A 142-YEAR CLIMATOLOGY OF NORTHERN CALIFORNIA LANDSLIDES AND ATMOSPHERIC RIVERS

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San Francisco Bay Area landslide days predominantly occur during December–March in Sonoma, Marin, San Mateo, and Santa Cruz Counties, where 82% of these days coincide with landfalling atmospheric rivers.

Extrême precipitation events can have a large influence on ecosystems, agriculture, infrastructure, and water resources that are particularly important to society. Costly effects from extreme precipitation events, depending on their location,

intensity, and duration can be attributed to subsequent hazards such as flooding and landslides. For example, floods caused more loss of life and property damage than any other natural disaster in the United States between 1900 and 1999 (Easterling et al. 2000), and landslides cause an estimated 25–50 deaths and ~\$3.5 billion (2001 USD) in damages in the United States annually (Highland 2004). The U.S. West Coast region is particularly susceptible to extreme precipitation events (Ralph and Dettinger 2012; Lamjiri et al. 2017), subsequent flooding (Kelley 1998), and landslides (Highland 2004).

A majority of the annual precipitation (30%–50%) and extreme precipitation events (60%–100%) along the U.S. West Coast are attributed to landfalling atmospheric rivers (ARs) that accompany North Pacific winter storms (Ralph and Dettinger 2012; Lamjiri et al. 2017). ARs are typically characterized by water vapor flux from lower latitudes along enhanced corridors of integrated water vapor (IWV) and IWV transport (IVT) (American Meteorological Society 2017) that can result in orographic precipitation along coastal and inland mountain ranges (e.g., Neiman et al. 2008). As a result, 24-h precipitation amounts

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of >100–150 mm have 2-yr recurrence intervals in the mountainous areas of the California Coast Ranges (NOAA 2011). These North Pacific winter storms and their associated precipitation are therefore known to produce both shallow and deep-seated landslides given appropriate antecedent conditions (e.g., saturated soils and/or prior wildfire activity; see next section) that may lead to significant damages in heavily developed areas such as the San Francisco Bay Area (Ellen and Wiecezorek 1988; Biasutti et al. 2016). A historical example of AR-associated landslides occurred during 3–5 January 1982 in conjunction with two landfalling ARs (Figs. 1a,b) that produced 400 mm (Marin County) to 600 mm (Santa Cruz County) of precipitation (NWS 1982). These ARs and their precipitation led to more than 18,000 landslides and debris flows, 25 landslide-related deaths, damage to thousands of homes, and damage to kilometers of transportation infrastructure throughout the San Francisco Bay Area (Fig. 1c; NWS 1982; Ellen and Wiecezorek 1988). Given that ARs and their precipitation are known to produce individual shallow

landslide events, the purpose of this study is to illustrate and quantify the extent to which landslides occurring in the San Francisco Bay Area have historically been associated with landfalling ARs using a novel 142-yr landslide dataset from 1871 to 2012.

BACKGROUND ON LANDSLIDES. This study focuses on shallow landslides associated with hillslope failures primarily involving soils that mobilize during or soon after a storm. A subset of these failures mobilize as debris flows, mixtures of soil, water, rock, and vegetation that flow down steep-land valleys (e.g., Iverson 1997; Stock and Dietrich 2003). Historic shallow failures occur during or shortly after storms that contain hourly rainfall rates >5–10 mm h⁻¹ (Campbell 1975; Wiecezorek 1987; Campbell et al. 1998). In the California Coast Ranges, and perhaps elsewhere, even intense storms do not seem to trigger failures unless the soils are already moist from early season rain. Historic events indicate that seasonal antecedent rainfalls (i.e., rainfall totaled from 1 October onward) must exceed 250 mm (Nilsen

a. Analysis for 0600 UTC 4 Jan 1982

b. Analysis for 0000 UTC 5 Jan 1982

c. Annotated Landslide Analysis by USGS for 3–5 January 1982

FIG. 1. (a),(b) Analyses of sea level pressure (hPa; gray contours with labeled storms L_1 and L_2), IWV (cm; shaded according to scale), and IVT vectors (plotted for magnitudes >150 kg m⁻¹ s⁻¹ and scaled according to reference vector) from the NOAA 20CR, and (c) annotated analysis by the USGS showing distribution of mapped debris flows and locations of deaths caused by landslides during 3–5 Jan 1982. Panel (c) provided by Fig. 2 of Ellen and Wiecezorek (1988, p. 3).

