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Title: Meteorological Conditions Associated with Rain-Related Periglacial Debris Flows on Mount Hood, Oregon and Mount Rainier, Washington

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Anne W. Nolin

In November of 2006 an intense rainstorm of tropical origin, known colloquially as the "Pineapple Express," inundated the Pacific Northwest region of the United States, initiating numerous periglacial debris flows on several of the stratovolcanoes in the Cascade Range of Oregon and Washington. These debris flows rapidly aggrade channels, deposit thick sediments in their path, and severely damage infrastructure. Consequently, this work seeks to understand the potential meteorological triggering mechanisms of these flow events.

Here we focus on Mount Hood, Oregon and Mount Rainier, Washington in the investigation of the meteorological conditions associated with rain-related periglacial debris flow events and the variability of these conditions over time. The objectives of this research are to assess the correlation between "Pineapple Express" and "Atmospheric River" events and rain-related debris flows, and to explore the meteorological conditions associated with debris flow events based on 5 parameters: storm track based on geostrophic flow patterns, temperature, precipitation and orographic enhancement, integrated atmospheric moisture transport, and antecedent snow water equivalent (SWE).

Dates for the debris flow events for each mountain were linked with corresponding Pineapple Express circulation and Atmospheric River events. Analysis from this work suggests that there is not a strong correlation between the occurrence of debris flows and the occurrence of Pineapple Express or Atmospheric River events as they are presently defined in the literature.

NCEP/NCAR reanalysis data were used to determine geostrophic flow from 500h-Pa heights. Radiosonde data from Salem, Oregon and Quillayute, Washington were used to examine freezing altitudes. Precipitation data from Government Camp and Paradise meteorological stations were used to determine total rainfall amounts for rain events, and these data were compared with precipitation data from coupled lower elevation sites (Three Lynx and Longmire, respectively) to determine orographic enhancement values for each event. Reanalysis data were again used to determine the strength and direction of atmospheric moisture transport. Snowpack Telemetry (SNOTEL) data were used to examine the antecedent snowpack conditions for each debris flow event.

Debris flows on both Mount Hood and Mount Rainier were found to be associated with both meridional and zonal flow regimes, variable precipitation, and unimpressive orographic enhancement values. However, the debris flow events virtually all experienced significantly high freezing altitudes and little or negligible antecedent SWE. Further, nearly all debris flow events were coupled with plumes of atmospheric moisture transport with high values relative to the surrounding region, implying Atmospheric River-like conditions. This finding evokes a potential need to re-examine the metrics used to classify or characterize Atmospheric Rivers, particularly through the lens of their relationship to natural hazards.

This research suggests that given the complexity of debris flow mechanics, the dynamic nature of the atmospheric system, and the small sample of data presented here, definitive conclusions cannot yet be made concerning the correlation between specific meteorological parameters and the occurrence of periglacial debris flows in the Cascades.

Meteorological Conditions Associated with Rain-Related Periglacial Debris Flows on Mount Hood, Oregon and Mount Rainier, Washington

by
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APPROVED:

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Chair of the Department of Geosciences

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Lauren E. Parker, Author

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Chapter 1: Introduction

The incidence of rain-related debris flows in the Pacific Northwest appears to have been increasing over the past three decades but the cause for this increase has not been determined. It is clear that glacier retreat has resulted in exposure of unconsolidated steep moraines that provide source material for the debris flows (O'Connor and Costa, 1993; O'Connor et al., 2001), with glaciers on Mount Hood retreating up to 61% in the last century (Lillquist and Walker, 2006) and an 18.5% decrease in glacier cover on Mount Rainier from 1913 to 1971 (Nylen, 2004). However, for rain-related debris flows, important questions remain regarding the climatology and meteorology of the associated rainfall events.

The possible increase in frequency of debris flow triggering events is cause for concern for personnel at the local, state, and federal levels because some of the largest and most destructive debris flows in the recent record have been the result of intense rainfall events. Rain-related debris flows have cost millions of dollars in damage to roads, hiking trails, buildings, irrigation systems and other infrastructure (Gallino and Pierson, 1984). In November of 2006, multiple drainages on Mount Rainier and Mount Hood experienced debris flows triggered by an intense rainfall event, known colloquially as a Pineapple Express storm. The debris flows resulting from this storm washed out part of Highway 35 on the eastern side of Mount Hood (Figure 1.1), and significantly damaged infrastructure at Mount Rainier National Park, resulting in the Park declaring the event to be the worst natural disaster in a century.

Figure 1.1 Assessing damage two days after the debris flow, near the intersection of the Clark River Drainage and Oregon Highway 35 (Photo by Bill Burns, Oregon Department of Geology and Mineral Industries, http://landslides.usgs.gov).

For rain-related debris flows, important questions remain regarding the meteorological conditions associated with the flows, as well as potential climatological trends which may address the apparent increase in debris flow events over the past several decades. This study investigates these meteorological conditions and possible climatological trends at Mount Hood, Oregon and Mount Rainier, Washington.

