Weather and Climate Extremes 14 (2016) 67–79

Contents lists available at ScienceDirect

Weather and Climate Extremes

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

Landslides in West Coast metropolitan areas: The role of extreme weather events

Michela Biasutti[a,*], Richard Seager[a], Dalia B. Kirschbaum[b]

[a] Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY, USA
[b] Hydrological Sciences Lab at NASA Goddard Space Flight Center, Greenbelt, MD, USA

ARTICLE INFO

MSC:
WACE_2016_32_R1

Keywords:
Landslides
Intense rainfall
Climate change impacts

ABSTRACT

Rainfall-induced landslides represent a pervasive issue in areas where extreme rainfall intersects complex terrain. A farsighted management of landslide risk requires assessing how landslide hazard will change in coming decades and thus requires, inter alia, that we understand what rainfall events are most likely to trigger landslides and how global warming will affect the frequency of such weather events. We take advantage of 9 years of landslide occurrence data compiled by collating Google news reports and of a high-resolution satellite-based daily rainfall data to investigate what weather triggers landslide along the West Coast US. We show that, while this landslide compilation cannot provide consistent and widespread monitoring everywhere, it captures enough of the events in the major urban areas that it can be used to identify the relevant relationships between landslides and rainfall events in Puget Sound, the Bay Area, and greater Los Angeles.

In all these regions, days that recorded landslides have rainfall distributions that are skewed away from dry and low-rainfall accumulations and towards heavy intensities. However, large daily accumulation is the main driver of enhanced hazard of landslides only in Puget Sound. There, landslide are often clustered in space and time and major events are primarily driven by synoptic scale variability, namely "atmospheric rivers" of high humidity air hitting anywhere along the West Coast, and the interaction of frontal system with the coastal orography. The relationship between landslide occurrences and daily rainfall is less robust in California, where antecedent precipitation (in the case of the Bay area) and the peak intensity of localized downpours at sub-daily time scales (in the case of Los Angeles) are key factors not captured by the same-day accumulations. Accordingly, we suggest that the assessment of future changes in landslide hazard for the entire the West Coast requires consideration of future changes in the occurrence and intensity of atmospheric rivers, in their duration and clustering, and in the occurrence of short-duration (sub-daily) extreme rainfall as well. Major regional landslide events, in which multiple occurrences are recorded in the catalog for the same day, are too rare to allow a statistical characterization of their triggering events, but a case study analysis indicates that a variety of synoptic-scale events can be involved, including not only atmospheric rivers but also broader cold- and warm-front precipitation.

That a news-based catalog of landslides is accurate enough to allow the identification of different landslide/rainfall relationships in the major urban areas along the US West Coast suggests that this technology can potentially be used for other English-language cities and could become an even more powerful tool if expanded to other languages and non-traditional news sources, such as social media.

1. Introduction

Intense and prolonged rainfall events are the predominant triggers of landslide worldwide (Petley et al., 2005). Thus, understanding how landslide hazard will change in the coming decades cannot leave out of consideration how anthropogenic climate change will affect the occurrence and intensity of heavy rain. Indeed, both theory (Trenberth, 1999; O'Gorman and Schneider, 2009) and observations (Donat et al., 2016) suggest that extreme rainfall becomes still more intense in a warming world, even in regions that are overall drying. Broadly, a warming world is also a more moist world. Theory indicates that the saturation humidity will adjust to the warmer surface temperatures without much changes in relative humidity and extreme rainfall events, those that are dynamically capable of strong upward motions, will become more intense. Thus, any given extreme rainfall amount is expected to become more frequent and the heaviest rainfall events are

---

* Corresponding author.
E-mail address: biasutti@ldeo.columbia.edu (M. Biasutti).

http://dx.doi.org/10.1016/j.wace.2016.11.004
Received 13 May 2016; Received in revised form 17 November 2016; Accepted 19 November 2016

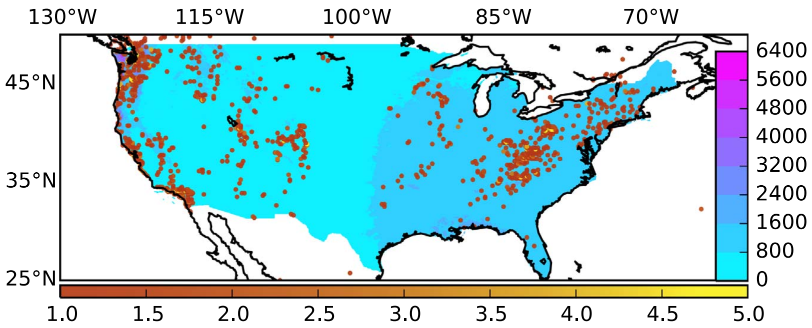

Fig. 1. Cold-colored shading: 2007–2015 mean annual total precipitation from PRISM (mm). Warm-colored dots: Number of recorded landslides over the same period in the Kirschbaum et al. (2010) dataset. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

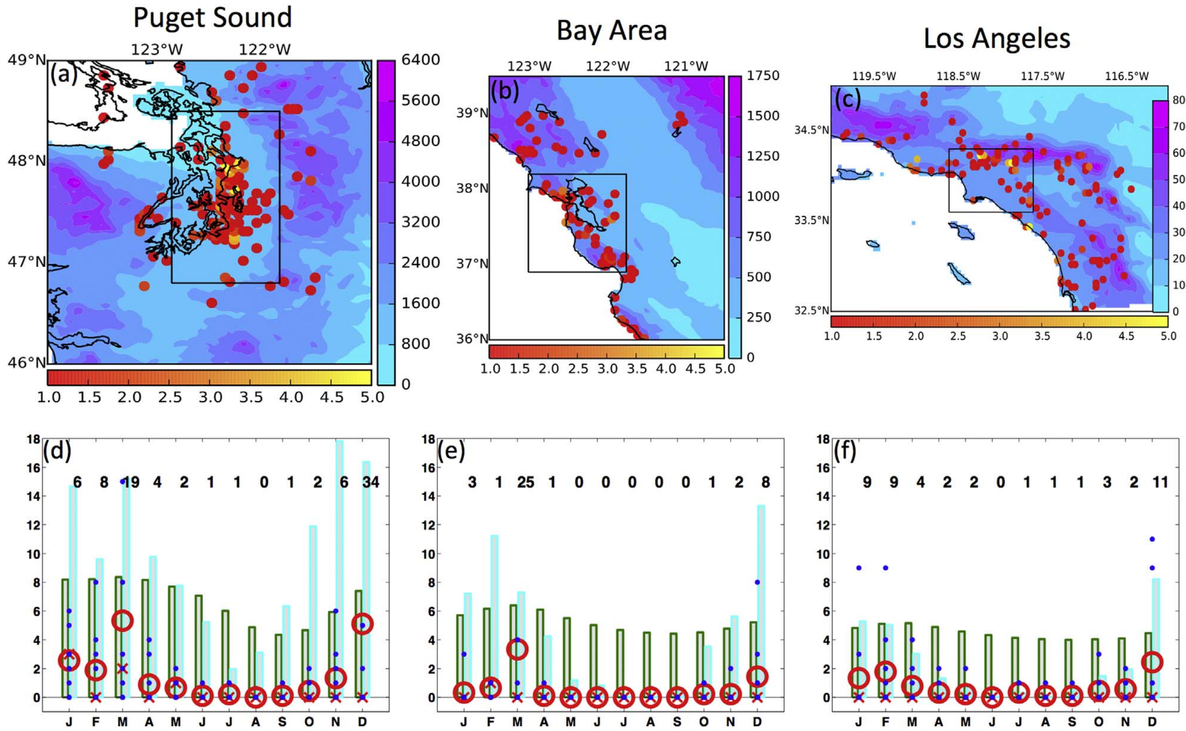

Fig. 2. Top Row: 2007–2015 mean annual total precipitation from PRISM (mm, cold-colored shading, vertical color bars) and number of recorded landslides (warm-colored dots, horizontal color bars) but for areas of the West Coast centered around Seattle (Puget Sound, left), San Francisco (Bay Area, center) and Los Angeles (LA Area, right). The black boxes indicate the domains of the urban areas included in this study. Bottom Row: Bars are the monthly climatology of 1-meter soil moisture (green bars, units of hundred of kg/m^2) and rainfall accumulation (cyan bars, units of tens of mm). Blue dots are the total number of landslides in the study areas in individual years (extreme years might fall outside the graph), the median is given by the cross and the mean by the open circle. The numbers on top indicate the maximum monthly occurrences of landslides. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

expected to have even heavier rainfall. Climate models agree with the theoretical scalings (O'Gorman and Schneider, 2009) and, at least for the mid-latitudes, provide a robust estimate of an expected increase in the intensity of the 99.9th percentile of daily rainfall of 6% per degree of global warming (O'Gorman, 2015).

While robust for very broad regions, these projections are more uncertain at any specific location. Regional changes in both mean rainfall accumulation and rainfall characteristics are more complex, as they result from the combination of temperature-induced changes in atmospheric humidity and changes in the atmospheric circulation. The expected annual mean rainfall change for coming decades in the US West Coast, for example, are of wetter rainfall totals in the northern region (the Pacific Northwest) and dryer totals in the Southern region (Southern California, Collins et al., 2013; Seager et al., 2014). The separation line, where rainfall anomalies will be small, is uncertain, as different models project slightly different changes, but is typically somewhere around central to northern California. Moreover, the annual changes are the combination of widespread wetting anomalies in winter and widespread dry anomalies in the summer. However, Simpson et al. (2015) argue that climate models likely overestimate the mid-winter wetting of the West Coast.