and Turner 1975; Campbell 1975; Nilsen et al. 1976; Cannon and Ellen 1985; Wieczorek 1987; Wilson and Jayko 1997) before steepland soils are susceptible to shallow landsliding. Threshold rainfall rates and accumulations may be greatly lowered for locations influenced by wildfire activity and changes in soil and vegetative characteristics (Florsheim et al. 1991; Turner 1996; Cannon and Gartner 2005). Individual shallow landslide events and debris flows have been linked to North Pacific winter storms such as the aforementioned January 1982 storms and those occurring during winter 1997/98 (Coe et al. 2004). Recently, Young et al. (2017) identified that 89% (25 of 28) of the days with a debris flow report in the National Centers for Environmental Information Storm Events Database over Northern California during October–March in 2004–14 were associated with a landfalling AR at the coast on the day of or the day before the storm event report.

Some of the landslide reports in our catalog (see next section) may also include deep-seated landslides that involve both soil and underlying bedrock. Consequently, they exceed a depth of several meters and have a wide range of failure geometries and styles (Varnes 1954). Many deep-seated landslides appear to be long-lived, creeping episodically once rainfalls have brought sufficient free water to their failure plane to generate positive pore pressures (Reid 1994). Failure planes and the hydraulic conductivities of the layers above them vary over orders of magnitude. For this reason, there appear to be a range of rainfall totals that activate these failures; motion may happen days, weeks, or months after a large storm. A subset of large landslides seems to happen catastrophically during or shortly after large storms, and these kinds of failures are among the deadliest (Jibson 2005; Iverson et al. 2015).

CALIFORNIA LANDSLIDE DATASET.

Timing and locations of known California-wide landslides of both types described above between 1871 and 2012 were compiled by the second author from published reports from the U.S. Geological Survey (USGS; e.g., Nilsen et al. 1976), digitized newspaper records and photos (e.g., published in the *San Francisco Chronicle* or the *San Francisco Call* newspapers with print dates beginning in the late nineteenth century), and unpublished sources. Thus, it is important to note that this dataset likely only includes a small fraction of all possible landslides that have occurred over California since 1871. The dataset provides an opportunity to understand the impact of known landslides on California prior to

published scientific studies on the topic in the 1970s. Each record includes the date, time of the event (if reported), location (or approximate location based on event details), and any text describing the failure or failures. The location description is used to associate a county with each event. To first order, this dataset was constructed using a similar methodology to the global landslide catalog by Kirschbaum et al. (2010) except for a longer period of record and a focus on California. Note that the reliance on newspaper reports prior to modern landslide mapping (e.g., Ellen et al. 1997) introduces strong biases. For instance, landslides that impacted infrastructure (e.g., railroads, roads, houses) are much more likely to appear in newspaper accounts and are therefore overrepresented in the dataset. The same effect means that populated areas like the San Francisco Bay Area are overrepresented in the dataset and form an ideal study population.

This study uses landslide events recorded between 1871 and 2012 in 10 San Francisco Bay Area counties: Marin, Sonoma, Napa, Solano, Contra Costa, Alameda, Santa Clara, Santa Cruz, San Mateo, and San Francisco. These counties contain 428 distinct landslide reports, occurring on 254 unique days across the region. Of these, 214 days represent an isolated day with a landslide report or the first day of a span of days with consecutive daily landslide reports. We call these “landslide onset days,” and we compare their occurrence to characteristics of ARs as discussed in the next section. Note that six landslide onset days occurred with a 1-day gap between events and are included in the subsequent analysis.