The first objective is to determine the strength of correlation between the full catalogue of debris flow events on these mountains with established dates of particular rain events and associated atmospheric circulation patterns, which have been hypothesized to be largely responsible for debris flows in the Pacific Northwest. The second objective is to assess the meteorological conditions associated with the individual flow events by exploratively examining the following parameters for across-the-board trends or similarities: geostrophic flow based on geopotential heights, temperature, precipitation and orographic enhancement, integrated moisture transport, and antecedent snowpack.

1.1 Debris Flow Processes

There are several definitions for debris flows in the literature and there have been a number of attempts to establish precise definitions and reduce ambiguity in the application of terminology (e.g. Hungr et al., 2001). Generally, debris flows are a mixture of water-saturated rock debris that flow down-valley under the influence of gravity (Miller, 1989). Work by Scott et al. (1995) and Vallance et al. (2003) define debris flows specific to Mount Rainier. Mount Rainier debris flows can be subdivided into cohesive and non-cohesive flows, dependent on percentage of clay particles present in the flow, with cohesive flows containing greater than 3-5% clay and non-cohesive flows containing less than 3-5% clay (Scott et al., 1995). Soil samples from initiation locations on Mount Rainier suggest that periglacial debris flows – those that are initiated at or near the glacier terminus, at roughly 1850 m – are all of a non-cohesive nature (E. Copeland, personal communication). Mount Rainier debris flows are defined as being "water-saturated mixtures of mud, rock, and water having a large sediment concentration that move down slope under the influence of gravity" and are the result of hydrologically released debris (Vallance et al., 2003). The hydrological origin of Mount Rainier debris flows distinguishes these events from lahars of eruptive origin and the failure of saturated hydrothermally altered rock as the result of seismic activity (Vallance et al., 2003).

1.11 Glacial Outburst Flood Related Debris Flows

Mount Rainier's natural hazards history since its last glacial maximum includes many instances of debris flows, which are considered one of the mountain's most significant hazards (Crandell, 1971; and Scott et al., 1992). There are two distinct populations of debris flows on both Mount Hood and Mount Rainier – those associated with dry weather and those associated with wet weather. Dry weather debris flows are typically coupled with anomalously warm temperatures and occur in the summer or early fall and, on the more heavily glaciated Mount Rainier, are surmised to be the result of a glacial outburst flood (Walder and Driedger, 1994) wherein a rapid release of water of subglacial or englacial origin (Driedger and Fountain, 1989) induces debris movement.

1.12 Rain-related Debris Flows

There have been many studies in the Alps on the mechanics of debris flows, where the events are common and often cause extensive damage to villages built in the paths of these flows (Jakob and Hungr, 2005). Several case studies have shown that copious rainfall is a primary triggering mechanism for Alpine debris flows, and have quantified the amount of rainfall necessary to initiate debris flows (e.g. Rebetz et al., 1997; and Bacchini and Zannoni, 2003).

Although Walder and Driedger (1994) conclude that, with a single exception, all wet weather debris flows in Mount Rainier's Tahoma Creek drainage were triggered by outburst floods, the authors note that the linkage between outburst floods and debris flows on wet weather days is "less direct." Further, extreme meteorological events can serve as a catalyst for debris flow initiation, including as a triggering mechanism for the outburst floods that induce debris flows such as during the 1947 flow at Kautz Creek on Mount Rainier (Vallance et al., 2003).

Fewer studies on the nature of rain-related debris flows at Mount Hood exist, so the mechanisms which produce wet weather flows there are less known. However, these events are known to be impressive and damaging mass wasting processes. Gallino and Pierson (1984) describe a 1980 rainfall-related debris flow/outburst flood on Polallie Creek at Mount Hood:

> "… intense rainfall and extremely wet antecedent conditions combined to trigger a landslide of approximately 5,000 cubic yards at the head of Polallie Creek Canyon on the northeast flank of Mount Hood. The landslide was transformed rapidly into a debris flow, which surged down the channel at velocities between about 40 and 50 ft/s, eroding and incorporating large volumes of channel fill and uprooted vegetation. When it reached the debris fan at the confluence with the East Fork Hood River, the debris flow deposited approximately 100,000 cubic yards of saturated, poorly sorted debris to a maximum thickness of 35 ft, forming a 750-ft-long temporary dam across the channel. Within approximately 12 minutes, a lake of 85 acre-feet formed behind the blockage, breached the dam, and sent a flood wave down the East Fork Hood River. The combined debris flow and flood resulted in one fatality and over $13 million in damage to a highway, bridges, parks, and a water-supply pipeline."

Although dry weather glacial outburst floods may be one source of water, only those debris flows that are associated with wet weather will be examined in this study. Given the lack of such a detailed study of debris flow triggers at Mount Hood as the Walder and Driedger study at Mount Rainier, and the uncertainty of potential interactions between particular meteorological parameters and the priming of conditions for wet weather debris flow triggers, rain-related debris flows will be examined at both Mount Hood and Mount Rainier.