An increase in intense daily events for regions that are expected to get wetter is, at least qualitatively, beyond serious doubt. But in regions where the mean rainfall is projected to decrease we expect that the distribution of rainfall will include more dry and low-rainfall events, and that only the most extreme events will intensify. If landslides tend to occur when rainfall exceeds a certain threshold that lies somewhere in between, changes in the occurrence of triggering events become more uncertain and in need of more detailed investigation. Other aspects of the changing climate (from the likelihood of thawing to the

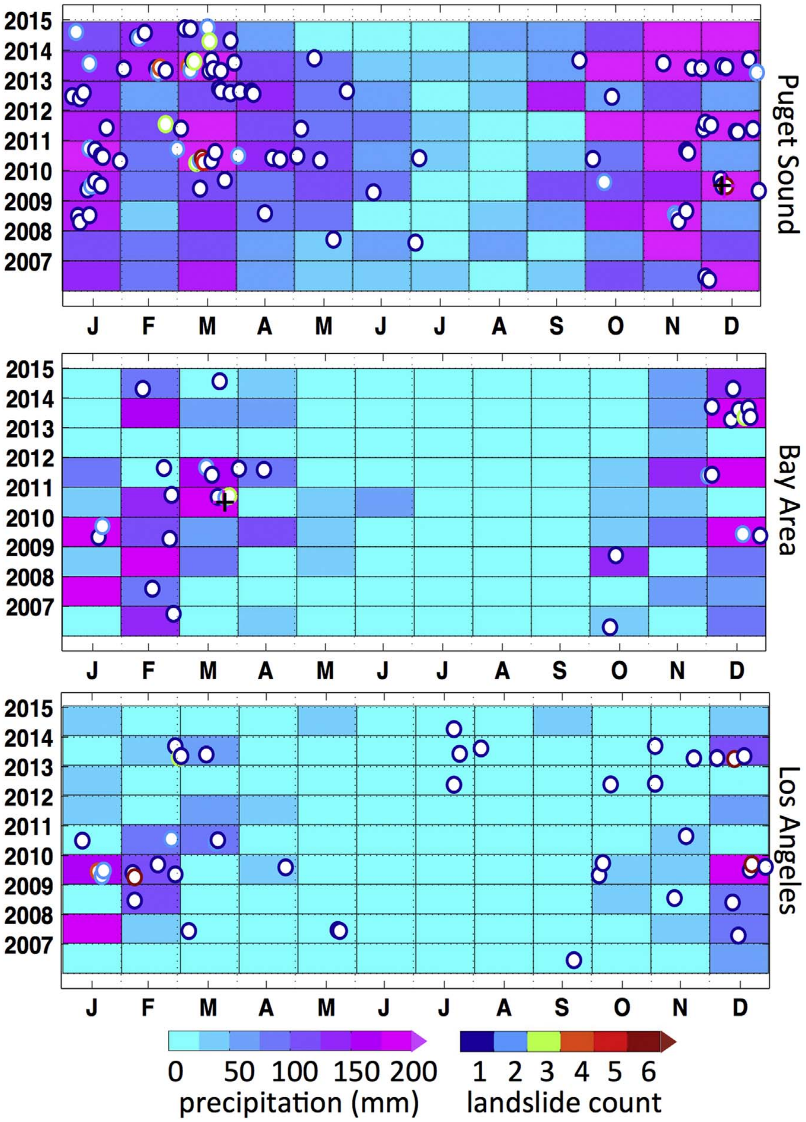

Fig. 3. Monthly mean rainfall (background shading) and landslides occurrences (dots). Each dot corresponds to a day in which at least one landslide was recorded but color-coded to show the total number of landslides on that day. The dots are randomly displaced in the vertical in order to minimize overlap. The two black crosses indicate days with more than 10 landslide occurrences in the region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

occurrence of long wet spells) might also be important, depending on the source of landslide vulnerability (Villani et al., 2015; Stoffel et al., 2014).

Thus, to fully assess projections of changes in landslide occurrence, we need to know both what rainfall events trigger landslides and how those specific events are going to change. There are literatures that either connect rainfall characteristics to landslide triggering (for example, Guzzetti et al., 2008; Godt et al., 2006; Wilson and Wieczorek, 1995) or assess regional climate change (for example, Neelin et al., 2013; Maloney et al., 2014; Seager et al., 2014), and a growing number of studies explore the datasets and techniques necessary to do both (for example, Crozier, 2010; Dijkstra and Dixon, 2010; Wood et al., 2015; Villani et al., 2015; Stoffel et al., 2013, 2014).

One major difficulty lies in the different spatial scales of the problems (Wood et al., 2004, Comegna et al., 2013). Climate projections, on the one hand, are generated at scales that only resolve features larger than a hundred kilometers (horizontal resolutions being typically of the order of 1° x 1°) and they become increasingly uncertain as one zooms from the continental scale to a specific region or focuses on a fine-scale characteristic of a meteorological field (such as a threshold exceedance in daily rainfall accumulation). Moreover, the rainfall at any given grid point needs to be interpreted as an area average and cannot be directly compared to the gauge measurements, nor does it display similar characteristics in terms of intermittency and intensity. On the other hand, landslide triggering relationships are often characterized by intensity-duration rainfall thresholds (Caine, 1980; Larsen and Simon, 1993; Guzzetti et al., 2008), e.g., which can vary in their geographic extent but usually consider gauge data over smaller spatial scales (e.g. a single city, watershed or valley). Rainfall accumulation (e.g. Aleotti, 2004) and critical rainfall (e.g., Govi and Sorzana, 1980), again from dense gauge networks, have also been used to characterize the triggering relationship between landslides and rainfall. Other work has used satellite-based rainfall data to evaluate landslide triggering at a global scale (Hong et al., 2006; Kirschbaum et al., 2012, 2015). Quantifying the changes in landslides over time has

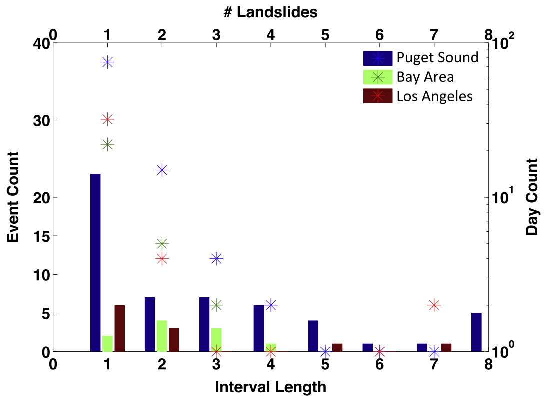

Fig. 4. Clustering of landslides in space and time. Bars (bottom and left axes) indicate the number of events that are followed by another event by a specified interval (1–8 days). Stars (top and right axes) indicate the number of days that saw a specified number of contemporary landslides (1 through 8, large events with more contemporary landslides are not included in this count). The different regions are color-coded as per the legend. (For interpretation of the references to color in this figure legend, the reader is

typically been difficult because landslide inventories are spatially limited and temporally inconsistent. Studies investigating the connection between climate change and landslide occurrence can also suffer from the same challenges (Coe and Godt, 2012).

Our approach to assessing climate-induced change in the landslide hazard along the West Coast and to working around the scale mismatch problem is to (1) assess the statistical connection between rainfall and landslides at regional scales from datasets whose spatial and temporal resolutions are more in line with the resolution of climate models, (2) identify landslide-triggering weather events in terms of a threshold rainfall daily accumulation at such resolution and in terms of their synoptic characteristics, and (3) use such characterizations to discuss the most up-to-date projections of changes in landslide forcing for the coming decades.

Landslide occurrences are obtained from a novel dataset that integrates information from news reports, online disaster databases, published literature, and other sources (Kirschbaum et al., 2010). Previous research (Kirschbaum et al., 2011, 2012, 2015) has shown that seasonal and interannual variations in landslide occurrences recorded in the Global Landslide Catalog (GLC) can be related to regional changes in daily and monthly rainfall totals and in the frequency of exceedance of a triggering threshold. We build upon these studies and use the GLC, satellite-derived rainfall, and atmospheric reanalysis data to identify triggering events in terms of regional rainfall distributions, column-integrated atmospheric humidity, and atmospheric circulation. As discussed below (Section 2), the temporal and spatial resolution of these data sources only allows us to identify *regional* connections between rainfall and landslide hazard. Given the broad scale of climate projections, though, a finer analysis of landslide hazards would not result in a finer climate impact assessment; thus a regional focus is sufficient.

We limit our analysis to major metropolitan areas on the West Coast of the United States. This limitation is mindful of two important prerequisites for obtaining reliable projections of landslide hazard. The first is that our regional records be reliable and contain enough events to provide significant statistics to represent the landslide-weather relationship. As we will show, the choice of the US West Coast fits this bill, at least in urban areas. The second is that the climate models perform well in the chosen region. Along the West Coast, the important rain-bearing disturbances are winter storms and these mid-latitude cyclones are reasonably well simulated by current climate models—which instead have a much harder time with tropical systems and mesoscale thunderstorms, whose relevant spatial scale is much smaller and for which convective processes are much more important. It should also be noted that the reliance on news reports to identify landslides introduces a bias towards inhabited areas but, since this work is ultimately motivated by assessment of disaster risk, the need to limit our investigation to urban areas is not problematic.