ANALYSIS METHODOLOGY. Characteristics of ARs on landslide onset days are investigated from data provided by the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (ESRL)/Physical Sciences Division (PSD) Twentieth Century Reanalysis Project (20CRP) version 2c dataset (Compo et al. 2011). The 20CRP dataset contains 6-h meteorological data between 0000 UTC 1 January 1871 and 1800 UTC 31 January 2012 on 24 pressure levels (every 50 hPa between 1000 and 50 hPa, and 70, 30, 20, and 10 hPa), and 3-h meteorological data for select surface variables, on a 2° latitude × 2° longitude global grid. The analyses in this study are constructed from the 20CRP ensemble-mean gridded fields of sea level pressure (SLP), IWV (which is contained in the 20CRP as total column precipitable water), the IVT vector that is calculated following the methodology of Neiman et al. (2008), and 3-hourly instantaneous precipitation rates. Linkages between landslide onset

days and ARs are determined using two characteristics of ARs specific to north coastal California. The first characteristic includes using a threshold IVT magnitude of $250 \text{ kg m}^{-1} \text{ s}^{-1}$ that is a common instantaneous threshold used by past studies to identify and forecast minimum “AR conditions” in this region as described by Rutz et al. (2014), Cordeira et al. (2017), and Ralph et al. (2019). Note that using this threshold may have obvious limitations, especially at times with ARs of marginal or uncertain intensity near the threshold chosen and with ARs of variable or uncertain locations. These uncertainties are derived from the relatively coarse grid spacing, ensemble-mean data, and innate uncertainty of the 20CRP dataset prior to the satellite era and for data derived from surface pressure observations (e.g., Compo et al. 2006). Some of these uncertainties are addressed by using a second characteristic that includes spatial analyses of SLP, IWV, and IVT in order to identify landfalling ARs (as already seen in Figs. 1a,b). This spatial identification of ARs is comparable to that performed by

Neiman et al. (2008) using IWV only [see Rutz et al. (2014) for justification of using IVT over IWV]. The spatial analyses allow for a more subjective analysis of the long (e.g., $>2,000 \text{ km}$), narrow (e.g., $<1,000 \text{ km}$), and intense (e.g., IVT magnitude $\geq 250 \text{ kg m}^{-1} \text{ s}^{-1}$) characteristics of atmospheric water vapor flux commonly used to identify ARs using objective criteria.

Composite analyses are constructed for landslide onset days in a “time of maximum IVT” framework. This framework identifies the time of maximum IVT magnitude from the 20CRP at 38°N , 122°W (i.e., the grid point located slightly inland over the San Francisco Bay) from a 73-h period from two days prior to one day after the landslide onset day. For example, the methodology identified the time of maximum IVT magnitude between 0000 UTC 2 January and 0000 UTC 5 January 1982 for a landslide report on 4 January 1982. The framework 1) allowed for flexibility and also specificity in linking the local calendar day associated with a landslide report to one of the 6-h UTC times associated with the 20CRP dataset,

a. Landslide days by water year

b. Landslide days by month

c. Days per decade by county

FIG. 2. Identified number of San Francisco Bay Area landslide onset days 1871–2012 (a) by water year, (b) by month with and without concurrence of IVT magnitudes $\geq 250 \text{ kg m}^{-1} \text{ s}^{-1}$ at 38°N , 122°W , and (c) by county per decade. Panel (c) created using Esri ArcMap 10.3.1 with county and state outlines obtained from the U.S. Census Bureau (www.census.gov/geo/maps-data/data/tiger-cart-boundary.html).

2) yielded more coherent and less smeared composite analyses of atmospheric parameters, and 3) shifted the composite time of events on average ~ 11.3 h earlier than just using 0000 UTC on the day of the landslide report.

RESULTS. Landslide onset days ($N = 214$) occurred in 78 of the 142 (55%) water years studied. In those years, the number of landslide onset days ranged from 1 yr^{-1} to 8–10 yr^{-1} , with 1890, 1952, 1973, and 2006 yielding the most (Fig. 2a). Landslide onset days occur primarily during the cool- and wet-season months between October and May, with a peak during January and February (Fig. 2b). The January–February peak in landslide onset days lags the December temporal peak in landfalling AR events identified by Rutz et al. (2014, see their Fig. 6).

