Atmospheric River Families and their Relationship to Landslides in Washington State

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ABSTRACT
Precipitation has long been identified as a driver for landslides, and atmospheric rivers (long, narrow corridors of water vapor in the lower atmosphere) are often associated with precipitation events that trigger landslides. This study aims to connect synoptic regimes, especially weather patterns involving atmospheric rivers, to geomorphic responses in Washington State. Specifically, I aim to determine how atmospheric river families (two or more atmospheric river events occurring within up to 120 hours of each other) affect the occurrence of landslides; this relates to how quickly soil moisture and other properties recover following atmospheric river events. I examine several mapped shallow landslide events cataloged by the Washington Department of Natural Resources and compare their occurrence to sequences of atmospheric rivers, precipitation, soil moisture, and other properties. This study includes analysis of an atmospheric river with integrated vapor transport peaking at $1463 \text{ kg m}^{-1}\text{s}^{-1}$ on December 3, 2007, leading to over 1,940 landslides and killing one person in western Washington. Further understanding the connection between specific synoptic regimes that cause precipitation and antecedent land conditions such as soil moisture could help improve lead time for forecasting landslides.

Key Words: Atmospheric Rivers; Atmospheric River Family; Landslides; Washington State; Geomorphology
INTRODUCTION

An atmospheric river (AR), a relatively new scientific concept colloquially referred to as a “Pineapple Express,” is defined as a long (> 2000 km), narrow (generally < 1000 km wide), and transient corridor of strong horizontal water vapor transport typically associated with an extratropical cyclone (Zhu and Newell, 1998; Ralph et al., 2005; Bao et al., 2006; Neiman et al., 2008). An extratropical cyclone is a counterclockwise-rotating (in the Northern hemisphere) low-pressure system generally in the mid to high latitudes that derives its energy from horizontal temperature differences; many of the weather systems that cross the entire United States, especially in the Fall and Spring, are extratropical cyclones. Atmospheric rivers often occur associated with extratropical cyclones and the maximum water vapor transport is just ahead of the cold front in the relatively warm portion of an extratropical cyclone (Fig. 1). Atmospheric rivers transport as much water, in water vapor, as the Amazon River with 75% of this transport occurring in the lower 2.25 km of the atmosphere, making them the largest mechanism for freshwater transport on Earth (Zhu et al., 1994; Ralph et al., 2005; Ralph et al., 2018). With the majority of its water vapor close to the Earth’s surface, orographic (mountain) forcing causes the water vapor in ARs to rise, cool, and condense leading to heavy precipitation, with the greatest storm totals at high elevations. Since atmospheric rivers are both the primary source of flooding and provide 25-50% of annual water supply for California (Northern California has the most robust research on ARs), it is integral to understand these features, especially from a water resource management perspective (Guan et al., 2010; Dettinger et al., 2011). Not only can atmospheric rivers
lead to damaging winds and flooding, but also mass wasting events, especially in burn scar regions.

Atmospheric rivers often occur successively (and usually cause more damage in succession), so the term “atmospheric river family” is introduced. An AR family is defined as two or more AR events occurring within one aggregation period, which can range from 24 to 120 hours (Fig. 2; Fish et al., 2019 in revision). Since AR families contain multiple AR events, successive precipitation in such events can saturate the soil and lead to slope failure. High-intensity precipitation over a short period of time can cause landslides, and moderate intensity rainfall over a long period of time can cause landslides; therefore, both intensity and duration of rainfall important (Caine et al., 1980). Similarly, the new classification scale of atmospheric rivers from Category 1-5 (similar idea to how hurricanes are classified) is dependent upon the amount of integrated vapor transport (IVT), how much water vapor is being carried by wind, and the duration of atmospheric river conditions (Fig. 3, Ralph et al., 2019). Using this scale, a Category 1 atmospheric river provides “primarily beneficial” precipitation whereas a Category 5 atmospheric river is “primarily hazardous” (Ralph et al., 2019). The concept of AR families is a helpful lens for viewing such situations since AR families often pose a greater threat than an individual AR; thus, the term “AR family” will be helpful for AR prediction, water resource management (especially for the Forecast Informed Reservoir Operations project in Northern California), and landslide prediction.

Landslides (including debris flows and rockfall) killed 32,322 people between 2004 and 2010 worldwide (likely an underestimate as some may not have been recorded) (Petley, 2012). Nationally, landslides account for more than $2 billion in losses annually
and result in an estimated 25 to 50 deaths a year (Spiker and Gori, 2003; Schuster and Highland, 2001; Schuster, 1996). In 1998, the Aldercrest–Banyon landslide in Kelso, Washington, damaged or destroyed 138 homes and accounted for $30 to $40 million in losses (Wegmann, 2006). Washington state is well-aware of its vulnerability to landslides as the Washington Department of Natural Resources estimates hundreds to thousands of events occur each year; thus, the Washington Department of Transportation budgets about $15 million per year for cleaning up landslides on highways.

Petley et al. (2005) established that landslides are mainly caused by intense and prolonged rainfall. Neiman et al. (2008) showed that winter storms associated with atmospheric rivers produce twice the normal precipitation compared to other winter storms along the West Coast. Similarly, atmospheric rivers cause 92% of the West Coast’s heaviest three-day rainfall events (Ralph and Dettinger, 2012).

Research concerning the relationship between ARs and mass-wasting (slope movement) events is still in its infancy, and Washington State does not yet have a statewide analysis of these processes. Recent work by Biasutti et al. (2016) used news-based landslide data to find that high-intensity daily precipitation from atmospheric rivers is the main cause for landslides in the Puget Sound in Washington State. Young et al. (2017) found that floods and debris flows are usually caused by winter atmospheric rivers in Northern California. Oakley et al. (2018) found that 60-90% of hourly precipitation events exceeding established landslide triggering thresholds occurred during atmospheric river events in the Transverse Ranges (north of Los Angeles), California Coastal Ranges, and the northwest Sierra Nevada. This study aims to build on this work to investigate the relationship between landslides and atmospheric rivers in Washington State, with a focus
on how having multiple, closely spaced atmospheric rivers—AR families—can provide the antecedent moisture and lack of recovery time that allows a subsequent AR to trigger landslides. Thus, the main science question is: What is the role of atmospheric rivers and atmospheric river families in producing impactful and widespread shallow landslides in Washington State?