In the rest of this paper we provide an overview of the datasets (Section 2), find a robust relationship between landslide occurrence and those rainfall characteristics that can be computed in climate models (Section 3), and identify the synoptic events that are associated with the triggering rainfall (Section 4). Section 5 concludes with a discussion of future projections of relevant weather phenomena and their implications for projected changes in landslide hazard.

2. Datasets and methods

The Global Landslide Catalog (Kirschbaum et al., 2010, 2015) is based on the collection of news reports and official sources. The dataset starts in 2007 and is continuously updated (we use the years 2007–2015); it provides information on the timing and location of the landslide event. We reorganized the event data into a daily 4 km×4 km gridded data set of number of landslide occurrences. We did not retain information about the nature of the land slide (rock fall, mudslide, etc) or its impacts: only the location and date of occurrence of the event are used. If multiple land slides were to happen at the same rough location during the same day, they would be reported by the media as one event and are coded as such in the catalog. Note that because the exact time of day when the slope moved is typically not known or reported, the date of occurrence refers to local time, not to UTC time. Along the West Coast, matching landslide events to daily weather states (which are averaged for the UTC day) is made more uncertain by the 8-h difference from UTC.

The GLC covers the entire globe. Fig. 1 shows the total landslide occurrence (warm-colored dots, superimposed on the annual mean rainfall field) over the United States over 2007–2015. The landslide dataset clearly captures the large scale pattern of occurrence: most landslides happen along the West Coast, the Rockies, and the Appalachian mountains, as well as along the Ozarks and the upper Mississippi River basin. Yet, because of the nature of news reports, it is likely that the landslide data is biased towards population centers. Furthermore, this catalog provides a minimum number of events. The total number of rainfall-triggered landslides is expected to be much higher. If we zoom in on subregions of the West Coast, we start seeing where the data is capturing a largest fraction of the events. Fig. 2a shows the total number of recorded landslides in Western Washington. The urbanized areas of Puget Sound show high occurrences of landslides, while the more mountainous and less densely populated areas do not. Given that both the presence of steep terrain and the larger rainfall totals on mountain slopes would be conducive to landslides, we interpret the spatial differences as indication that news report are sufficient to comprehensively detect landslides in urban areas, but that they are limited in their ability to account for events away from population centers. Thus, we focus our research on urban areas.

Our aim in this study is to identify the rainfall events that are most relevant for landslides in different urban areas in terms of characteristics that can be calculated from climate models. This precludes a full investigation of the triggering rainfall threshold in terms of the Intensity-Duration diagrams for two reasons: high-frequency time series of simulated rainfall are not routinely available (climate model simulations do not routinely save hourly data, and rain duration can at best be estimated from 6-hourly accumulations) and high-frequency variations have worse biases than longer-accumulation averages. The rainfall produced by climate models is, in part, the result of parameterizations that are predicated on principles that—while they describe well the atmospheric equilibrium—are not capable of capturing the evolution and organization of convective rainfall (Mapes and Neale, 2011; Del Genio, 2012); models that are tuned to optimize climate-scale variations are strongly biased in their rainfall character-

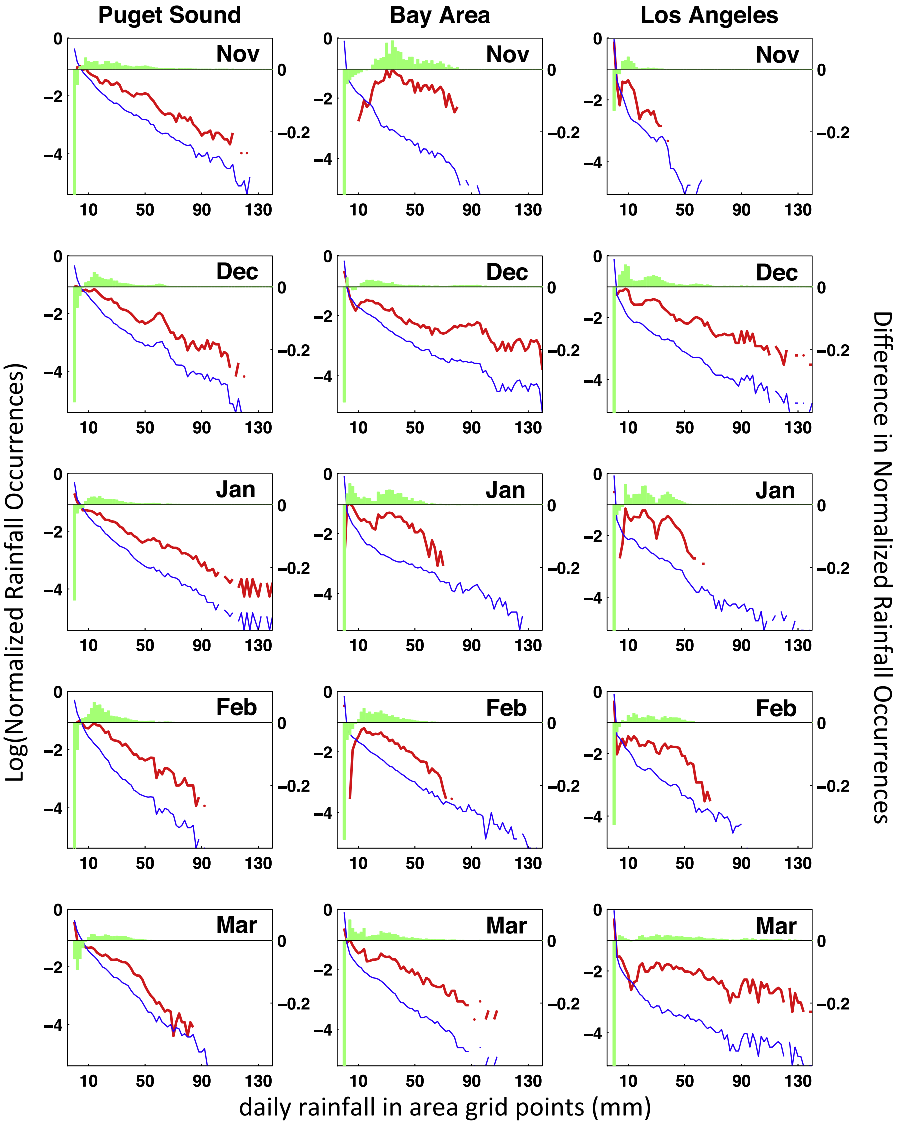

Fig. 5. Left axes: Daily accumulation frequency distributions on all days (blue) and days with landslides (red) for the extended winter months (November through March, from top to bottom) and for three metropolitan areas (Puget Sound, left; Bay Area, center; Los Angeles, right). The frequency distributions are obtained by dividing the rainfall intensity histograms by the total number of data points (number of days in each record times number of grid points in the area) in each set. Right axes: the green bars are the difference in rainfall distribution between days in the month that recorded landslides and all the days for that month and show a consistent shift of the distribution towards heavier precipitation. (Note that the differences for the lowest rainfall bin are off scale in some of the panels.) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

istics at shorter accumulation intervals (Dai, 2006; Nuijens et al., 2015). While this is less of a problem for mid-latitude cyclones, in which the main mechanism producing rainfall is large scale ascent in fronts, most intense rainfall events do include embedded convection and are thus affected by these parameterization errors. As we will see, at least in the Pacific Northwest and Northern California landslide occurrence at a regional scale is primarily related to the daily and synoptic timescale precipitation variability that models can simulate with some degree of skill. With this in mind, we selected to analyze the co-variability (from intraseasonal to interannual) of landslide occurrences with rainfall accumulations over one day and longer.

The main rainfall dataset used in this study is the PRISM daily rainfall of Daly et al. (2002), which blends remote-sensing estimates of precipitation and direct gauge measurements with information about the local orography to provide a best estimate of daily rainfall that is interpolated to a very high spatial resolution (4 km×4 km).

Atmospheric meteorological fields and soil moisture are obtained from the National Center for Environmental Prediction (NCEP) North America Regional Reanalysis (NARR).[1] Reanalyses are obtained by assimilating all available atmospheric observations with a weather forecasting model. The regional product used here assimilates the same observations typically included in the global reanalyses (temperatures, winds, and moisture from radiosondes, pressure data from surface observations, as well as data from dropsondes, pibals, aircraft temperatures and winds, and cloud drift winds from geostationary satellites), but it additionally assimilates PRISM precipitation. This

---

[1] National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce. 2005, updated monthly. NCEP North American Regional Reanalysis (NARR). Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. http://rda.ucar.edu/datasets/ds608.0/.