The highest spatial frequency of landslide onset days in the San Francisco Bay Area occurs along coastal and steep-land regions of Sonoma, Marin, San Mateo, and Santa Cruz Counties (Fig. 2c). Additional analysis reveals that there is no correlation (correlation coefficient of -0.028) between the annual frequency of landslide onset days per year and December–February monthly mean values of the 20CRP El Niño–Southern Oscillation index (not shown; e.g., Ropelewski and Jones 1987; NOAA 2017). It is important to note, however, that trends in the annual frequency of landslides onset days, especially during the nineteenth and early twentieth centuries, cannot necessarily be analyzed due to the possibility of unknown remote landslide events that are not identified in the dataset.

Landslide onset days occur primarily during 8–10-day periods with enhanced IVT magnitudes relative to climatology ($\sim 150 \text{ kg m}^{-1} \text{ s}^{-1}$ as compared to $\sim 50 \text{ kg m}^{-1} \text{ s}^{-1}$) at 38°N , 122°W (Fig. 3). The composite mean IVT magnitude increases from ~ 150 to $\sim 386 \text{ kg m}^{-1} \text{ s}^{-1}$ in the 36 h leading up to the time

FIG. 3. Time-lagged composite mean time series of IVT magnitude ($\text{kg m}^{-1} \text{ s}^{-1}$ red line) and 3-h instantaneous precipitation rate [mm (3 h)^{-1} ; gray and green bars] relative to the time of maximum IVT magnitude for San Francisco Bay Area landslide onset days ($N = 214$) at 38°N , 122°W . The $+1$ and -1 standard deviation of the IVT magnitude (solid blue lines), climatology of mean IVT magnitude (solid black line), and IVT magnitude of $250 \text{ kg m}^{-1} \text{ s}^{-1}$ (dashed black line) are provided for reference. Green bars emphasize the 3-h instantaneous precipitation rate for the time from 12 h before to 60 h after the time of maximum IVT magnitude as discussed in the text. Inset: 6-h values of IVT magnitude and direction for 1871–2012 (gray circles) and maximum IVT for landslide onset days (red circles) plotted in rotated polar coordinates similar to a wind rose such that IVT magnitude is indicated by the radial coordinate, the IVT direction is indicated by the angular coordinate rotated such that a westerly water vapor flux is on the left-most portion of the diagram. The IVT magnitude climatology is created using an 1871–2012 climatological mean value using a random sample Monte Carlo-type simulation with 1,000 iterations.

of maximum IVT. The daily average IVT magnitude centered on the time of maximum IVT is $\sim 288 \text{ kg m}^{-1} \text{ s}^{-1}$. The total duration of the composite mean IVT magnitude $\geq 250 \text{ kg m}^{-1} \text{ s}^{-1}$ is 20.7 h, which is similar in duration to results presented by Rutz et al. (2014), who found an average AR duration using IVT magnitude $\geq 250 \text{ kg m}^{-1} \text{ s}^{-1}$ over north coastal California of ~ 18 – 20 h (see their Fig. 7; Ralph et al. 2013). The time of maximum IVT magnitude coincides with the average time of maximum 3-h precipitation rates, which is enhanced with respect to the 10-day analysis for the 72-h period from ~ 12 h before to ~ 60 h after the time of maximum IVT magnitude. While these average precipitation rate values are relatively low in the time of maximum IVT framework [e.g., a composite mean rate of $\sim 3 \text{ mm (3 h)}^{-1}$], they do represent precipitation rates in the 98.8th percentile of all 3-h precipitation rates and the 96.2th percentile of all nonzero 3-h precipitation rates at 38°N , 122°W derived from the relatively coarse-resolution 20CRP dataset from 1871 to 2012. The average of the *maximum* precipitation rates identified during each event

for the period from 12 h before to 60 h after the time of maximum IVT magnitude was $4.75 \text{ mm (3 h)}^{-1}$ and represents values in the 99.6th and 98.6th percentiles, respectively, as partitioned above.