1.2 Pineapple Express Storms

Characterized by warm temperatures, high winds, and heavy rainfall, the Pineapple Express (PE) is a colloquial term for such strong storms that impact the West Coast of the United States (Figure 1.21). They are so called because of their transport path from the Hawaiian tropics, from which they draw their characteristic warm, wet air (Colle and Mass, 2000; and Higgins et al., 2000). Pineapple Express circulations that impact the Pacific Northwest often cause flooding, particularly when the system is orographically enhanced by the Coast and Cascade Ranges in Oregon and Washington (Colle and Mass, 2000). The warm temperatures and latent heating due to the high winds moving upslope can result in rapid snowmelt, further increasing the magnitude of flooding and subsequent mass movement events (Lackmann and Gyakum, 1999). Lackmann and Gyakum (1999), using a composite of 46 sample events to document winter Pineapple Express events in the Pacific Northwest, found characteristic patterns in 500-hPa geopotential height anomalies and moisture transport regimes that indicate that storm tracks are driven by synoptic scale flow while moisture transport within the large scale flow is modified at the cyclonic scale. Further, Dettinger (2004) identified more than 200 PE circulations over a 50-year period between 1948 and 1999, creating a catalogue of these days. This catalogue is used in this project as a means of examining the correlation between such storms and the incidence of debris flows.

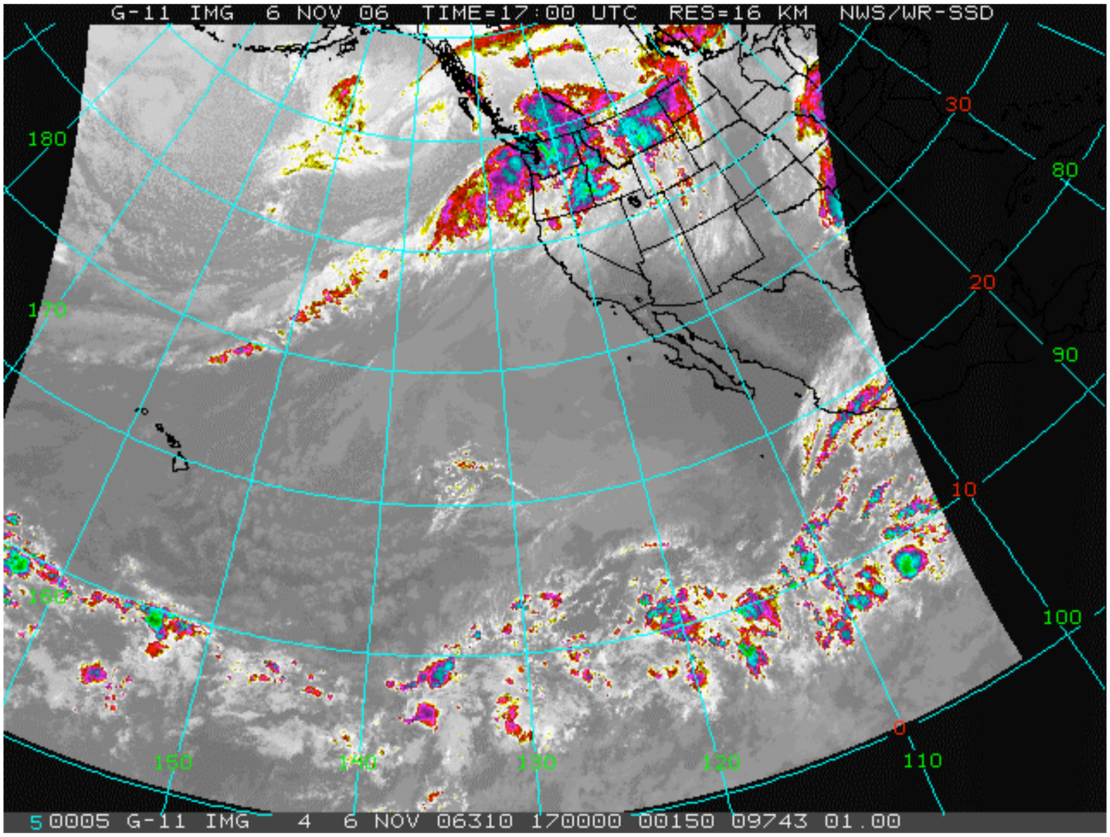

Figure 2.21 NOAA National Weather Service satellite image of the November 6, 2006 Pineapple Express impacting the Pacific Northwest (http://en.wikipedia.org/wiki/File:IR16.png).

1.3 Exploring Meteorological Parameters

1.31 Geopotential Heights and Geostrophic Flow

Geostrophic wind, which flows parallel to geopotential height isobars, although theoretical, can be a reasonable approximation of synoptic scale upper air flow in the mid-latitudes where the Coriolis force and pressure gradient force approach balance (Holton, 1979). Winds will flow roughly parallel to geopotential height isobars at the 500-hPa pressure level because at this level surface friction is typically negligible. In addition to large-scale flow patterns, maps of 500-hPa geopotential heights can show approximations for temperature, snow line, wind direction and speed (Aguado and Burt, 2007). This project explores the 500-hPa geopotential heights associated with the debris flow events as a means of examining steering winds and storm origins, as is standard in meteorological literature (e.g. Neiman et al., 2008b; Lackmann and Gyakum, 1999; Konrad and Colucci, 1989; and Sanders 1986).