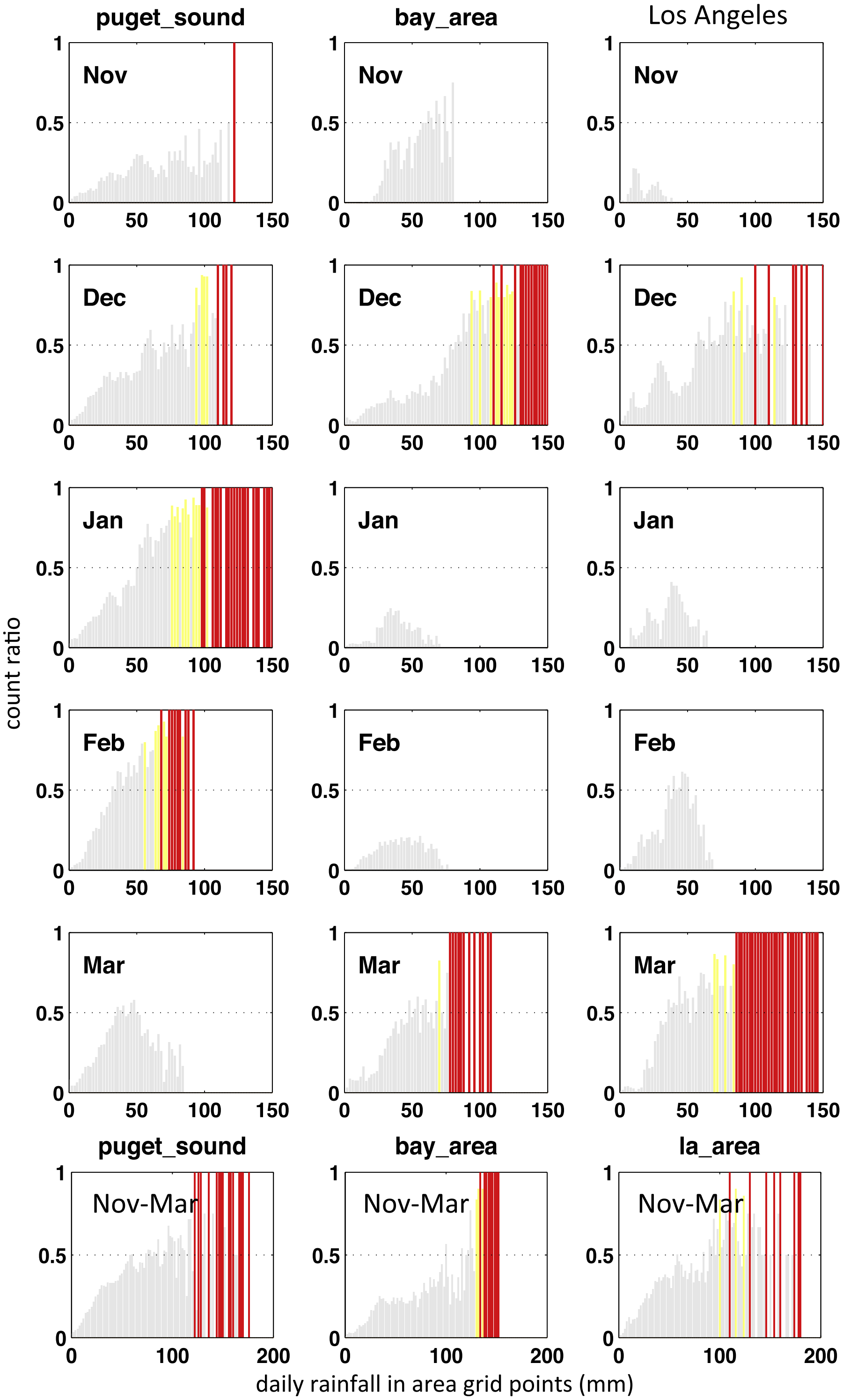

Fig. 6. Histogram of daily rainfall accumulations on landslide days divided by the histogram for all days (for each winter month, or for the November-March season, as noted in each panel). Values equaling 1 (indicating that all such precipitation events were associated with landslides in the area) are in red, values above 0.8 (indicating an 80% chance that such precipitation events were associated with landslides) are in yellow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

additional observational constraints ensures the credibility of both the large scale rainfall and the soil moisture field. Yet, it should be noted that because the reanalysis estimate of soil moisture is not derived from direct field measurements, it suffers from some of the same pitfalls we ascribed to climate models, including coarse resolution. The 1-meter soil moisture used in this study should be considered an integrated,

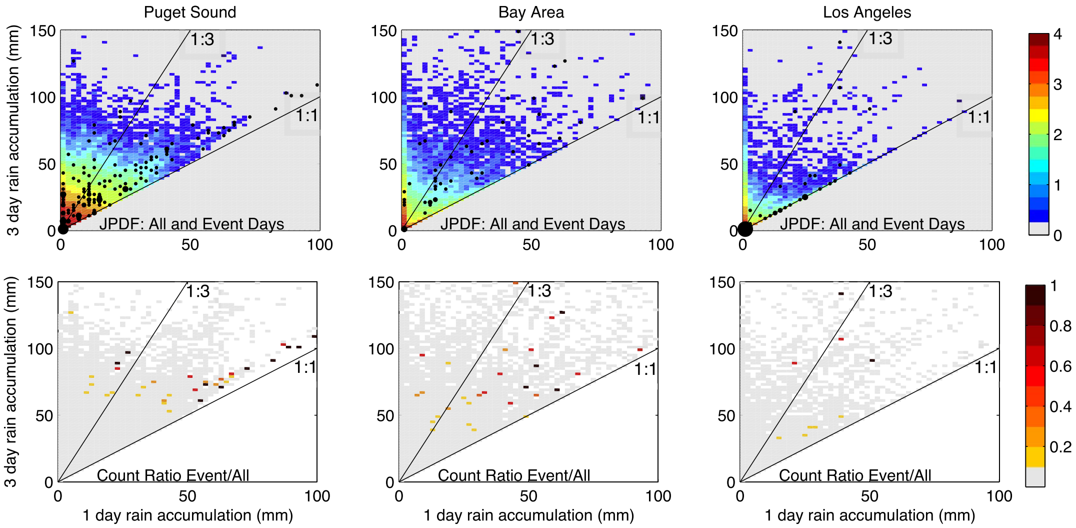

Fig. 7. Top: In color is the joint distribution of occurrences (not normalized by total number of data points) of 1-d (x axis) and 3-d (y axis) rainfall accumulations for all days, but limited to the locations that have experienced at least one landslide in the period of record; the color scale is logarithmic. Superimposed black dots are for the landslide events and the size of the dot indicates the number of occurrences. Bottom: Landslide-days/All-days ratio of the joint rainfall accumulation frequency (normalized by dataset size). In all panels the lower and upper lines are the 1:1 and 1:3 lines; points close to the 1:1 lines are for days in which rainfall followed 2 dry days (such that the 3-d accumulation is close to the 1-d accumulation) while points close to the 1:3 line are for days in which rainfall accumulated more evenly, so that rainfall accumulation on the third day was similar to the mean over the previous two days. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

regional quantity, and cannot reflect the local soil moisture at the location of the landslides.

3. The relationship between landslide occurrence and rainfall at different time scales

Fig. 2 shows mean annual rainfall and the total occurrences of landslides in the urban areas of Puget Sound, the Bay Area, and Los Angeles, as well as the boundaries of the domains chosen for analysis. The seasonalities of rainfall, soil moisture, and landslides for the inner domains are also shown. The landslide record is highly variable, with extreme years dominating the mean landslide occurrence, while the median occurrence is nearly uniformly close to zero (see also Fig. 3). Yet, some broad correspondences between landslide frequency and seasonal rainfall accumulation can be drawn. In all three urban areas, the greatest number of landslides occurs during winter, between November and March, when precipitation also peaks. Since geology and geomorphology vary greatly between the three regions, the correspondence is suggestive of a dominant influence of climate on landslide occurrence; it also confirms that variations within the the landslide dataset are physical, and not an artifact. In the mean climatology, seasonal variations in soil moisture are smaller and do not seem to match the large seasonality of landslides. This mismatch might indicate that the reanalysis-based estimate of soil moisture in the upper 1-meter layer is biased or simply that it is too coarse an indicator to be meaningfully related to the conditions of landslide-prone terrain. Whatever the reason behind it, the fact that the climatology of landslide frequency best matches that of rainfall reinforces our interest in the link of landslide occurrence to regional meteorology. Puget Sound is both the wettest among the regions (in rainfall as well as soil moisture) and the one most prone to landslides, consistent with susceptibility measures (Radbruch-Hall et al., 1982).

Both the broad relationship between landslides and rainfall and the variability of the occurrence record are in full display in Fig. 3, which shows month-to-month variations over the entire record. The climate-landslide correspondence is well exemplified by the December values in all three domains: it is clear that the variations of rainfall and landslides are well coordinated across the years and that months with above 150 mm of rain overwhelmingly have landslides. Yet there are exceptions, such as 2015 in Puget Sound. Another surprise that speaks to the difficulty of linking landslide to coarse climatic fields is the occurrence of landslides in the summer time in Los Angeles, during months with extremely low mean precipitation. Deep-seated landslides can result from preceding large long-term accumulation, as rainfall takes some time to infiltrate the soil and lubricate its movement, and are thus not linked to any one heavy rainfall event. Yet the isolated summertime landslides identified in the catalog are typically shallow debris flow and are listed as connected to rainfall events; this suggests that they are the results of high intensity-short duration downpours that do not have a signature in the monthly rainfall.

