: 28: 925–938.

Jaedicke, C., Solheim, A., Blikra, L.H., Stalsberg, K., Sorteberg, A., Aaheim, A., Kronholm, K., Vikhamar-Schuler, D., Isaksen, K., Sletten, K., Kristensen, K., Barstad, I., Melchiorre, C., Høydal, Ø.A. & Mestl, H. 2008. Spatial and temporal variations of Norwegian geohazards in a changing climate, the GeoExtreme Project. *Natural Hazards and Earth System Sciences* 8: 893–904.

Jakob, M. & Lambert, S. 2009. Climate change effects on landslides along the southwest coast of British Columbia. *Geomorphology* 107: 275–284.

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). *Climatic Change* 85: 119–137.

Karl, T.R., Meehl, G.A., Miller, C.D., Hassol, S.J., Waple, A.M. & Murray, W.L. (eds.). 2008. *Weather and climate extremes in a changing climate, Regions of focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands: Synthesis and Assessment Product 3.3 Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research*. Washington, D.C.: U.S. Climate Change Science Program, p. 162.

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.

Mass, C., Skalenakis, A. & Warner, M. 2011. Extreme precipitation over the west coast of North America: is there a trend? *Journal of Hydrometeorology* 12: 310–318.

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.

Meehl, G.A. 13 others. 2007. Global Climate Projections. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, & H.L. Miller (eds.), *Climate Change 2007, The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge: Cambridge University Press, 747–845.

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.

Petley, D.N. 2010. On the impact of climate change and population growth on the occurrence of fatal landslides in South, East and SE Asia. *Quarterly Journal of*

Engineering Geology and Hydrogeology 43: 487–496. doi: 10.1144/1470-9236/09-001

Pierce, J. & Meyer, G. 2008. Long-term fire history from alluvial fan sediments: the role of drought and climate variability, and implications for management of Rocky Mountain forests. *International Journal of Wildland Fire* 17: 84–95.

Ralph, F.M. & Dettinger, M.D. 2011. Storms, floods, and the science of Atmospheric Rivers. *EOS Transactions of the American Geophysical Union* 92: 265–266.

Randall, D.A. 12 others. 2007. Climate Models and Their Evaluation. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, & H.L. Miller (eds.), *Climate Change 2007, The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge: Cambridge University Press, 589–662.

Schmidt, J. & Dikau, R. 2004. Modeling historical climate variability and slope stability. *Geomorphology* 60: 433–447.

Sidle, R.C. 2007. Using weather and climate information for landslide prevention and mitigation. In M.V.K. Sivakumar & N. Ndiang'ui (eds.), *Climate and Land Degradation*: 285–307. Berlin: Springer.

Soldati, M., Corsini, A. & Pasuto, A. 2004. Landslides and climate change in the Italian Dolomites since the Late glacial. *Catena* 55: 141–161.

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. *Geophysical Research Letters* 33: L16404. doi:10.1029/2006GL026805.

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 and Planetary Science Letters* 179: 243–256. doi:10.1016/S0012-821X(00)00127-8.

van Westen, C.J., van Asch, T.W.J. & Soeters, R. 2006. Landslide hazard and risk zonation—why is it still so difficult?: *Bulletin of Engineering Geology and the Environment* 65: 167–184.