1.32 Temperature and Free Air Freezing Levels

The National Weather Service (NWS) launches hydrogen-filled radiosonde balloons twice daily – at 0000 and 1200 Greenwich Mean Time (GMT) – which record pressure, temperature, and wet bulb temperature (Aguado and Burt, 2007). The Integrated Global Radiosonde Archive (IGRA) provides sounding data at all standard observational levels, the surface, and the tropopause for variables including pressure, temperature, geopotential height, dew point, wind speed and wind direction (http://www.ncdc.noaa.gov/oa/climate/igra/index.php).

Tropospheric free air freezing levels, which can be used as proxies for both general storm temperature and snowline, can be estimated from radiosonde data. Seidel and Free (2003) used radiosonde from coupled low and high elevation sites to examine "atmospheric freezing level variability in mountainous regions." Barry (1992) notes that although free air lapse rates are poor predictors of slope surface temperature gradients because mountain air is affected by "radiant and turbulent heat fluxes," it is possible to use radiosonde data as a reference for surface temperatures. This may be particularly true for Mount Hood and Mount Rainier, which are isolated peaks and therefore experience increased mixing with the free air relative to mountain massifs (Barry, 1992). Free air freezing levels will be used in this study to compare the temperature of debris flow related storms relative to other fall season rain events.

1.33 Rainfall and Orographic Enhancement

Precipitation can be important for the generation of rain-related debris flows as both a primary effect in the case of the intensity or amount of debris flow date rainfall, and as a secondary effect in the case of antecedent rainfall (Rotunno and Ferretti, 2001). Walder and Driedger (1994) qualitatively qualify precipitation amounts on wet-weather debris flow dates occurring during their study on Mount Rainier as ranging from “drizzly” to “very rainy” or “with heavy rainfall.” Precipitation amounts for rain-related debris flows have been quantitatively analyzed to create precipitation thresholds for debris flow generation in the Dolomites (Bacchini and Zannoni, 2003).

In addition to the quantification of precipitation amounts, orographic enhancement can play an important role in the generation of precipitation at high altitude as air is forced to its lifting condensation level (Barry, 1992). Orographic enhancement ratios from coupled low and high elevation meteorological stations can be used to assess the intensity of orographic enhancement for individual storms (Dore et al., 2006; Dettinger et al., 2004; and Dettinger, 2005). Orographic enhancement values are determined by atmospheric circulation, air parcel stability and moisture content (Dettinger et al., 2004; and Barry, 1992). Because of their weak static stability and high moisture flux, Atmospheric River events are generally associated with high levels of orographic precipitation (P. Neiman, personal communication). Precipitation amounts were quantified for all debris flow dates at both mountains in this study for the debris flow dates as well as for three days preceding and succeeding the debris flow (e.g. Neiman et al., 2008b). Further, orographic enhancement was examined at both mountains using coupled low and high elevation meteorological station precipitation data.

1.34 Moisture Transport

Higgins et al. (2000) found that during extreme precipitation events in the western U.S., anomalously high atmospheric moisture transport extends westward from the west coast to the tropical or subtropical western Pacific. Such bands of strong moisture flux are known as “Atmospheric Rivers” (ARs), which are responsible for more than 90% of the meridional transport of atmospheric water vapor (Zhu and Newell, 1998). Neiman et al. (2008) used Special Sensor Microwave Imager (SSM/I) between water years 1998 and 2005 to identify and catalogue Atmospheric Rivers that had integrated water vapor (IWV) greater than 2cm, and were greater than 2000km in length and less than 1000km in width (Figure 1.341). These bands of high moisture transport are characterized by warm temperatures and high winds in the lower troposphere (Ralph et al., 2004), and the aforementioned Pineapple Express circulations are a specific kind of these Atmospheric Rivers (Dettinger, 2005). In fact, there is a nearly 1:1 match between the catalogues used in this project of strong vapor transports identified with Dettinger’s PE circulations and Atmospheric Rivers identified by Neiman et al. (2008) using SSM/I (P. Neiman, personal communication). The National Center for Environmental Protection (NCEP) and National Center for Atmospheric Research (NCAR) Reanalysis dataset (Kalnay et al., 1996) is used here to examine daily composites for integrated moisture flux and vector wind related with debris flows as a method for detecting and quantifying atmospheric moisture plumes and their paths (e.g. Neiman et al., 2008b).