Fig. 3 also captures how landslides have a slight tendency to occur in clusters (this is especially significant given that small landslide with negligible impacts are unlikely to be included in the news-based count): although the vast majority of events include only one landslide per day, there are many events that include several, and there are many instances in which landslides occur on consecutive days. All these major events occur outside the summer months. The degree of clustering is shown more quantitatively in Fig. 4, which shows the occurrences of days with one or multiple (up to 8) landslides (upper and right axes) and the occurrences of events that are followed by another event within the next 1–8 days (lower and left axes). These distributions are not normalized, so that it is no surprise that the Puget Sound area shows up as the place with more landslides clustering in both space and time, as this is the place with most events overall. More significant is the fact that the Los Angeles area tends to have more events with a single landslide, while the Bay Area tends to have more events with two or three. In the rest of the paper, we consider as major events those that include three or more landslides in California and four or more in Puget Sound. In terms of clusters in time, we see that it is unlikely that landslides that come in clusters are separated by more than three days. (We assume that events separated by more than a few days are triggered by independent storms and not likely to be connected other than by virtue of the effect of accumulating soil moisture.) The importance of time and space clustering again supports our assumption that synoptic scale variability (both in time and in space) is appropriate for assessing regional frequency of high-impact events.

We now turn to a comparison of rainfall intensity distributions in

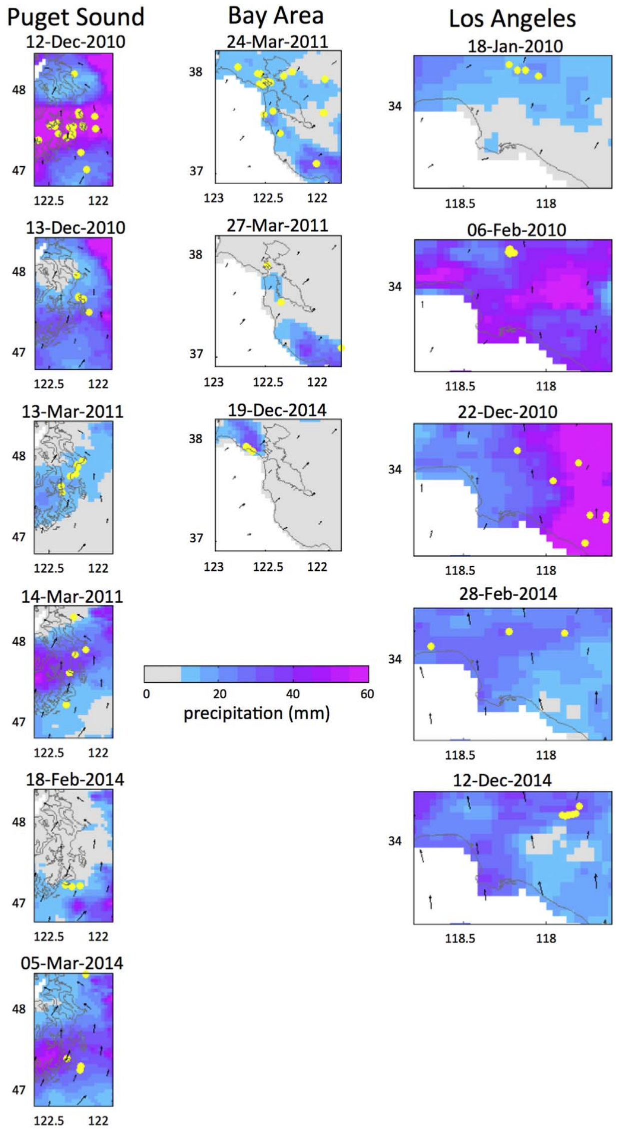

Fig. 8. Daily accumulated rainfall for the days with the most landslides in each region (shading), 10 m winds (arrows), and the location of the landslides (yellow dots). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the case of landslide events against the climatological distributions. For each month in the extended winter season November through March, and including all grid points comprising the three metropolitan area under investigation, we calculate the distributions of rainfall accumulations on days when landslides occur and compare those distributions against the average (calculated for the same grid points, but using all 2007–2015 days for the same month). The difference in the frequency distribution of rainfall (the number of days with rainfall falling into a certain intensity bin, divided by the total number of days) between landslide days and the average (Fig. 5) tells us how rainfall during landslide days is skewed towards heavy accumulations. As expected, landslides occur on days that bring heavier than average rainfall to the region, in the sense that dry grid points and low accumulations are much less common (but still occur, see as one example November distributions in Los Angeles), and moderate and heavy rainfall values are more common; the threshold between the negative and positive differences changes across months and regions. We also compare the raw rainfall histograms (the number of days with rainfall falling into a certain intensity bin, *not* divided by the total number of days) for landslide days to those calculated for all days by taking the ratio of the two (Fig. 6). Values close to one indicate that a certain amount of rainfall is extremely likely to be associated with a landslide event (i.e. all days with that much rainfall are associated with landslides) and, as expected, they are mostly at the right hand side of the distribution. When all months are combined, we see that daily rainfall above about 120 mm tend to be overwhelmingly associated with the occurrence of landslides. But we also see several instances (especially in California) in which days with exceptionally heavy rainfall fail to produce landslides: for example, Februaries in the Bay Area and Januaries in the Los Angeles area have recorded accumulations as high as 130 mm (Fig. 5), but those heavy-rain days were not the ones that experienced landslides (Fig. 6). Although one does not necessarily expect landslides to be a sure consequence of every heavy rainfall events, the disconnect is still puzzling. It is possible that it is simply a matter of timing, i.e. that such rain events did provoke landslides in subsequent days. Because these distributions are calculated for all gridpoints in the three domains, it is also possible that the most intense precipitation fell where the local topography was least susceptible to slope movement. We thus repeat this analysis including only gridpoints in which landslides occurred, but we expand it to include the role of accumulations over longer periods than one day.

This is done in Fig. 7, in which we analyze the joint distributions of the 1-d and 3-d accumulations of rainfall for landslide events, compared to the climatology for the same locations. The climatologies of the 3 regions are shown in color in the top row. Unsurprisingly, LA is the driest region, with a rainfall distribution that reaches intensities similar to those of the other regions, but that is more heavily skewed towards dry days. Puget Sound's wetness is a consequence of having the most days of moderate rainfall, but the region experiences fewer days with very extreme accumulations; the latter are most common in the Bay Area. The joint precipitation distributions for just the days with landslides is shown as black dots (superimposed on the climatological distribution in the top row of Fig. 7). They reveal some interesting differences across the regions. In particular, there is a large percentage of events in the Los Angeles area that are occurring at very low daily rainfall accumulations. A closer investigation indicates that these are all events that had one single landslide in the Los Angeles area. The location of the landslide might have been reported inaccurately, but inspection of the rainfall field on landslide days indicates that this is not the likely reason for the mismatch. The original dataset confirms the many of these single-landslide events were associated with downpours. An isolated downpour might not be captured by the satellite-based rainfall dataset, or it might be so short that the accumulation for the day is nonetheless modest. Whatever the case, our use of gridded daily and longer accumulations does not allow the relationship between landslides and rainfall to emerge in the Los Angeles area. Nevertheless, in all regions the difference in the normalized joint distributions (not shown) for landslide days and climatology confirms for the 3-d accumulation what we already saw for the 1-d accumulation: on average landslide occurs on days with 3-d accumulations that are skewed towards moderate and heavy values.

The ratio of the accumulation distribution for event days to all days (Fig. 7, bottom row) gives a measure of how likely it is that a given set of 1-d and 3-d rainfall accumulations will induce landslides: a ratio of one indicates that that combination of 1-d and 3-d rainfall always induces a landslide, a ratio close to zero indicates that it is extremely unlikely that a landslide would occur under those circumstances. This likelihood measure, though, is made uncertain by the limited number of landslides; the uncertainty is revealed by the fact that very similar rainfall values give raise to wildly different probabilities (see for example the isolated red points, indicating a probability of 1 but surrounded by probabilities less than 10%). Moreover, the GLC records only a fraction of the occurring landslides, so that these probabilities