GEOLOGIC AND METEOROLOGICAL SETTING

Western Washington is especially susceptible to landslides due to the steep terrain and areas with unconsolidated sediment or shallow soil receiving large amounts of precipitation. The main geologic regions are the Puget Lowland, the Olympic Mountains, the Willapa Hills, the Cascades, the Okanogan Highlands, the Columbia Basin, and the Blue Mountains (Fig. 4; Roloff et al., 2013). The Puget Lowland, where most of Washington’s population is (Seattle, Olympia, etc.), has mostly young, unconsolidated glacial sediments which are vulnerable to landslides. The Olympic Mountains are mostly young (23-66 mya) sedimentary rocks. The Willapa Hills are 23-66 mya igneous and sedimentary rocks with shallow soil on steep slopes that make them vulnerable to landslides. The Northern Cascades have the oldest (Precambrian to Pre-Tertiary) metamorphic and sedimentary rocks while the Southern Cascades have many young (0-66 mya) igneous rocks and even active volcanoes including Mt. Rainier, Mt. Adams, and Mt. St. Helens. These volcanoes can lead to lahars, debris flows, and earthquake-induced landslides; however, such events are not the focus of this paper. The Okanogan Highlands in the northeast part of Washington is divided into west and east by the Columbia River with the western part containing mainly Tertiary igneous and
sedimentary rocks while the eastern part contains the oldest rocks in the state---Precambrian metasedimentary rocks. The Tertiary Columbia River Basalt and non-glacial Quaternary sediments dominate the south-central and eastern portion of the state in the Columbia Basin. Uplift of these units in the southeast corner of the state formed the Blue Mountains with peaks exceeding 6,000 ft (1829 m).

The geology of Washington State modulates the topography which in turn affects the precipitation patterns. The highest precipitation totals are on the windward (western) side of the Olympic and Cascade mountains with areas exceeding 100 inches (2540 mm) each year while the lowest precipitation totals are in the rain shadow the Cascades in south-central Washington with under 10 inches (254 mm) each year (Fig. 5). The snow level is generally at around 1,500 to 2,000 feet (457-610 m) in mid-winter with areas above 4,000 ft (1219 m) receiving 400-600 inches (10160-15240 mm) of snow each year and peaks bearing snow year-around (Western Regional Climate Center). The northeast part of the state, the Okanogan Highlands, is generally in the rain shadow of the Cascade mountains, but its high elevation including peaks exceeding 8,000 ft (2438 m) enables portions of this region to exceed 35 inches (889 mm) per year. These precipitation patterns are consistent with how ARs have most of their moisture in the lower 2.25 km (7382 ft) of the atmosphere and therefore mountain ranges lead to abrupt rising and condensation of water vapor producing orographically-driven heavy precipitation. The month with the greatest AR frequency in Washington State is November (AR conditions greater than 25% of the time), closely followed by January and then December (Rutz et al., 2014).
DATA AND METHODS

I used atmospheric river data from the Rutz et al. (2014) catalog that requires ARs to have a length > 2000 km, no width requirement, and IVT > 250 kg m\(^{-1}\)s\(^{-1}\). This catalog comes from the Modern-Era Retrospective Analysis (MERRA) dataset (Rienecker et al., 2011), a NASA global reanalysis (meteorological data assimilation of observations over a long time period) product that uses satellite data and the Goddard Earth Observing System Data Assimilation System Version 5 (GEOS-5). These data have a temporal resolution of every three hours from 1980 through 2017 and a spatial resolution of 0.5 degrees. In addition, I used the AR family catalog from Fish et al. (2019) for the West Coast of the United States; this catalog was derived from 9+ hour ARs from the Rutz et al. (2014) catalog.

I compared the location and timing of the AR and AR family data to the location and timing of rainfall-driven shallow landslides in Washington State. I chose to study rainfall-driven shallow landslides instead of deep-seated landslides since shallow landslides are more easily linked to rainfall events. Such a comparison of continuous AR catalog data to discontinuous landslide data inherently poses challenges. The catalog data may not match exactly what actually happened (especially on scales smaller than its spatial resolution) and the landslide datasets likely missed several landslides that were either not observed or not reported (often the case if they occurred in a remote area or did not cause any damage). Despite these pitfalls, the Washington Department of Natural Resources (WA DNR) has a list of the most significant shallow landslide events from 1984-2014 (Goldmark, 2014) and a media database with reports from late November 2016 through June 2018 (Personal communication, Slaughter, S., 2018).
There are ten significant shallow landslide events on the WA DNR’s list. Many of these events included more than one landslide with some of the events exceeding 1,000 landslides. The locations affected and approximate time period of the landslide events are also given. I did not analyze shallow landslides that occurred on February 28, 2001, since they were prompted by a 6.8 magnitude earthquake; even so, it is important to recognize that there are many ways to cause shallow landslides. Two other events on this list are left out due to not enough information about the timing or locations of landslides; this is one of the main challenges of comparing landslide data (often recorded after the event without an exact date) to atmospheric data since a meaningful comparison is impossible without the date for the landslide event. One of these landslide events likely corresponded to the 2006 Hanukkah storm that was a Category 2-3 atmospheric river upon landfall and caused significant damage related to wind; however, the locations of the landslides caused by this storm were poorly documented so it is not included.¹

The WA DNR media landslide database was compiled starting in late 2016 using GIS from landslide reports found on the Internet, Twitter, and reports from geologists. Each event has a latitude, longitude, date, and time (some may have times estimated to the nearest day) (Stephen Slaughter, personal communication). Since the location of the landslides is generally more specific in the media landslide database, the 0.5° resolution of the AR data may not exactly capture what is happening at the landslide location. It is also likely that there are types of landslides other than shallow landslides in this dataset.