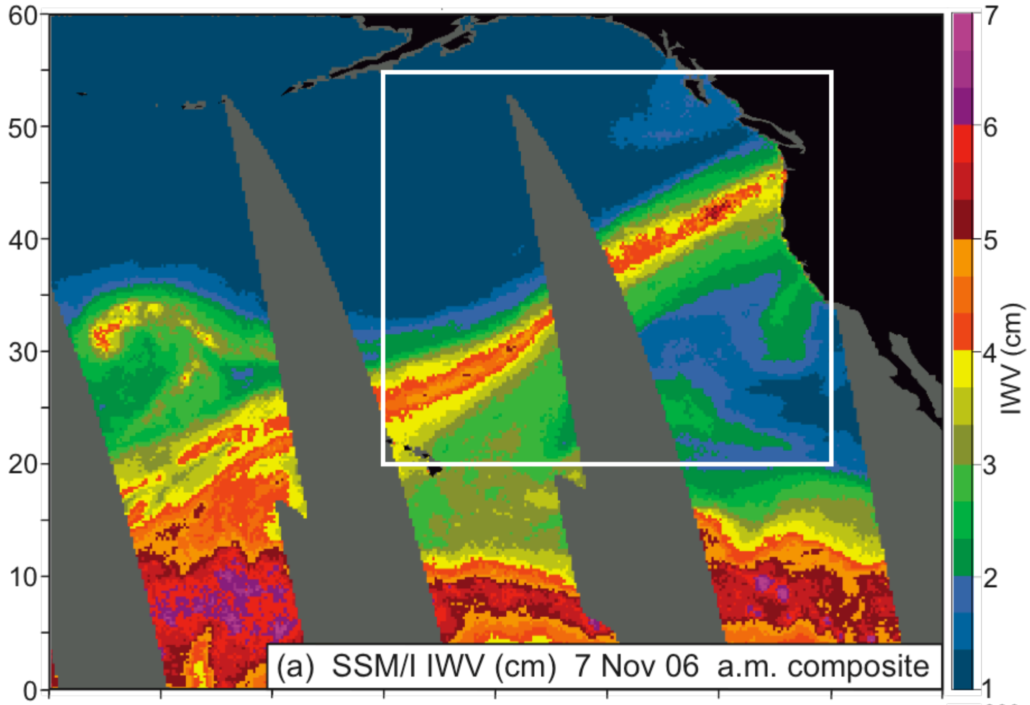

Figure 1.341 SSM/I image of an Atmospheric River impacting the Pacific Northwest on November 6, 2006 (Neiman et al., 2008b).

1.35 Antecedent Snowpack

Snow melt is dependent upon many heat sources (Equation 1.351) which vary in importance dependent upon geography and season (Harr, 1981).

$$M_t = M_{rs} + M_g + M_{rl} + M_{ce} + M_p \tag{1.351}$$

where M_t is the total melt, M_{rs} is melt due to short-wave radiation, M_g is melt from ground heat, M_{rl} is melt resulting from long-wave radiation, M_{ce} is melt due to convection and condensation, and M_p is melt from the latent heat transfer caused by rain on snow (Harr, 1981).

Shallow snowpacks with temperatures near 0°C are more easily melted by the latent heat energy released during rainfall events, and it is common for particularly warm rainfall events to melt an entire snowpack (Marks et al., 1998). Further, during these warm and wet rain events, the snowpack encourages runoff due to its low storage capacity for liquid water during melting, and high outflow is exacerbated by the lack of vegetation cover at debris flow initiation sites (Harr, 1981; and Berris and Harr, 1987). Additional work based on the Berris and Harr data by van Heeswijk et al. (1996) shows that although rainfall rates and high temperatures have some effect on snowmelt, high wind speeds have a great effect on intensifying snowmelt (Marks et al., 1998) – all characteristics attributed to Pineapple Express events. Given the potential importance of snowmelt and runoff on debris flow initiation (Harr, 1981; and Rebetez et al., 1997), this research examines snow water equivalent (SWE) values for one day prior to debris flows as a measure of antecedent snowpack conditions.

1.4 Site Description

Mount Rainier and Mount Hood are part of the Cascade Range, a mountain chain lying on the western seaboard of North America, lying approximately 100-150 miles inland and extending from northern California to southern British Columbia (Figure 1.41). The region to the west of the Cascades experiences substantial amounts of rainfall, as do the western slopes of the mountains due to the proximity to the Pacific Ocean. The majority of this precipitation falls during the winter months, between November and March, as a result of seasonal changes in large-scale atmospheric circulations over the North Pacific (Figures 1.42 and 1.43). Some variability in precipitation amounts exists as a result of both latitudinal effects and synoptic-scale influences of El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), which may be further amplified during periods of ENSO-PDO synchronicity (Gershunov and Barnett, 1998). During the wet winter months, much of the precipitation falls as snow, particularly at high elevation. However, increasing winter temperatures over time has resulted in a decrease in snowpack and more precipitation falling as rain rather than snow (Mote et al., 2005; Bales et al., 2006; and Knowles et al., 2006).