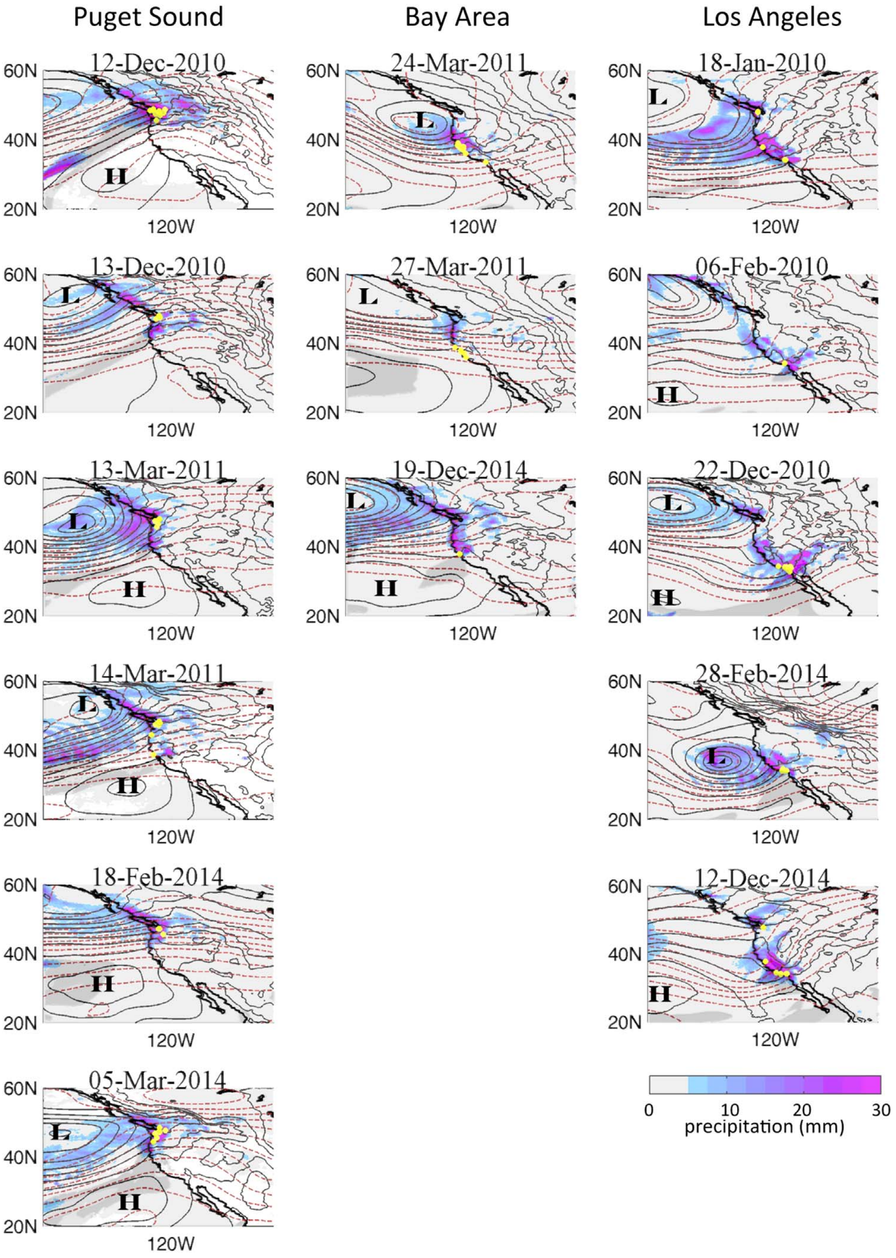

Fig. 9. Rainfall (color), sea level pressure (black contours) and 500hPa height (red dashed contours), and landslide locations (yellow dots) for the major landslide events in Puget Sound (left), the San Francisco Bay Area (center), and the Los Angeles area (right). The transparent dark gray surfaces are the tongues of high atmospheric humidity (more than 22 mm). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

are likely to be biased low and are best considered as qualitative estimates. Still, the general pattern of what rainfall accumulations produce enhanced probability of landslide does provide some insight. For example, we can compare the Puget Sound region with the Bay Area. Despite the fact that more landslides are recorded by the GLC in the Puget Sound Area, higher rainfall accumulations are necessary there than in the Bay Area to bring the probability of landslides above the 10% threshold. This is consistent with measures of landslide susceptibility that have been derived from terrain characteristics (Radbruch-Hall et al., 1982). In both regions landslides are more probable for accumulations that fall between the 1:1 and 1:3 lines (meaning that same-day accumulation is higher than average accumulation in the days preceding the event), indicating that high accumulation on the day of the event is more important than the overall accumulation over the course of the previous three days. This is particularly true of Puget Sound, where we see a cluster of landslide points just off the 1:1 line. The pattern for Los Angeles is most similar to the Bay Area case, although it emerges from just few data points. Note though that the accumulations that span these joint distributions are far from equally possible, so that this measure does not indicate what weather state is, in general, more likely to produce a landslide. For example, most landslides in Los Angeles occur for low rainfall accumulations values, but because this is by far the most likely state and the vast majority of low-accumulation days do not produce landslides, these events are not picked up by this analysis.

We repeated the same analysis looking at even longer accumula-

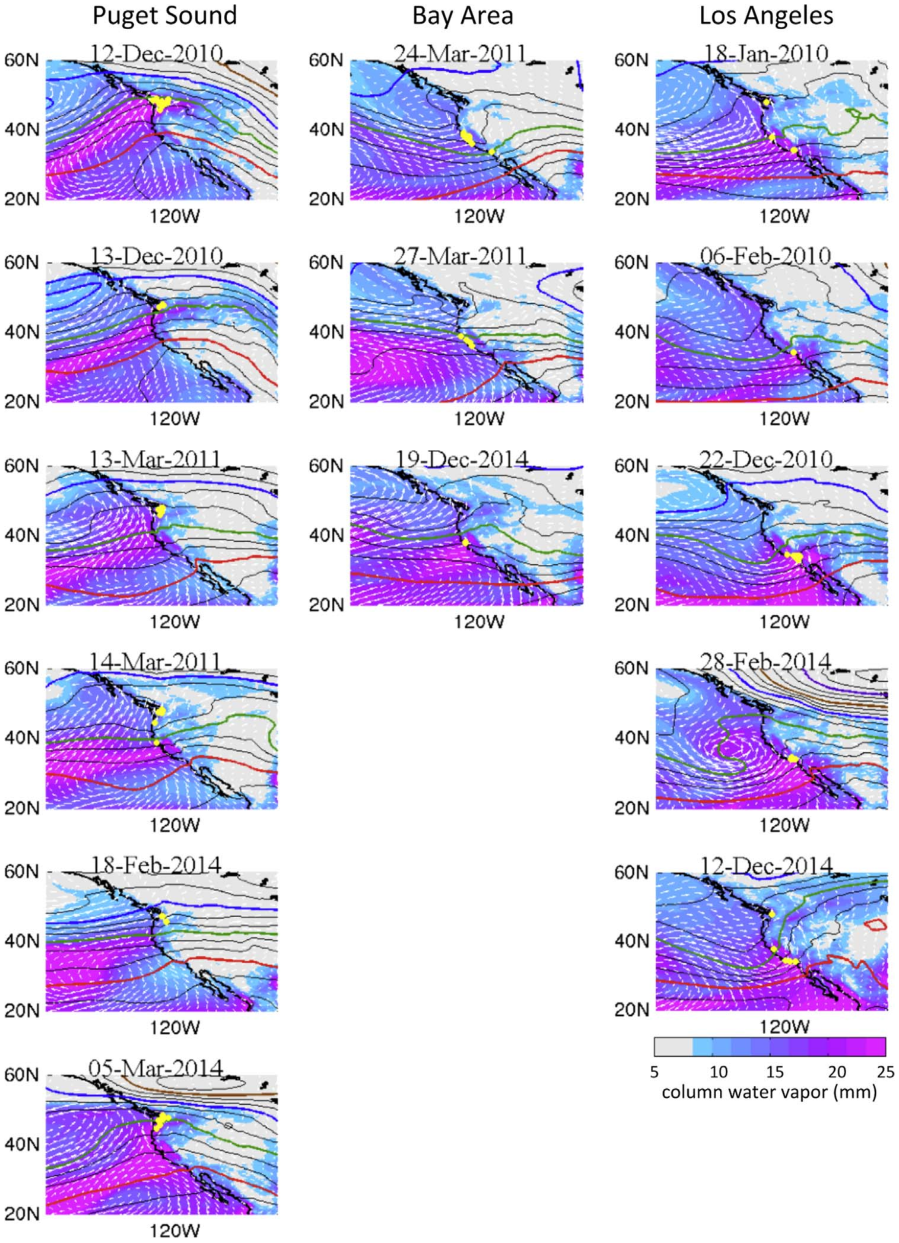

Fig. 10. Column integrated atmospheric water vapor (cool shading, mm), 10 m winds (white vectors, m/s), and 500–1000 mb atmospheric thickness (contours, c.i.=60 m, some contours are colored according to standard) and landslide locations (yellow dots) on the days of the major landslide events in Puget Sound (left), the San Francisco Bay Area (center), and the Los Angeles area (right). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

tions: 5 and 15 days (not shown). In the Puget Sound area the landslide points remain concentrated towards the 1:1 line, confirming that the intensity of precipitation on the same day as the event is key. This is not the case in California. In particular we notice that many landslide points cluster around the 1:5 and 1:15 lines in the case of San Francisco, suggesting that antecedent accumulation and soil moisture play a more important role there.

The above analysis points to wintertime weather events that produce rainfall accumulations over 3 days in the neighborhood of 50 mm with especially heavy one-day accumulations in the case of Puget Sound, and to the role of successive rainfall events and soil moisture accumulation for the Bay Area. The case of Los Angeles is different as most single-landslide events are the result of downpours, but here too clustered events are associated with heavy one-day accumulations.

Such major landslide events, those in which earth movements are a widespread occurrence, are too rare to allow a statistical approach to their triggering mechanism. Yet, their potential for provoking considerable damage makes it especially important that we assess how their frequency might change in a changing climate. In the next section we take a case-study approach and select individual days with multiple landslide to look more closely at what kind of meteorological event is most likely to trigger severe events in each area.

4. Triggering major events: a synoptic view

We identify the events with most landslides in a single day in the three regions of interest. All happen during the winter months. Some days are clustered together in close succession, likely indicating that they comprise one prolonged event. We select the six days in the Puget Sound Area with more than four landslides, three days in the Bay area (one with more than four landslides, and two with three) and 5 in the Los Angeles area (four with more than four landslides, one with three). The PRISM regional rainfall accumulation on each such day and the locations of the landslides are shown in Fig. 8. Figs. 9 and 10 provide a view of the regional meteorological fields. While the local view clearly portrays the difficulty of trying to match rainfall intensity and landslide occurrence at the point scale, the larger-scale view indicates a clear connection between landslide occurrence and rainfall maxima linked to the transport of high-moisture air into the region by the synoptic flow. Indeed, on several of the chosen dates, landslides occur all along of the west coast.