¹ A paper explaining the impacts of this storm did explain that trees were more vulnerable to blowing down in sporadic hurricane-force winds of the storm due to November 2006 having precipitation of ~170% of normal (Read and Reed, 2013). This is another consequence of saturated soil that is important when thinking about atmospheric river impacts since ARs generally have both high wind and heavy rain.
Both of the WA DNR datasets estimate the timing of the landslide to the nearest day instead of the nearest third hour (as in the AR catalog), so there may be a mismatch in the timing of land-based events compared to atmospheric events.

I delved deeper into the meteorological context of the most devastating rainfall-driven shallow landslide events with a variety of model-based and observational datasets. The Applied Climate Information System’s precipitation products were used to demonstrate the precipitation totals surrounding the rainfall-driven shallow landslide events (Eggleston, 2013). I used two different sources of precipitation data from this website: Northeast Regional Climate Center (NRCC) station interpolated and Parameter-elevation Regressions on Independent Slopes Model (PRISM). The NRCC station interpolated data uses daily observation data from stations and interpolates them into a 1/120° grid; there are certainly issues with such an interpolation scheme especially because it does not account for topography that may affect precipitation. The PRISM method also uses stations and the same grid size but accounts for elevation, topographic orientation, proximity to the coast, and other variables in order to incorporate the current climate knowledge of the area to each grid cell. Thus, both methods generate slightly different data, but it is helpful to look at both to approximate the amount of uncertainty in the precipitation data.

In order to zoom into specific station locations, I used the Snow Telemetry (SNOTEL) and Snow Course Data and Products Interactive Map and the Applied Climate Information System’s map to find stations at a variety of locations in Washington State. Specifically, I used the Burnt Mountain station (4170 ft. at 47.04°N, 121.94°E) and the Tacoma No. 1 station (25 ft. at 47.25°N, 122.41°E) to compare
observed precipitation and temperature patterns at both high and low elevations during the December 1-3, 2007 atmospheric river event.

The broader context for events was supplemented by further understanding the antecedent moisture of the region and the atmospheric regimes preceding each rainfall-driven shallow landslide event. The UCLA Drought Monitoring System for the Pacific Northwest has maps of Total Moisture Percentile, Snow Water Equivalent Percentile, and Soil Moisture Percentile for each month from 1920-2010 (Wood, 2008). I used these maps for December 2007 for establishing the context for the December 1-3, 2007 atmospheric river and widespread shallow landslide event.

Meredith Fish, a Climate Science graduate student at University of California San Diego, helped me generate maps of the atmospheric context (variables such as temperature, pressure, integrated vapor transport, etc.) for each event with MERRA-2 (Gelaro et al., 2017). In addition to these resources, reports from the National Oceanic and Atmospheric Administration (NOAA) and the Washington Department of Natural Resources were helpful in adding to my understanding of some of the major events.

RESULTS

Atmospheric River Families in Coastal Washington State

Near the middle of the Washington coastline (124.375°W, 47.000°N) there are about 48 ARs (each individually at least 9 hours long) each year, and 84% of these are part of atmospheric river families using the 120-hour aggregation threshold (Table 1). This value is the same if calculated at 46.500°N or 46.000°N. If the 48-hour aggregation
threshold is used, then 68% of these ARs are part of AR families. This number decreases slightly northward with 124.375°W, 48.000°N having 44 ARs per year with 80% of these being part of an AR family. Thus, ARs are very common on the coast of Washington State and often occur as part of families.

**Atmospheric River Context for Media Reported Landslides**

These data from the Department of Natural Resources media database gives a broad idea of when landslides occurred since late 2016 and were especially useful for analyzing the 2016-17 winter. There were 166 landslide reports across Washington from December 2016 through April 2017; note that some of these reports encompass more than one landslide (Fig. 6A). The timing of these landslide reports compared to ARs is shown in Figure 6B. The landslide reports cluster around the ARs with 86% of them being reported within a day of one AR and 70% of them within one day of an AR family. 51% of them correspond with the timing of the longest AR family of the period—28 days.

**Atmospheric River Context for Significant Shallow Landslides**

In order to see whether atmospheric rivers or atmospheric river families are commonly part of the meteorological regimes associated with the initiation of significant shallow landslides, I plotted the occurrence of atmospheric rivers and atmospheric river families prior to and during each of the seven significant rainfall-driven shallow landslide events from the Department of Natural Resources (Table 2).
An in-depth explanation of the December 1-3, 2007 event is provided in the Case Study section, but I will briefly remark on the other six events here and show the meteorological context for each. Much of the information I have about the significant shallow landslides comes from the Department of Natural Resources reports on these extreme events, and most of these reports mentioned precipitation but did not mention atmospheric rivers by name (part of this is due to the term “atmospheric river” only being commonly used for the past 10-15 years). Despite the general lack of mention of ARs, all seven events were associated with an atmospheric river, with all but one associated with an atmospheric river family. Five of the seven corresponding AR events had a peak integrated vapor transport exceeding 750 kg m⁻¹ s⁻¹, classifying them as at least a strong atmospheric river event (Ralph et al., 2019).

November 2, 1985 Event

The Marblemount debris flow in Skagit County, WA killed four people on November 2, 1985 (WA DNR Landslide list). This event was part of an over 2-week long atmospheric river family that had several Category 1-2 ARs (Fig. 7). There are no records of rainfall for the exact location of the debris flow, but nearby locations such as Upper Baker Dam reported over two inches on both November 1st and 2nd. PRISM estimates that some areas of Skagit County received over 15” in the two weeks leading up to the event (not shown) and over 8” of rain in the three days leading up to the event (Fig. 8).

February 5-9, 1996 Event

The February 5-9, 1996 widespread landslide event was part of a family of four successive ARs (classified as weak to moderate at 124.375°W, 47.000°N) (Fig. 9). Landslides occurred statewide with areas of primary loess in the Blue Mountains
(southeast WA) having areas with over 100 individual failures per square mile (Harp et al., 1996). Many areas experienced rain on snow events that led to rapid melting of snow and subsequent floods and landslides (estimated at $300 million in damage); the rain on snow events were due to a rapid increase in temperature typical of ARs as shown in the dramatic increase in 850 hPa (generally ~1.5 km above sea level) temperature from February 2nd to 8th throughout the state (Fig. 10). More information on this event can be found in the U.S. Geological Survey Administrative Report.