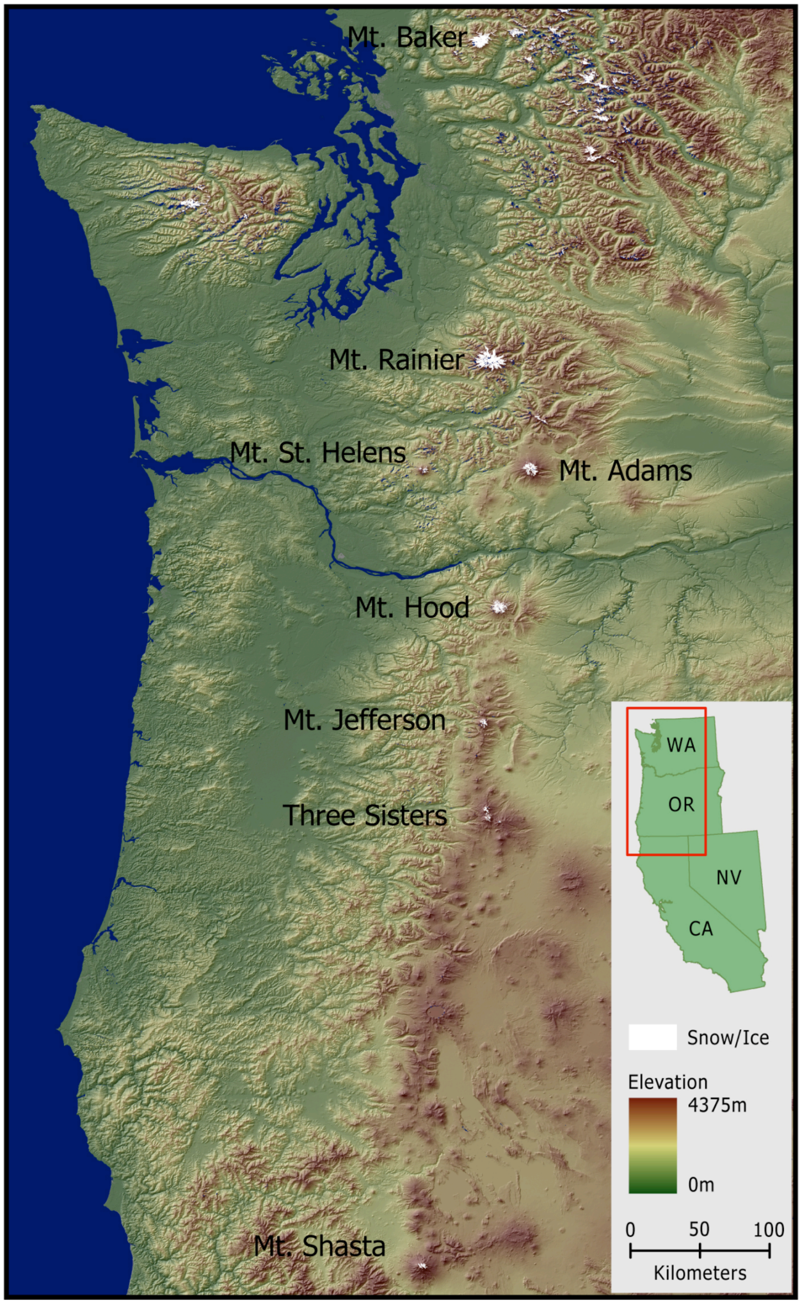

Figure 1.4 The locations of Mount Rainier and Mount Hood among the Cascade Mountains (Figure courtesy B. Medley).

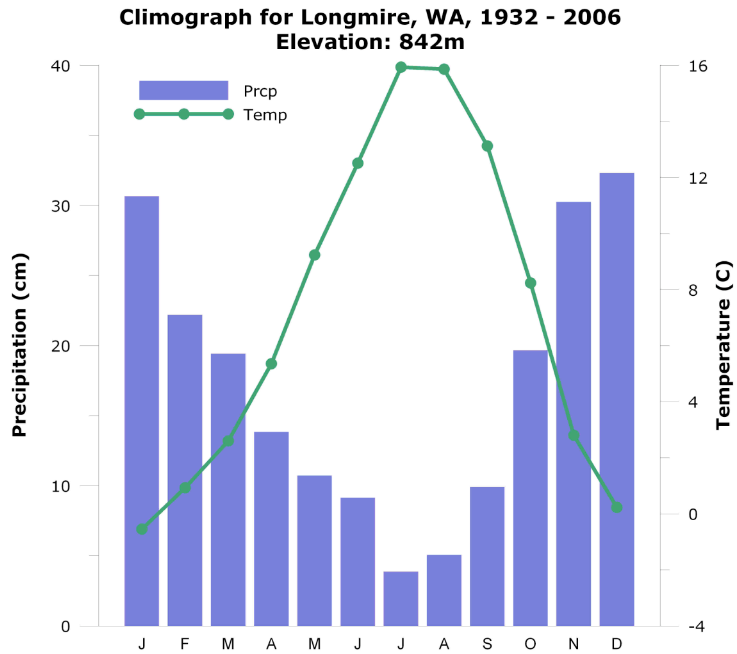

Figure 1.42 A climograph of mean monthly temperature and precipitation for Longmire, WA. This climograph is representative of the Northwest regional climate in its depiction of the cool, wet winter season and the warm and relatively dry summer season (Figure courtesy B. Medley).