The low-level flow approximately flows along the lines of constant sea level pressure (Fig. 9, black contours), but with a friction-induced component towards lower pressures; the flow is cyclonic around closed lows (counter-clockwise). The upper level westerly flow that steers the winter storms towards the West Coast is modified by waves in the 500 mb geopotential field (Fig. 9, red contours). The Puget Sound events tend to be associated with a coastal ridge in the geopotential height and a low-high dipole in sea level pressure between the northeast and southeast Pacific. This creates strong southwesterly flow that brings warm moist tropical air into Washington State. In contrast, the large scale flow that is most conducive to landslides in California tends to be associated with more zonal 500-mb geopotential height contours or an off-shore trough, and thus westerly and southwesterly flow into the Bay Area and Los Angeles, respectively. The events impacting Puget Sound in this analysis are warm fronts, while those that affect Los Angeles can be either cold or warm fronts (see how the surface wind crosses the isopleths of atmospheric thickness in Fig. 10, indicating warm and cold advection in each case), but are in any case fueled by high humidity values within the warm sector. As indicated by the sea level field, the main wind direction at the surface is similar to that at upper levels (Fig. 10): it has a strong southerly component in the case of Puget Sound, it is westerly in the case of the Bay Area, and mostly southerly in Southern California (this is not so obvious in the January and February 2010 cases when one looks at the large scale, but zooming in over land in Fig. 8 reveals a southerly flow).

As the storms impinge on either the Sierra Nevada of California or the Cascades in Washington and Oregon, moist air is uplifted by the orography, and a broad maximum of precipitation develops over the coastal regions. The rainfall maximum can be extensive: reaching well into British Columbia for the northern systems, and covering the length of California (and sometimes further north) for the southern systems. Zooming in (Fig. 8), one can see a rain shadow in northern Puget Sound, a consequence of the disruption of the Southwesterly flow by the Olympic Mountains. Windward enhancement of rainfall on sloping terrain is most visible in the case of Los Angeles, as the southerly flow impinges against the Santa Monica and San Gabriel mountains, and in the Bay Area, where westerly flow directly impinges on the Marin Range and Santa Cruz Mountains.

Most major landslide events are associated with high atmospheric moisture flowing into the region (Fig. 10, color). In some cases there is a well-defined maximum of moisture (in what has been described as an "atmospheric river", Zhu and Newell (1994)); in other cases the maxima are wide or do not point directly to the location of the landslides. The clearest cases of a filament of tropical moist air being instrumental in triggering a major event is for 12/13 Dec 2010 in the Puget Sound region. In the other cases, the high-humidity plume is centered over California, not Washington, yet the rainfall maximum is in the Pacific North West and extends well into British Columbia. This highlights how the warm front precipitation and orographic rainfall on the coastal terrain can be as important as the presence of an "atmospheric river" in producing the heavy rainfall that triggers landslides. Importantly, it makes clear that meteorological conditions more diverse than simply those that could be dubbed atmospheric rivers can trigger landslides in all three regions of the West Coast. During three events in Los Angeles (12/22/10, 2/28/14, 12/12/14), high moisture is not brought into the region as a narrow stream, but more generally within the warm sector of a cyclone; in the remaining events a narrow maximum in humidity is more evident, but the maximum itself is not that high. In the case of the Bay Area, the large events selected here occurred without a well-defined atmospheric river, but as consequence of a westerly-moving frontal system interacting with the local mountains. In all Bay Area cases, a series of antecedent storms had already brought near-record rainfall to the region. The broad ranges of triggering events for major landslide events in these regions makes even more difficult the task of quantifying future changes in landslide hazard, and underscores how a more complete compilation of landslide occurrence data is needed to provide more than anecdotal information on the causes of major events.

5. Discussion and conclusions

The Global Landslide Catalog, a news-based dataset of landslide occurrences, provides 9 full years of data. In this study we pair it with satellite-based rainfall data and use it to identify the kind of weather events that triggers landslides along the US West Coast. We focus on populated areas, where landslides are relatively common, English-language news reports are likely to capture most main events, and where vulnerable infrastructure and populations can benefit from this kind of hazard assessment. Because of the different characteristics of the Puget Sound, Bay Area, and Los Angeles regions, in terms of their landslide susceptibility and of the typical triggering events, the US West Coast provides a test bed for the feasibility of using these kinds of datasets as research tools.

In all regions, days that recorded landslides have rainfall distributions that are skewed away from dry and low-rainfall accumulations and towards heavy intensities, but a robust quantitative relationship between large daily accumulation and enhanced hazard of landslides is not universal. Such relationship appears most clearly in our analysis of Puget Sound where, during the winter months, daily accumulations of rainfall above 50 mm anywhere in the region are associated with a one-in-two chances of landslide occurrences. Moreover, the region has a significant chance of landslide occurrence (10%) for daily accumulations as low as 10 mm, if the 3-d accumulations are above about 60 mm. The relationship between landslide occurrences and daily rainfall is less robust in California, where antecedent precipitation (in the case of the Bay area) and the peak intensity of localized downpours at sub-daily time scales (in the case of Los Angeles) are key factors not captured by this same-day accumulations.

Major landslide events, with three or more landslides in any one of the urban areas recorded by the catalog, are rare and the triggering meteorological event cannot identified via statistical analysis. A case study approach suggests that such major landslide events can be linked to synoptic scales and daily accumulations in the Los Angeles area as well as in Puget Sound (too few such events occur in the Bay Area within our period of record to allow for robust conclusions there). All these events are associated with the approach of high-humidity air towards the coast and the interaction with the local orography, but in general they do not require that a so-called atmospheric river makes a direct hit on the region. In events that affect Puget Sound, tongues of high-humidity that can be interpreted as atmospheric rivers do hit the West Coast in all cases, but they directly reach Washington State only in the 2010 event, and are otherwise centered further south and the heavy precipitation in Puget Sound is the product of the interaction with coastal orography of the warm front to the north. The events that cause major landslides in Los Angeles can be either warm or cold fronts, but in all cases are characterized by high humidity air in the warm sector of the approaching cyclones.

According to this analysis, understanding to what degree landslide occurrence will increase in the future involves understanding how weather will change along several dimensions. For Puget Sound, the frequency and intensity of atmospheric rivers are the key parameters, independent of where exactly we can expect these "rivers" to flow. Thus, we can turn to results such as those by Warner et al. (2015) to project a staggering increase in weather events capable of triggering major landslide events in the region: according to that study's analysis of CMIP5 models' simulations of the end of the century under business-as-usual scenarios, precipitation on days with extreme water vapor transport onto the West Coast (those exceeding the historical 99th percentile threshold) will increases by 15–39%, and the frequency of such days will increases as much as 290% (because the distribution of vapor transport is very skewed, an increase in the mean transport implies a much larger increase in the extreme tail; in addition, the tail of the distribution actually gets fatter in CMIP5 simulations of the future). These findings are similar to results based on CMIP3 simulations (Dettinger, 2011), and are made more credible by the fact that they follow from robust thermodynamic changes in the low-tropospheric humidity not dissimilar from what expected from Clausius-Clapeyron scaling (Warner et al., 2015; Payne and Magnusdottir, 2015; O'Gorman, 2015). However, common biases across the current-generation of climate models are such that even well understood and robust responses can be off in magnitude, and there are reasons to believe that CMIP models overestimate the southerly anomalies that are the cause of increased West Coast winter-time rainfall in future projections (Simpson et al., 2015) and future changes in very wet days (with rainfall over 60 mm/day) appear to be especially uncertain across models (Pierce et al., 2013).

With due allowance for the above mentioned caveats, the projected large increases in the intensity and frequency of atmospheric rivers are likely to translate into heightened landslide hazard for the Bay Area as well. Here, though, a more detailed analysis of the clustering of the events (and thus the overall effect on soil moisture) is necessary to provide a more quantitative hazard assessment. Payne and Magnusdottir (2015) suggest that events in which atmospheric rivers impinge on the West Coast for multiple days in a row will increase, even though the average length of such events is not projected to change.

The hazard for major landslide events in the Los Angeles area would be expected to increase in consequence of the equatorward expansion of the landfalling area of atmospheric rivers (Chang et al., 2015; Payne and Magnusdottir, 2015), but other aspects of the seasonal precipitation change in the opposite direction (for example, the number of rainy days and the mean intensity of rainfall are both expected to decrease in wintertime Pierce et al., 2013). Yet, the most likely hazard there appears to be for smaller landslide event that are associated with downpours at sub-daily time scales. For these events, predicted changes in the frequency and intensity of synoptic events are less relevant than the prediction of changes in extreme hourly rainfall. The latter are expected to increase with warming (Lenderink and van Meijgaard, 2010), but the rate of increase is still uncertain for the West Coast (Lepore et al., 2015, in press).

Projections of changing landslide hazard, even leaving aside the uncertainties in rainfall projections, remain hindered by a too qualitative assessment of the triggering relationship. A more quantitative assessment will require a longer and more complete landslide dataset. The GLC does not represent a systematic, complete record of rainfall-triggered landslides and therefore is underestimating the number of landslides for a specific storm as well as the total number of landslides in the region. Future work will involve expanding this database leveraging and integrating local and regional inventories to improve the characterization of these extreme landslide-triggering weather events.