**Early January 1997 Event**

Storms in early to mid-January following a December with 191% of normal precipitation in Seattle caused hundreds of landslides, mainly in glacial sediments, especially in the Puget Lowland region of western Washington (Baum et al., 1998; Fig. 11). The almost double normal precipitation in Seattle makes sense because most of the days in December were part of an AR family including two Category 4 ARs at the end of December (Fig. 12). There were millions of dollars of damage from these landslides (deep-seated landslides are likely included in this calculation), landslides cut off phone service to homes on Salmon Beach, and “two interstate natural gas lines were ruptured due to landslides, causing explosions, fires, and evacuations” (Baum et al., 1998). Primed by the antecedent moisture of a wet December, two ARs (Categories 2 and 3) in mid-January preceded the January 19, 1997 event when a planar, shallow landslide that became a debris flow killed a family of four at Rolling Bay Walk on Bainbridge Island (Fig. 13).
**September 17, 1997 Event**

A debris flow-avalanche killed one person in Port Angeles tavern (beneath a steep slope) in Clallam County; the WA DNR says there was only 0.5” of rain before the event. This was preceded by two Category 1 atmospheric river events (Fig. 14).

**January-February 3, 2006 Event**

December 2005 contained a 25-day long AR family in which precipitation totals exceeded 55” in parts of the Olympic Peninsula and exceeded 10” in much of the Puget Lowland (Figs. 15, 16). Table 3 summarizes the atmospheric rivers (including three Category 4 ARs) that occurred from December 19, 2005, through February 3, 2006, when the Governor signed an emergency proclamation to request federal funding for damage. The Washington Department of Transportation reported closed lanes from landslides and slumps on I-5, US 101, SR’s 4, 9, 14, 107, 105, 112, 116, 166, 302, and 530 for various periods. Thus, this incredibly long AR family produced extreme precipitation that caused widespread shallow landslides that affected the entire state.

**January 7-8, 2009 Event**

The January 7-8, 2009 event involved ~1,500 shallow landslides and occurred during a 60-hour long AR with maximum IVT of 893.63 kg m⁻¹ s⁻¹ (Fig. 17, 18). This AR was the fourth in an AR family (using the 120 hour aggregation period); thus, there was ample antecedent moisture provided between this and the snowy December 2008 (Fig. 19). This made many locations in Western Washington exceed 20” of rain from December 28, 2008, through January 8, 2009 (Fig. 20). The Department of Natural Resources report indicates that the source of this rainfall was from “a stream of moisture originating from around Kauai,” likely referring to the atmospheric river (Sarikhan and
Contreras, 2009). The maps of IVT show this to be close to correct with the peak IVT values over the western Pacific (> 1,000 kg m$^{-1}$ s$^{-1}$) originating northwest of Kauai (Fig. 21). This atmospheric river brought warm air to the region causing the temperature to go from below freezing at 850 hPa on January 3, 2009, to well above freezing on January 7, 2009 (Fig. 22). This caused many areas to have rain on snow events that rapidly melted the snowpack leading to flooding. The flooding was especially extreme in the Puyallup River watershed leading to “the largest evacuation in the state’s history...forcing more than 30,000 people...to flee. The town of Orting, with a population of more than 26,000, was almost completely flooded” (Sarikhan and Contreras, 2009). One of the many landslides associated with this event hit a fish farm and killed over 200,000 Arctic Char and Steelhead. This AR was a Category 4 AR that hit following three Category 1-2.

**CASE STUDY: DECEMBER 1-3, 2007**

The ~1,940 observed landslides (Fig. 23) caused by the December 1-3, 2007 storm was part of an atmospheric river event that recorded the maximum integrated vapor transport value--1,545 kg m$^{-1}$s$^{-1}$--since 1980 at 124.375°W, 47.000°N (Fig. 24). This storm followed a slightly drier than normal November and a wet October causing soil moisture to be between the 30th and 70th percentile in the areas where most of the landslides occurred (Fig. 25). However, in the northern Cascades and northern Olympic Peninsula, the soil moisture was in the 5th to 30th percentile, and no landslides were reported in those areas.

Figure 26 shows the meteorological context and antecedent conditions for this event at two different locations: Tacoma No. 1 and Burnt Mountain (locations shown in
These were chosen to compare a low elevation location to a higher elevation location. Figure 26B shows slightly below average precipitation at Tacoma No. 1 just before the December 3, 2007 event. Following the event, the cumulative precipitation is back to normal. Figure 26C shows that a small snowpack essentially vanishes in response to the warm temperatures (Figure 26D) brought by the AR. Following the AR, the temperatures at Burnt Mountain and Tacoma No. 1 are almost the same and above freezing despite their elevation difference. This warming of the lower atmosphere is common during ARs since they transport moisture from warmer latitudes to colder latitudes; this is part of why they can cause such destructive flooding and landslide events to areas that have a prior snowpack.

In the Northern Cascades, the lack of reported landslides is likely due to having less rainfall than the southwestern part of the state, and more of the precipitation falling as snow. The northwest Cascades received less precipitation than the southwest part of the state and the north-central Cascades are the only part of the snowpack that was not experiencing melting on December 4, 2007 (Fig. 27). In addition, the geology in the northern Cascades is different and generally older than the southern Cascades: a complex mixture of Precambrian to Mesozoic primarily sedimentary rocks comprises the northwest Cascades and metamorphic rocks comprise the northeast Cascades. It is surprising that the northern Olympic Peninsula did not have many landslides despite having similarly high precipitation totals to further south. This may be due to the sedimentary component of the Tertiary Crescent Formation being more prevalent in the northern part of the Olympic Peninsula since where this unit was present in the Chehalis headwaters there were not many landslides. The low-permeability basalt from the igneous
portion of the Tertiary Crescent Formation had the most landslides---707 landslides. This is likely due to the thin (< 25 ft depth) soil overlying a relatively impermeable surface on steep slopes. The lower number of recorded landslides may also be due to the lack of aerial reconnaissance in northern Washington State.

The WA DNR report notes that locations of landslides were likely also affected by the maturity of the timber in the region with the recently clearcut regions having the most landslides (547) closely followed by sub-mature (5-15 years old) forests (403). No landslides were observed in mature forests, but it is also difficult to observe such events.