A large majority (163 of 214; 76%) of landslide onset days coincided with maximum IVT magnitudes $\geq 250 \text{ kg m}^{-1} \text{ s}^{-1}$ at 38°N , 122°W (Figs. 2b and 3). The fraction of landslide onset days that coincided with maximum IVT magnitudes $\geq 250 \text{ kg m}^{-1} \text{ s}^{-1}$ at 38°N , 122°W by month is between 73% and 83% during October–March, 67% in April, and 0% (0 of 2) in May (Fig. 2b). The composite mean IVT vector direction at 38°N , 122°W at the time of maximum IVT magnitude is west-southwest at $\sim 220^\circ$, with a majority (174 of 214; 81%) of IVT directions between 180° and 270° (Fig. 3, inset). The identified IVT characteristics (magnitude and direction) are common characteristics of water vapor transport associated with landfalling ARs in the San Francisco Bay Area as shown by Neiman et al. (2008).

Although composite mean IVT magnitudes over the San Francisco Bay Area on landslide onset days are $386 \text{ kg m}^{-1} \text{ s}^{-1}$, they occur at the terminus of an offshore composite mean corridor of maximum IVT magnitudes $> 500 \text{ kg m}^{-1} \text{ s}^{-1}$ and IWV values $> 2.6 \text{ cm}$ that resembles an AR over the northeast Pacific (Fig. 4a). Consequently, 12 landslide onset days with maximum IVT magnitudes $< 250 \text{ kg m}^{-1} \text{ s}^{-1}$ at 38°N , 122°W contained maximum IVT magnitudes $\geq 250 \text{ kg m}^{-1} \text{ s}^{-1}$ at 36°N , 124°W ($\sim 285 \text{ km}$ upstream; not shown). This result motivated visual inspection of all 214 landslide onset days, of which 176 of 214 (82%) were found to contain spatial characteristics consistent with landfalling ARs (e.g., a corridor of IVT magnitude $\geq 250 \text{ kg m}^{-1} \text{ s}^{-1}$ with a length $> 2,000 \text{ km}$). Note that this analysis found both days with coastal IVT magnitudes $\geq 250 \text{ kg m}^{-1} \text{ s}^{-1}$ that were not associated with ARs offshore and days with coastal IVT magnitudes $< 250 \text{ kg m}^{-1} \text{ s}^{-1}$ that were associated with ARs offshore. As a result, this analysis found 82% of the identified landslide onset days to be associated with ARs even if the coastal IVT magnitudes did not necessarily exceed $250 \text{ kg m}^{-1} \text{ s}^{-1}$. This 82% fraction of events associated with ARs is similar in magnitude to the 89% of debris flow reports tallied across Northern California that occurred in association with a landfalling ARs located somewhere along the Northern California coastline studied by Young et al. (2017).

Composite analysis for the subset of landslide onset days associated with ARs offshore ($N = 176$) illustrates a prominent AR with a corridor of maximum IVT magnitudes of $> 500 \text{ kg m}^{-1} \text{ s}^{-1}$ and IWV values $> 2.6 \text{ cm}$ located between a region of low

pressure $< 996 \text{ hPa}$ located west of Vancouver and British Columbia and a region of high pressure $> 1,016 \text{ hPa}$ located over the subtropical northeast Pacific (Fig. 4b). Alternatively, those landslide onset days not associated with ARs ($N = 38$) occur in conjunction with IWV values $> 1.8 \text{ cm}$ and IVT magnitudes $< 200 \text{ kg m}^{-1} \text{ s}^{-1}$ downstream of a region of high pressure $> 1,022 \text{ hPa}$ over the northeast Pacific and in the wake of a region of low pressure $< 1,010 \text{ hPa}$ over the Great Basin (Fig. 4c). While not associated with landfalling ARs, these landslide onset days appear to occur in a moist postfrontal environment where convective precipitation (i.e., thunderstorms) or shallow orographic precipitation may influence landslide occurrence.