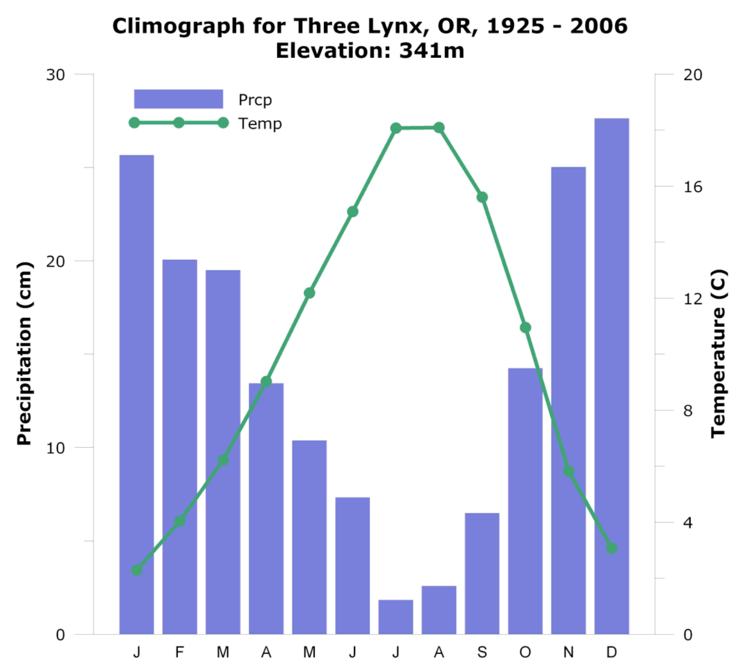

Figure 1.43 A climograph of mean monthly temperature and precipitation for Three Lynx, OR shows that the lower latitude and elevation site is typically drier and warmer (Figure courtesy B. Medley).

1.41 Mount Rainier

With a summit elevation of 4,392 m, Mount Rainier is the highest peak in the Cascade Range and dominates the skylines of Seattle, Tacoma and other Washington cities. Mount Rainier is the most glaciated mountain in the coterminous United States, with approximately 92 million m^2 and 4.4 billion m^3 of snow and ice from glaciers and permanent snowfields, more than 80% of which is at or above 1800 m (Driedger and Kennard, 1986). The mountain has five major river drainages (Carbon, White, Cowlitz, Nisqually, and Pullayup), all of which originate at glacier termini. Of these, only the White and Nisqually have experienced debris flows in their upper reaches. As previously mentioned, a significant decline in glacier area on Mount Rainier is the result of glacial retreat due to warming temperatures since the end of the Little Ice Age in the mid-1800s. Nylen (2004) showed that between 1931 and 1971 south facing glaciers declined 26.5% in area, compared with 17.5% decline in area of those glaciers with a northerly aspect.

1.42 Mount Hood

Approximately 80km southeast of Portland, Oregon, Mount Hood rises to 3,424 m, making this dormant stratovolcano the fourth highest mountain in the Cascade Range and an iconic part of the Portland skyline. The mountain covers an area of 200 km^2, has a volume of 50 km^3 (Scott et al., 1997), and has four major river drainages that originate on its flanks – the White, Hood, Zigzag and Sandy rivers – all of which drain to the Columbia River (Driedger and Kennard, 1986). Mount Hood has 11 glaciers, which cover a total area of 13.5 million m^2 and are 400 million m^3 in volume (Lillquist and Walker, 2006). The glacier area resides almost entirely above

1800 m, which is also roughly the elevation of tree line on Mount Hood (Driedger and Kennard, 1986). Like Mount Rainier's glaciers, the glaciers on Mount Hood have experienced significant retreat since the end of the Little Ice Age in the mid-1800s. In fact, all eleven glaciers on Mount Hood have receded over the last century, some by as much as 61% in length (Lillquist and Walker, 2006; and Jackson and Fountain, 2007).

Chapter 2: Methodology

2.1 Relating PE/AR Events to Debris Flows

Dettinger (2004) developed a catalogue of Pineapple Express circulations using vertically integrated water vapor (IWV) transport vectors, calculated from the NCEP Reanalysis data set (Kalnay et al., 1996). Atmospheric circulation patterns were considered to be Pineapple Express events if the IWV transport vectors created continuous pathways from 120ºW longitude to the tropical pacific east of 170ºW longitude. Only transport pathways crossing 120ºW longitude between 32.5ºN and 52.5ºN latitudes were considered for IWV intensity analysis, and only pathways with IWV transport averages of 500 kg/m/s were catalogued as PE circulations (Dettinger, 2004). These methods were later altered such that the transport pathways crossed the physical west coast of North America between 32.5ºN and 52.5ºN latitudes rather than the less complex single line of longitude at 120ºW. Further, the revised methods used a dataset of IWV transport vectors to detect the PE events developed by C. Smith at the National Oceanic and Atmospheric Administration Climate Diagnostic Center (NOAA CDC) (M. Dettinger, personal communication). This amended catalogue, beginning in 1948 and continuing through 2006, is used for all PE analysis in this project (Appendix A).

A catalogue of IWV plumes impacting the west coast of North America, between 32.5ºN and 52.5ºN latitudes, was created by Neiman and others using Special Sensor Microwave Imager (SSM/I) satellite observations (Neiman et al., 2008). Plumes of IWV were included in the catalogue if they had a core value >2 cm of integrated water vapor, if their dimensions were >2000 km in length and <1000 km in width, and if the plumes made landfall during both the ascending and descending passes of the SSM/I satellite (Neiman et al., 2008). Coupled with vertically integrated horizontal water vapor fluxes from the NCEP-NCAR reanalysis dataset, these plumes were quantitatively determined to be Atmospheric Rivers (Neiman et al., 2008). The catalogue of Atmospheric River events, spanning water years 1998 to 2005 impacting the Oregon and Washington coasts, from 41ºN to 52.5ºN latitudes, is used for all AR analysis in this project.