This case study shows that geologic conditions, soil depth, bedrock permeability, the age of timber, steepness of topography, precipitation type, and precipitation rate are all important factors for landslide occurrence. A notable attribute of this event is that it was not preceded by multiple atmospheric river events and did not occur with wet antecedent conditions. This shows that it is possible to have a single strong storm cause widespread landslides. Since this is the only event out of seven significant landslide events to not be part of an AR family, it suggests that it is rare for a single event to cause a significant landslide event. It seems more common for a scenario like the January 7-8, 2009 event in which significant landslides are not triggered during weak ARs, but that these weak ARs provide the antecedent moisture that makes a strong AR impactful.

**DISCUSSION**

The amount of atmospheric river events (9+ hours long) along the Washington State coastline (44-48 ARs per year) is greater than that of Bodega Bay in Northern California (123.125°W, 38.000°N: 29 nine or more hour long ARs per year). Fish et al.
(2019) used a more restrictive AR definition and observational data to find that about 19 ARs impact Bodega Bay each year. And, from November 2004 through April 2017, Bodega Bay reported 228 AR events, with 109 of these events occurring within the 120 hour aggregation period (Fish et al., 2019 in revision). Thus, 48% of ARs were part of AR families compared to 84% along the coast of Washington State (for the 120 hour aggregation period). This difference may be mainly due to the fact that Washington State simply has more ARs each year (Rutz et al., 2014; Gershunov et al., 2017).

In order to analyze the general atmospheric context for the DNR significant shallow landslide events, I looked at composite averages of the atmospheric conditions during the week that included each event. The four days leading up to the main event day, the event day, and two days following the event were averaged (Fig. 28-34). The goal of this is to see if there is a dominant weather pattern to be aware of for anticipating these events.

There were several trends visible in the composites: location of low-pressure regions, strong 250 hPa wind speeds, and orientation of 850 hPa heights. In most of the 500 and 850 hPa heights, a low-pressure region is discernable in the Gulf of Alaska. This is a common location for the low-pressure center of mid-latitude cyclones that can impact the Pacific Northwest. One exception is January 10-17, 1997 where the primary low-pressure region was west of Alaska. Another exception is September 12-19, 1997 where there were two low-pressure regions just north of 35°N in the western and eastern Pacific likely showing locations of mid-latitude cyclones. All of the events had strong 250 hPa

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2 Integrated water vapor (IWV) equal to or exceeding 2 cm, upslope IWV flux perpendicular to the local mountains equal to or exceeding 15 cm (m s\(^{-1}\)) and both variables continuously meeting or exceeding these conditions for a minimum of 8 hours (Ralph et al., 2013). This method has been shown to be consistent with reanalysis data estimates despite being an underestimate.
wind speeds with the weakest wind speeds in the October 28-November 4, 1985 and September 12-19, 1997 events; these both had the high wind speeds at higher latitudes (~50°N) than the other events. This difference may be partially due to these events being in the Fall. Both of these events also were the only events to not include a SW-NE orientation of the 500 and 850 hPa heights as they approached Washington State. Such an orientation is common for ARs since it allows water vapor to be transported from the moist low-latitude regions to the dryer mid-latitude regions. This SW-NE orientation also generally brings the characteristically warm air of an AR into Washington State. Since the main 250 hPa wind speeds for October 28-November 4, 1985 and September 12-19, 1997 are greatest at high latitudes these systems are less able to entrain the moist air with high integrated water vapor at lower latitudes. Therefore, it is not surprising that these events had the lowest IVT of the seven events. Therefore, the strongest AR events had a low-pressure center near Alaska, a strong, continuous jet streak (visible in the 250 hPa wind speeds), and a SW-NE orientation of the 500 and 850 hPa heights.

Young et al. (2017) found that 80.8% of high impact hydrologic events (HIHE: floods, flash floods, and debris flows) in Northern California from the National Center for Environmental Information Storm Events Database were caused by atmospheric rivers and that these ARs correspond with the top 5% of 48-hour quantitative precipitation estimates. In contrast, only 41.8% of HIHE events were associated with ARs in Southern California as many of the HIHE events in Southern California were associated with the warm season monsoon. Since ARs generate so much precipitation and often have a long duration, they are perfect for saturating the soil either to the point of landslides or to precondition the soil for a later AR. Though this study used a smaller
dataset than Young et al. (2017), ARs appear to be the primary mechanism for causing impactful rainfall-driven shallow landslides in Washington State since all seven significant shallow landslide events were associated with at least one AR and 86% of the media landslide reports were within one day of an AR. It is even likely that Washington has a greater percentage of high impact hydrologic events caused by ARs than Northern California, but a more extensive study using similar methods to Young et al. (2017) for Washington State would need to be done to prove this. If true, this would be consistent with Neiman et al. (2011) that showed how 46 out of 48 annual peak daily flow for water years 1998 through 2009 in several Western Washington watersheds were associated with landfalling ARs. Two of the top ten annual peak daily flows from Neiman et al. (2011) were from the same event that caused widespread landslides: December 3, 2007, and January 7, 2009. Like landslides, peak streamflow is dependent on local precipitation, and therefore the orientation of the atmospheric river with respect to the slope orientation and steepness are integral to determining runoff and landslide susceptibility.

CONCLUSIONS

The purpose of this paper is to link the atmospheric patterns—specifically atmospheric rivers—to the occurrence of rainfall-driven shallow landslides in Washington State. Since ARs are part of the atmospheric context for all of the Washington DNR’s significant rainfall-driven shallow landslides and ARs occurred within one day of 86% of the media landslide reports, it is evident that ARs are a significant part of the atmospheric regime associated with such events. The concept of
atmospheric river families provides a term for the weather pattern that generally provides the precipitation necessary to either precondition a region for landslides or cause a landslide event. Since prediction skill is continually improving, the atmospheric river family concept is something that can be applied to predicting conditions in which landslides are probable to occur.