December–February (DJF) landslide onset days associated with ARs ($N = 127$; Fig. 4e) comprise 72% of the total number of events and the composite patterns for this season resemble those for all landslide onset days associated with ARs (cf. Figs. 4b and 4e). September–November (SON) landslide onset days associated with ARs ($N = 13$; Fig. 4d) are fewer in number and occur in conjunction with a quasi-zonal water vapor pattern that contains IVT magnitudes of $\sim 600 \text{ kg m}^{-1} \text{ s}^{-1}$ and IWV $> 3.0 \text{ cm}$ over the northeast Pacific, whereas March–May (MAM) landslide onset days associated with ARs ($N = 36$; Fig. 4f) occur in conjunction with an amplified water vapor pattern that contains IVT magnitudes of $350\text{--}400 \text{ kg m}^{-1} \text{ s}^{-1}$ and IWV values of $2.3\text{--}2.4 \text{ cm}$ over the northeast Pacific. When the three 3-month seasons are considered, SON landslide onset days appear to occur in association with more amplified synoptic-scale flow patterns and more intense ARs as compared to DJF and MAM onset days; however, the low sample sizes of SON and MAM landslide onset days relative to the sample size of DJF landslide onset days challenge the integrity of this assertion with the available data.

A 72-h analysis of the time-integrated 3-hourly instantaneous precipitation rate from $\sim 12 \text{ h}$ before to $\sim 60 \text{ h}$ after the time of maximum IVT magnitude (i.e., a proxy for 72-h precipitation) for landslide onset days associated with landfalling ARs illustrates that SON, DJF, and MAM landslide onset days occur on average in association with 72-h precipitation totals of 52.5, 45.8, and 35.7 mm, respectively (not shown). Keeping the sample size in mind, these results may also suggest that on average more intense early-season landfalling ARs that result in higher precipitation totals may be needed to trigger a landslide as compared to less intense late-season landfalling ARs (e.g., Oakley et al. 2018). A similar time-integrated analysis from the start of the water year (1 October) to 12 h before

the time of maximum IVT magnitude (i.e., a proxy for water-year-to-date precipitation) for all landslide onset days identified average antecedent precipitation totals of 265.3 mm (262.5 mm for those associated with ARs and 278.0 mm for those not associated

with ARs). These values are comparable to earlier described estimates that establish a 250 mm minimum threshold for antecedent precipitation totals associated with historic shallow landslides. Further analysis related to precipitation and environmental

a. All Days; N=214

b. Days assoc. with ARs; N=176

c. Days not assoc. with ARs; N=38

d. Days assoc. with ARs in Sep–Nov; N=13

e. Days assoc. with ARs in Dec–Feb; N=127

f. Days assoc. with ARs in Mar–May; N=36

FIG. 4. Composite analyses at time of maximum IVT magnitude of sea level pressure (hPa; gray contours), IWV (cm; shaded according to scale), and IVT vectors (plotted for magnitudes $>150 \text{ kg m}^{-1} \text{ s}^{-1}$ and scaled according to reference vector) are shown for (a) all landslide onset days, (b) days associated with landfalling ARs, (c) days not associated with ARs, and (d)–(f) days associated ARs in Sep–Nov, Dec–Feb, and Mar–May, respectively.

hydrological conditions associated with landslides is beyond the scope of this study and is considered more in depth by Oakley et al. (2018).