Yet, we have shown that a landslide dataset based on news report provides accurate enough information to identify the weather event most likely to trigger isolated landslides or major earth movement events in urban areas of the US West Coast. This success suggests that the same dataset can be used to study other urban areas around the globe and that expanding the data acquisition to news reports in languages other than English as well as social media might provide a reliable and yet very inexpensive way to record landslides where it matters most: where people and infrastructure are in harm's way.

Acknowledgement

This work was supported by NSF through Grant AGS 12-43204.

References

Aleotti, P., 2004. A warning system for rainfall-induced shallow failures. Eng. Geol. 73, 247–265.

Caine, N., 1980. The rainfall intensity: duration control of shallow landslides and debris flows. Geogr. Ann. Ser. A Phys. Geogr. 62, 23–27.

Chang, E.K.M., Zheng, C., Lanigan, P., Yau, A.M.W., Neelin, J.D., 2015. Significant modulation of variability and projected change in California winter precipitation by extratropical cyclone activity. Geophys. Res. Lett. 42, 5983–5991.

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, K., Leroueil, S. (Eds.), Landslides and Engineered Slopes, Protecting Society Through Improved Understanding In: Proceedings of the 11th International and 2nd North American Symposium on Landslides and Engineered Slopes, Banff, Canada, 3–8 June. Taylor and Francis Group, Reston, VA, pp. 371–377.

Collins, M, Knutti, R., Arblaster, J., Dufresne, J.L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W.J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A.J., M Wehner, 2013. Long-term Climate Change: Projections, Commitments and Irreversibility, In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

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, 373–391.

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

Dai, A., 2006. Precipitation characteristics in eighteen coupled climate models. J. Clim. 19, 4605–4630.

Daly, C., Gibson, W.P., Taylor, G.H., Johnson, G.L., Pasteris, P., 2002. A knowledge-based approach to the statistical mapping of climate. Clim. Res. 22, 99–113.

Del Genio, A.D., 2012. Representing the sensitivity of convective cloud systems to tropospheric humidity in general circulation models. Surv. Geophys. 33, 637–656.

Dettinger, M., 2011. Climate change, atmospheric rivers, and floods in california – a multimodel analysis of storm frequency and magnitude changes. JAWRA J. Am. Water Resour. Assoc. 47, 514–523.

Dijkstra, T.A., Dixon, N., 2010. Climate change and slope stability in the UK: challenges and approaches. Q. J. Eng. Geol. Hydrogeol. 43, 371–385.

Donat, M.G., Lowry, A.L., Alexander, L.V., O'Gorman, P.A., Maher, N., 2016. More extreme precipitation in the world's dry and wet regions. Nature Climate Change , 10.1038–nclimate2941.

Godt, J.W., Baum, R.L., Chleborad, A.F., 2006. Rainfall characteristics for shallow landsliding in Seattle. Wash., USA, Earth Surf. Process. Landf. 31, 97–110.

Govi, M., Sorzana, P.F., 1980. Landslide susceptibility as a function of critical rainfall amount in Piedmont Basin (North-Western Italy). Stud. Geomorphol. Carpatho-Balc. 14, 43–61.

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, 3–17.

Hong, Y., Adler, R., Huffman, G., 2006. Evaluation of the potential of NASA multi-satellite precipitation analysis in global landslide hazard assessment. Geophys. Res. Lett. 33, L22402.

Kirschbaum, D.B., Adler, R., Hong, Y., Hill, S., Lerner-Lam, A., 2010. A global landslide catalog for hazard applications:. Nat. Hazards 52, 561–575.

Kirschbaum, D.B., Adler, R., Hong, Y., Kumar, S., Peters-Lidard, C., Lerner-Lam, A., 2011. Advances in landslide nowcasting: evaluation of a global and regional modeling approach. Environ. Earth Sci. 66, 1683–1696.

Kirschbaum, D., Adler, R., Adler, D., Peters-Lidard, C., Huffman, G., 2012. Global distribution of extreme precipitation and high-impact landslides in 2010 relative to previous years. J. Hydrometeorol. 13, 1536–1551.

Kirschbaum, D., Stanley, T., Zhou, Y., 2015. Spatial and temporal analysis of a global landslide catalog. Geomorphology 249, 4–15.

Larsen, M.C., Simon, A., 1993. A rainfall intensity-duration threshold for landslides in a humid-tropical environment. Puerto Rico. Geogr. Ann. Ser. A Phys. Geogr. 75, 13–23.

Lenderink, G., van Meijgaard, E., 2010. Linking increases in hourly precipitation extremes to atmospheric temperature and moisture changes. Environ. Res. Lett. 5, 025208.

Lepore, C., Veneziano, D., Molini, A., 2015. Temperature and CAPE dependence of rainfall extremes in the eastern United States. Geophys. Res. Lett., 74–83.

Lepore, C., Allen, J.T., Tippett, M.K, 2016. Relationships Between Hourly Rainfall Intensity and Atmospheric Variables Over the Contiguous United States. J. Climate 29 (9), 3181–3197. http://dx.doi.org/10.1175/JCLI-D-15-0331.1.

Maloney, E.D., Camargo, S.J., Chang, E., Colle, B., Fu, R., Geil, K.L., Hu, Q., Jiang, X., Johnson, N., Karnauskas, K.B., Kinter, J., Kirtman, B., Kumar, S., Langenbrunner, B., Lombardo, K., Long, L.N., Mariotti, A., Meyerson, J.E., Mo, K.C., Neelin, J.D., Pan, Z., Seager, R., Serra, Y., Seth, A., Sheffield, J., Stroeve, J., Thibeault, J., Xie, S.P., Wang, C., Wyman, B., Zhao, M., 2014. North American Climate in CMIP5 Experiments: Part III: assessment of twenty-first-century projections*. J. Clim. 27, 2230–2270.

Mapes, B., Neale, R., 2011. Parameterizing convective organization to escape the entrainment dilemma. J. Adv. Model. Earth Syst. 3.

Neelin, J.D., Langenbrunner, B., Meyerson, J.E., Hall, A., Berg, N., 2013. California winter precipitation change under global warming in the coupled model intercomparison project phase 5 ensemble. J. Clim. 26, 6238–6256.

Nuijens, L., Medeiros, B., Sandu, I., Ahlgrimm, M., 2015. The behavior of trade-wind cloudiness in observations and models: the major cloud components and their variability. J. Adv. Model. Earth Syst. 7, 600–616.

O'Gorman, P.A., Schneider, T., 2009. The physical basis for increases in precipitation extremes in simulations of 21st-century climate change. Proceedings Natl. Acad. Sci. 106, 14773–14777.

O'Gorman, P.A., 2015. Precipitation extremes under climate change. Curr. Clim. Change Rep. 1, 49–59.

Payne, A.E., Magnusdottir, G., 2015. An evaluation of atmospheric rivers over the North Pacific in CMIP5 and their response to warming under RCP 8.5. J. Geophys. Res.-Atmospheres 120.

Petley, D.N., Dunning, S.A., Rosser, N.J., 2005. The analysis of global landslide risk through the creation of a database of worldwide landslide fatalities. Landslide Risk Management, CRC Press.

Pierce, D.W., Cayan, D.R., Das, T., Maurer, E.P., Miller, N.L., Bao, Y., Kanamitsu, M., Yoshimura, K., Snyder, M.A., Sloan, L.C., Franco, G., Tyree, M., 2013. The key role of heavy precipitation events in climate model disagreements of future annual precipitation changes in california. J. Clim. 26, 5879–5896.

Radbruch-Hall, D.H., Colton, R.B., Davies, W.E., Lucchitta, I., Skipp, B.A., Varnes, D.J., 1982. Landslide Overview Map of the Conterminous United States. Technical Report Geological Survey Professional Paper 1183. Washington.

Seager, R., Neelin, D., Simpson, I., Liu, H., Henderson, N., Shaw, T., Kushnir, Y., Ting, M., Cook, B., 2014. Dynamical and thermodynamical causes of large-scale changes in the hydrological cycle over north america in response to global warming*. J. Clim. 27, 7921–7948.

Simpson, I.R., Seager, R., Ting, M., Shaw, T.A., 2015. Causes of change in northern hemisphere winter meridional winds and regional hydroclimate. Nat. Clim. Change 6, 65–70.

Stoffel, M., Mendlik, T., Schneuwly-Bollschweiler, M., Gobiet, A., 2013. Possible impacts of climate change on debris-flow activity in the swiss alps. Clim. Change 122, 141–155.

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.

Trenberth, K.E., 1999. Conceptual framework for changes of extremes of the hydrological cycle with climate change. Clim. Change 42, 327–339.

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.

Warner, M.D., Mass, C.F., Salathé, E.P., Jr, 2015. Changes in winter atmospheric rivers along the north american west coast in CMIP5 climate models. J. Hydrometeorol. 16, 118–128.

Wilson, R.C., Wieczorek, G.F., 1995. Rainfall thresholds for the initiation of debris flows at la honda, california. Environ. Eng. Geosci. I, 11–27.

Wood, A.W., Leung, L.R., Sridhar, V., Lettenmaier, D.P., 2004. Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. Clim. Change 62, 189–216.

Wood, J.L., Harrison, S., Reinhardt, L., 2015. Landslide inventories for climate impacts research in the european alps. Geomorphology 228, 398–408.

Zhu, Y., Newell, R.E., 1994. Atmospheric rivers and bombs. Geophys. Res. Lett. 21, 1999–2002.