The Center for Western Weather and Water Extremes (CW3E) has an AR probability tool that predicts up to two weeks in advance (Cordeira, J., 2019; Fig. 35). This captures the general pattern quite well up to about a week in advance and has good confidence for the timing, location, and intensity of ARs two to three days in advance. Further in advance than a week, the prediction is often noisy, but even then a signal of whether it will be relatively wet or dry can be discerned. Thus, this AR probability tool can be used to forecast for the next week along with observations of current conditions to provide early warning of when landslide-conducive conditions are going to occur. This can increase situational awareness concerning these storms by improving early warning systems, bolstering infrastructure prior to storms, or giving early warning to emergency responders. It would be helpful to look at the output of past events from the AR Probability tool to see how far out past predictions detected ARs that corresponded with past landslide events.

In the future, differences in the patterns between the frequency and timing of AR families along the West Coast should be further analyzed in order to understand why some areas are more prone to experiencing AR families. Understanding the variability of these patterns along the West Coast will also help in projecting how such patterns will alter with climate change. Places that experience a greater percentage of their ARs as part
of AR families are likely at a greater risk for flooding and rainfall-driven shallow landslide events.

Another compelling question is investigating when ARs and AR families did not correspond with landslide events. Unfortunately, the landslide datasets often miss landslides when they are not observed or are not damaging enough to be reported so it can be challenging to know whether landslides did not occur or whether they were simply not reported. However, the new media based DNR landslide catalog has a more continuous time series of landslide events that may make such an analysis possible. Using the media catalog, it would be helpful to perform statistical analysis (such as logistic regression) to see what the main drivers of the landslide events were. Identifying which drivers to include is a confounding question in itself since there are so many variables to consider: precipitation total, precipitation type, rainfall rate, geology, slope steepness, AR, AR family, the orientation of the storm, antecedent moisture, etc. Rainfall rate is a variable to explore further because it relates well to landslide thresholds; it is likely that the ARs that produce the most landslides had high rainfall rates.

This study shows that in Washington State strong individual ARs and strong AR families, especially when accompanied by wet antecedent conditions, often bring warm temperatures and precipitation that lead to rainfall-driven shallow landslides. These are the key points from this paper:

1. The seven rainfall-driven shallow landslide events deemed “significant” by the WA DNR occurred during either an exceptionally strong atmospheric river or an atmospheric river family.
2. 70% of the landslides reported by the media from December 2016 through April
2017 occurred within 1 day of an AR family.

3. CW3E’s AR landfall tool can be used to increase situational awareness up to about a week in advance of atmospheric river families that may lead to landslides. This could potentially help landslide early warning systems.

ACKNOWLEDGMENTS

Thank you to Dr. Marty Ralph for his generous support at the Center for Western Weather and Water Extremes (CW3E) at University of California San Diego this summer. Thank you to Dr. Julie Kalansky and Lillian Perry for making working at CW3E and traveling to the American Geophysical Union conference possible. Thank you to Meredith Fish and Dr. Anna Wilson for their constant mentorship, answering tons of science questions, and helping with my AGU presentation. Thank you especially to Meredith Fish for making the MERRA-2 figures. Thank you to Dr. Nina Oakley and Stephen Slaughter for generously collaborating with landslide data and for their advice on my AGU presentation. Thank you to Maryam Asgari-lamjiri for working with me on the atmospheric river catalog. Thank you to Dr. Sarah Titus and Dr. Andy Poppick for their academic guidance. Thank you to the Carleton College Geology Department for supporting us and teaching us the skills necessary for our comprehensive project.
### TABLE 1

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Longitude</th>
<th>Number of ARs per Year (ARs &gt;= 9 hours duration)</th>
<th>Percentage of ARs Part of Families (Using 120 hour aggregation period)</th>
</tr>
</thead>
<tbody>
<tr>
<td>46.000°N</td>
<td>124.375°W</td>
<td>48</td>
<td>84%</td>
</tr>
<tr>
<td>46.500°N</td>
<td>124.375°W</td>
<td>48</td>
<td>84%</td>
</tr>
<tr>
<td>47.000°N</td>
<td>124.375°W</td>
<td>48</td>
<td>84%</td>
</tr>
<tr>
<td>47.500°N</td>
<td>124.375°W</td>
<td>45</td>
<td>81%</td>
</tr>
<tr>
<td>48.000°N</td>
<td>124.375°W</td>
<td>44</td>
<td>80%</td>
</tr>
</tbody>
</table>

Table 1. Number of ARs per year and percentage of ARs that are part of families (using 120 hour aggregation period) at different latitudes along the Washington coast (1980-2017). ARs must be nine or more hours in duration.
<table>
<thead>
<tr>
<th>Time of Landslide(s)</th>
<th>Location</th>
<th>AR Family</th>
<th>IVT &gt; (750 \text{ kg m}^{-1} \text{ s}^{-1}) (Strong AR)</th>
<th>Selected Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>November 2, 1985</td>
<td>Skagit County (NW WA)</td>
<td>yes</td>
<td>no</td>
<td>Four deaths from one reported debris flow.</td>
</tr>
<tr>
<td>February 5-9, 1996</td>
<td>entire state</td>
<td>yes</td>
<td>yes</td>
<td>Destroyed thousands of homes. Cost: $800 million</td>
</tr>
<tr>
<td>Early January 1997</td>
<td>Puget Lowland</td>
<td>yes</td>
<td>yes</td>
<td>Hundreds of landslides, 4 deaths</td>
</tr>
<tr>
<td>September 17, 1997</td>
<td>Clallam County (North Olympic Peninsula)</td>
<td>yes</td>
<td>no</td>
<td>One death from one debris flow in Port Angeles.</td>
</tr>
<tr>
<td>January-Feb 3, 2006</td>
<td>entire state</td>
<td>yes</td>
<td>yes</td>
<td>Governor signs Emergency Proclamation</td>
</tr>
<tr>
<td>December 3, 2007</td>
<td>Western Washington</td>
<td>no, single AR</td>
<td>yes (1,545 \text{ kg m}^{-1} \text{ s}^{-1}) (max IVT in the record)</td>
<td>~1,940 landslides, one death</td>
</tr>
<tr>
<td>January 7-8, 2009</td>
<td>Western Washington</td>
<td>yes</td>
<td>yes</td>
<td>~1,500 landslides</td>
</tr>
</tbody>
</table>