DISCUSSION AND CONCLUSIONS. We use a 142-yr record of San Francisco Bay Area landslides between 1871 and 2012 to illustrate a spatiotemporal relationship between 214 identified landslide onset days and the atmospheric conditions commonly associated with landfalling ARs. The onset of landslides in the San Francisco Bay Area occurs during winter with a peak in January and February and is particularly focused in coastal counties with steep topography across Sonoma, Marin, San Mateo, and Santa Cruz Counties. A majority (76%) of the identified landslide onset days occurred in association with strong atmospheric water vapor flux quantified by coastal IVT magnitudes $\geq 250 \text{ kg m}^{-1} \text{ s}^{-1}$ that persist for $\sim 20 \text{ h}$ and intense precipitation characterized by precipitation rates above the 98th percentile with respect to climatology over the San Francisco Bay Area. Upon closer examination of all 214 landslide onset days, 82% of these days occurred in association with long and narrow corridors of enhanced I WV and IVT that are consistent with ARs over the near-offshore northeast Pacific. These results suggest that extreme precipitation associated with landfalling ARs precede or may trigger a large majority of landslides across the San Francisco Bay Area. The duration of enhanced IVT magnitudes, extreme precipitation rates with respect to climatology, and spatial patterns of I WV and IVT are all generally consistent with previous studies of hydrological extremes over California and their association with ARs. For example, landfalling ARs have been linked with $\sim 40\%$ – 75% of extreme wind and precipitation events over 40% of the world's coastlines (Waliser and Guan 2017), 31%–65% of coastal western U.S. avalanche fatalities (Hatchett et al. 2017), $\sim 64\%$ of high-impact hydrological events (i.e., floods, flash floods, or debris flows) over Northern California (Young et al. 2017), and 60%–90% of extreme precipitation events (Oakley et al. 2018) that may produce shallow landslides.

This study specifically provides insight into what fraction of known San Francisco Bay Area landslide onset days likely occurred in association with landfalling ARs and their associated synoptic-scale atmospheric processes from a relatively coarse reanalysis dataset with innate uncertainties (e.g., Compo et al. 2006). Given that the landslide dataset does not include all possible landslides, it is problematic to perform a complementary analysis that identifies those characteristics of ARs that produce

landslides and those that do not for the 1871–2012 period from the 20CRP. With this caveat, the IVT data for the San Francisco Bay Area reveal possible landfalling ARs on 4,373 days with an instantaneous IVT magnitude $\geq 250 \text{ kg m}^{-1} \text{ s}^{-1}$ at any of the 6-h synoptic times and 1,854 days with a daily average IVT magnitude $\geq 250 \text{ kg m}^{-1} \text{ s}^{-1}$. These data suggest that a small fraction of possible AR days (4.9% and 11.5%, respectively) occurred on the same day as a known landslide onset day. In other words, relatively few ARs of all possible ARs produced the known landslides in this study.

Of those landfalling ARs that produced known landslides, many of these were likely all accompanied by mesoscale processes that promoted orographic precipitation (e.g., Lamjiri et al. 2017; Oakley et al. 2018) or may have been accompanied by narrow cold-frontal rainbands (Hobbs and Persson 1982; Oakley et al. 2017) that helped trigger the landslide or landslides in regions of complex terrain. In these cases, it is not necessarily the enhanced IVT (i.e., with a magnitude $\geq 250 \text{ kg m}^{-1} \text{ s}^{-1}$) and long duration of orographic precipitation associated with a landfalling AR that triggered the landslide, but rather the period of intense short-duration precipitation. These aforementioned processes are not resolvable by the 20CRP. This study also suggests that higher IVT magnitudes and more intense precipitation along landfalling ARs during SON may be required to produce an early-season landslide as compared to lower IVT magnitudes and less intense precipitation along landfalling ARs during DJF or MAM, with a noted limitation due to sample size. This result potentially underscores the role of antecedent soil moisture provided by season-to-date precipitation and also complements findings by Chen et al. (2018), who show that higher IVT magnitude thresholds in landfalling ARs are more predictive of extreme precipitation. The veracity of this particular result is ultimately contingent upon the complex relationship among the IVT vector, precipitation processes, and the location-dependent antecedent hydrometeorological conditions (e.g., soil moisture, terrain, antecedent wildfire activity). Future work is aimed at investigating forecasts and analyses of meso-synoptic-scale atmospheric processes and location-dependent hydrometeorological ingredients that might help differentiate between landfalling ARs that may trigger a landslide (or multiple landslides) and those that may not trigger a landslide. For example, landfalling ARs in this study could be categorized based on their maximum intensity and duration following the AR scale developed by Ralph et al. (2019) in order to determine whether

those ARs categorized as “mostly hazardous, also beneficial” or “primarily hazardous” are more likely to trigger a landslide (or multiple landslides) as opposed to those categorized as “primarily beneficial” or “mostly beneficial, also hazardous” (see their Table 2 and their Fig. 4).

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