Table 2. Atmospheric river atmospheric river family context and selected consequences for the Washington Department of Natural Resources significant shallow landslide events from 1984-2014.
<table>
<thead>
<tr>
<th>Start Date of AR</th>
<th>Duration (hours)</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/19/2005</td>
<td>75</td>
<td>4</td>
</tr>
<tr>
<td>12/23/2005</td>
<td>48</td>
<td>4</td>
</tr>
<tr>
<td>12/27/2005</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>1/4/2006</td>
<td>48</td>
<td>4</td>
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<tr>
<td>1/12/2006</td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>1/16/2006</td>
<td>18</td>
<td>1</td>
</tr>
<tr>
<td>1/29/2006</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>1/31/2006</td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td>2/3/2006</td>
<td>18</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 3. Start date, duration, and Category (colored according to the scale from Ralph et al., 2019) of ARs at 124.375°W, 47.500°N from December 19, 2005, through February 3, 2006, when the State of Emergency was declared. Note that there are other times where AR conditions were present at this location during this time period, but those were weaker than Category 1.
Figure 1. A) Plan view schematic summary of a Northern Hemisphere atmospheric river adapted from Ralph et al. (2018). This schematic is based on reanalysis data and dropsonde measurements from research aircraft flying over ARs. The low-pressure center (L) of the mid-latitude cyclone is shown next to the surface occluded front (black semicircle and triangle). The center of the AR is just right of the surface cold front (black triangles) and just below the surface warm front (black semicircles) in the warm, moist sector of the mid-latitude cyclone. IVT is shown with color fill, with the most water vapor transport indicated in red. The white arrow shows that the direction of water vapor transport is towards the upper right corner (~NE in the Northern Hemisphere). Integrated water vapor (cm) is shown in black contours. The values shown are averages for a midlatitude atmospheric river. The average width of 850 km is based on IVT, and the depth of 3 km is the altitude below which 75% of water vapor is transported. The total water vapor transport is the amount of transport along the AR below 300 hPa bounded by where IVT $\geq 250 \text{ kg m}^{-1}\text{s}^{-1}$. B) Representation from NASA and JPL-Caltech of what happens when an AR makes landfall.
Figure 2. Integrated Water Vapor (color) and 850 hPa heights (contour) over the Pacific Ocean on February 3, 2017, showing three consecutive atmospheric rivers (labeled “AR”). Figure modified from Fish et al. (2019) in revision.
Figure 3. Scale from Ralph et al. (2019) that categorizes AR events based on maximum instantaneous IVT during an AR and the duration of that AR.
Figure 4. Physiographic provinces (subprovinces marked with dashed lines) of Washington State from the Washington Department of Natural Resources. Additional text in red are places referred to in the text.
Figure 5. Washington State 1981-2010 annual average precipitation from the Parameter-elevation Regressions on Independent Slopes Model (PRISM). Figure modified from the Western Regional Climate Center, September 2018.
Figure 6. A) Approximate locations of media reported landslides in Washington State from December 2016 through April 2017. Note that individual dots may represent more than one landslide event. The blue dot indicates the approximate location of IVT in Panel B. B) Atmospheric rivers (cyan) and AR families using the 120-hour aggregation period (grey) at 124.375°W, 47.000°N from December 1, 2016 through April 30, 2017. Dates on the x-axis show the month and day. The blue line is IVT for 124.375°W, 47.000°N (the location of the blue dot indicated in Panel A). Note that the IVT and ARs have spatial variation across the state and the IVT and ARs are only shown for one point on the coast.
Figure 7. Atmospheric rivers (cyan) and AR families using the 120-hour aggregation period (grey) at 124.375°W, 48.500°N for early August 1985 through early November 1985. Dates on the x-axis show the month and day. The blue line is IVT for 124.375°W, 48.500°N (near coastal AR landfall location) and the magenta line is IVT for 121.875°W, 48.500°N (near where the majority of landslides occurred). The final AR in the AR family associated with the Marblemount debris flow is circled in red.
Figure 8. Total precipitation (inches) from PRISM for October 31, 1985, through November 2, 1985. The black rectangle shows the region in which the Marblemount debris flow occurred.
Figure 9. Atmospheric rivers (cyan) and AR families using the 120-hour aggregation period (grey) at 124.375°W, 47.000°N for late November 1995 through late February 1996. Dates on the x-axis show the month and day. The blue line is IVT for 124.375°W, 47.000°N (near coastal AR landfall location) and the magenta line is IVT over 120.000°W, 47.000°N (approximately where the majority of landslides occurred). The AR family associated with the statewide precipitation and landslides is circled in red.
Figure 10. Averaged 850 hPa temperature in Kelvin for February 2, 1996 (top) and February 8, 1996 (bottom).
Figure 11. Landslide locations in the Puget Lowland in late December 1996 and January 1997.
Figure 12. Atmospheric rivers (cyan) and AR families using the 120-hour aggregation period (grey) at 124.375°W, 47.000°N late October 1996 through late January 1997. Dates on the x-axis show the month and day. The blue line is IVT for 124.375°W, 48.000°N (near coastal AR landfall location) and the magenta line is IVT over 122.500°W, 48.000°N (approximately where the majority of landslides occurred). The family of four passed away following an AR family on January 19, 1997.
Figure 13. “Oblique aerial view of the landslide at Rolling Bay Walk on Bainbridge Island (photograph by T. Tamura, The Seattle Times)...This thin slide is three lots north of a slide that pushed an adjacent house off its foundation during the spring of 1996” (Baum et al., 1998).
Figure 14. Atmospheric rivers (cyan) and AR families using the 120-hour aggregation period (grey) at 124.375°W, 48.000°N from late June 1997 through late September 1997. Dates on the x-axis show the month and day. The blue line is IVT for 124.375°W, 48.000°N (near coastal AR landfall location) and the magenta line is IVT over 123.125°W, 48.000°N (approximately where the majority of landslides occurred). The red oval circles the two Category 1 ARs that occurred right before the fatal landslide on September 17, 1997.
Figure 15. Atmospheric rivers (cyan) and AR families using the 120-hour aggregation period (grey) at 124.375°W, 47.500°N from early November 2005 through early February 2006. Dates on the x-axis show the month and day. The blue line is IVT for 124.375°W, 47.500°N (near coastal AR landfall location) and the magenta line is IVT over 122.500°W, 47.500°N (near where the majority of landslides occurred). The State of Emergency was declared on February 3, 2006 (2 ARs surrounding this are circled).
Figure 16. Total precipitation (inches) from PRISM in the 25-day long AR family from December 19, 2005, through January 17, 2006. Note that parts of the Olympic Peninsula exceeded 55 inches of precipitation.
Figure 17. Approximate locations of landslides (red stars) from the January 7-8, 2009 storm (WA Department of Natural Resources).
Figure 18. Average integrated water vapor transport (IVT) in kg m\(^{-1}\) s\(^{-1}\) from MERRA-2 for January 7, 2009, when the peak IVT of 893.63 kg m\(^{-1}\) s\(^{-1}\) occurred at 47.000°N, 124.375°W.
Figure 19. Atmospheric rivers (cyan) and AR families using the 120-hour aggregation period (grey) at 124.375°W, 47.00°N from early October 2008 through early January 2009. Dates on the x-axis show the month and day. The blue line is IVT for 124.375°W, 47.00°N (near coastal AR landfall location) and the magenta line is IVT over 122.500°W, 47.500°N (approximately where the majority of landslides occurred).
**Figure 20.** Total precipitation (inches) from PRISM for December 28, 2008, through January 8, 2009.
Figure 21. Average integrated water vapor transport (IVT) in kg m\(^{-1}\) s\(^{-1}\) from MERRA-2 for January 3, 2009, preceding the January 7-8, 2009 event. Kauai is circled in light blue.
Figure 22. 850 hPa temperature in Kelvin for January 3, 2009 (top) and January 7, 2009 (bottom).
Figure 23. Modified from Figure 1 of the Washington Department of Natural Resources report. NASA Multi-satellite Precipitation Analysis of western Washington from November 28 through December 4, 2007, overlain with landslide initiation points.
Figure 24. Atmospheric rivers (cyan) and AR families using the 120-hour aggregation period (grey) at 124.375°W, 47.000°N from early September 2007 through early December 2007. Dates on the x-axis show the month and day. The blue line is IVT for 124.375°W, 47.000°N (near coastal AR landfall location) and the magenta line is IVT over 122.500°W, 47.500°N (near where the majority of landslides occurred). The peak IVT of the entire IVT record since 1980 that corresponded with widespread landslides is circled.
Figure 25. Total moisture percentile (Soil moisture plus snow water equivalent) for December 1, 2007, from UCLA Drought Monitoring System for the Pacific Northwest. Warm colors indicate dryer than normal whereas shades of green indicate wetter than normal (Wood, 2008).
Figure 26. Summary of meteorological context and antecedent conditions for the December 3, 2007 event with the timing of ARs shown in cyan in all plots. A) Same as Figure 24. B) Cumulative daily precipitation (inches) for Tacoma No. 1 (magenta; 122.41°W, 47.25°N, Elevation: 25 ft) and Burnt Mountain (black; 121.94°W, 47.04°N, Elevation 4170 ft). The average precipitation for Tacoma No. 1 is shown in blue. C) Burnt Mountain Soil Moisture Percent at 8” (magenta) and 20” (black). D) Burnt Mountain Snow Water Equivalent. It decreases dramatically in response to the December 3, 2007 event. E) Burnt Mountain (black) and Tacoma No. 1 (grey) Daily Temperature Average. Freezing (0°C) is shown by the black horizontal line.
Figure 27. Snowmelt on December 4, 2007.
Figure 28. Composite averages for October 28, 1985, through November 4, 1985. A) 250 hPa wind speed (m/s) with 500 hPa heights (black contours). B) Integrated Water Vapor (IWV, mm) with 850 hPa heights (black contours).
Figure 29. Composite averages for February 3-10, 1996. A) 250 hPa wind speed (m/s) with 500 hPa heights (black contours). B) Integrated Water Vapor (IWV, mm) with 850 hPa heights (black contours).
Figure 30. Composite averages for January 10-17, 1997. A) 250 hPa wind speed (m/s) with 500 hPa heights (black contours). B) Integrated Water Vapor (IWV, mm) with 850 hPa heights (black contours).
Figure 31. Composite averages for September 12-19, 1997. A) 250 hPa wind speed (m/s) with 500 hPa heights (black contours). B) Integrated Water Vapor (IWV, mm) with 850 hPa heights (black contours).
**Figure 32.** Composite averages for December 27, 2005, through January 3, 2006. A) 250 hPa wind speed (m/s) with 500 hPa heights (black contours). B) Integrated Water Vapor (IWV, mm) with 850 hPa heights (black contours).
Figure 33. Composite averages for November 28, 2007, through December 5, 2007. A) 250 hPa wind speed (m/s) with 500 hPa heights (black contours). B) Integrated Water Vapor (IWV, mm) with 850 hPa heights (black contours).
Figure 34. Composite averages for January 3-10, 2009. A) 250 hPa wind speed (m/s) with 500 hPa heights (black contours). B) Integrated Water Vapor (IWV, mm) with 850 hPa heights (black contours).
Figure 35. Center for Western Weather and Water Extremes AR Probability tool from December 11, 2018, when four ARs (with IVT > 250 kg m\(^{-1}\)s\(^{-1}\)) were predicted to hit Washington State in the next 10 days. The right panel shows the grid cell along the coastline where each General Forecast System (GFS) Ensemble probability of IVT > 250 kg m\(^{-1}\)s\(^{-1}\) making landfall is evaluated. The right panel’s x-axis shows the forecast day from Day 0 (December 11, 2018) on the far right to 16 days ahead on the far left. The y-axis is the latitude of landfall for an AR on the U.S. West Coast. The colors in the left panel indicate the percentage of ensemble members that agree on IVT > 250 kg m\(^{-1}\)s\(^{-1}\) for each grid cell. Therefore, warm colors indicate AR conditions being likely at a specific latitude on the U.S. West Coast whereas cool colors indicate that AR conditions are unlikely.
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PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created Sept 2018 by Western Regional Climate Center.