A catalogue of debris flow events was compiled for Mount Hood (T. DeRoo, personal communication), which was made available to this project (Appendix B). The catalogue of debris flow events for Mount Rainier (Appendix C) included the list of Walder and Driedger (1994) with additional dates provided by P. Kennard and E. Copeland (personal communication). These debris flow date catalogue compilations make no distinction between those debris flows that are associated with rainfall events and those that are not. However, for all subsequent analysis, the debris flow event catalogues for both mountains were subset to include only those debris flow events for which there was rainfall recorded within three days before or after a debris flow event. The rainfall data were obtained from the Government Camp and Paradise meteorological station records[1], for Mount Hood and Mount Rainier, respectively. Appendix D contains the listing of rain-related debris flow dates.

The catalogues for PE and AR events were combined and cross-referenced to the catalogues of debris flow dates at each mountain to determine which debris flow

[1] For information on this data, refer to section **2.3 Precipitation**

event dates were associated with Pineapple Express circulations or Atmospheric Rivers. If a debris flow occurred on a date that was found in the combined PE/AR catalogue, it was listed as PE/AR related. Because completely accurate cross-referencing requires a year, month and day (YMD) for the debris flow event, debris flow events that were catalogued as occurring in a particular year, or particular year and month but without a definitive date associated with them, were not counted in the cross-referencing. However, if a debris flow occurred in a year and month in which no PE or AR event occurred at all, it was counted as a non-PE/AR event, even if the debris flow event catalogue did not have the full YMD date recorded.

2.2 Geostrophic Flow

As a means to determine the origin of debris flow associated storms and their progression, maps of geopotential heights from the NCEP-NCAR Reanalysis were examined for each debris flow date ± 3 days. Geopotential readings at hours 0, 6, 12, and 18 GMT were averaged to produce the daily 500-hPa height variable used in this work. The height map was restricted to latitudes 10ºS to 80ºN and longitude 150ºE to 110ºW.

2.3 Temperature

Free air temperature data were taken from IGRA radiosonde soundings at Quillayute, Washington (KUIL) and Salem, Oregon (KSLE) for all available years through 2006 (Table 2.31). These sites served as proxies for determining the free air freezing levels at Mount Rainier and Mount Hood, respectively.

Table 2.31 Site specifications for the Salem and Quillayute IGRA radiosonde stations.

Station	Call Name	IGRA Station ID	Latitude	Longitude	Elevation (m)	Period of Record
Salem	KSLE	72694	44.917	-123.01	61	1956 – present
Quillayute	KUIL	72797	49.95	-124.55	58	1966 – present

Radiosonde soundings at KUIL and KSLE are taken twice daily at 0000 and 1200 GMT, equating to 1600 and 0400 Pacific Standard Time (PST). Both the KUIL and the KSLE records are incomplete, however roughly 97% of the KUIL record and 98% of the KSLE record necessary for the temperature analysis performed here are complete for the period of study at each location.

The altitude for the 0ºC isotherm was computed assuming a linear decrease in temperature with height (Seidel and Free, 2003). If inversions were present, the first altitude at which the 0ºC isotherm was reached, when moving up in altitude from the surface, was used. If the temperature was at or below 0ºC at the surface, then the surface elevation was recorded as freezing altitude. In this way, a table of freezing altitudes for every available date and time stamp at both KUIL and KSLE was created.

In order to determine how fall (September, October, November – SON) rain-related debris flow event freezing altitudes compared with the freezing altitudes of other fall dates which experienced significant rainfall, precipitation data from the Quillayute and Salem stations were used to subset the freezing altitudes for all fall dates to a smaller catalogue containing only the freezing altitudes for fall dates with significant rainfall. To determine the threshold for “significant” rainfall at each location, the median amount of precipitation for all rain-related debris flow dates was found for both KUIL and KSLE. Freezing altitudes were then found for the dates where the precipitation equaled or exceeded the threshold values for significant rainfall. These freezing altitudes were then compared to the freezing altitudes for rain-related debris flow dates at each mountain for both the 0000 and 1200 GMT time stamps. For both the freezing altitudes associated with dates of significant rainfall and with dates of rain-related debris flows, in order to reconcile precipitation measurements taken in local time with radiosonde temperature measurements taken in GMT, freezing altitudes were taken for the significant rainfall or debris flow date at the 1200 GMT time stamp and for the significant rainfall or debris flow event "date +1 day" at the 0000 GMT time stamp. This provides freezing altitudes for the significant rainfall and debris flow event dates at sounding times of 0400 and 1600 Pacific Standard Time (PST), respectively.

2.4 Precipitation

2.41 Precipitation Trends

To examine whether fall season wet days are getting wetter, days of notable precipitation were charted versus time for both KSLE and KUIL, where the precipitation threshold is defined as those days where the total daily precipitation equals or exceeds the median amount of total daily precipitation associated with debris flow event dates. This threshold value is 0.42 cm at KSLE and 3.05 cm at KUIL. These values are ultimately expressed in centimeters for analysis. Linear regression analysis for precipitation amount versus time was performed.

2.42 Precipitation Associated with Debris Flows

Precipitation data for Mount Hood were acquired from the Government Camp cooperative meteorological station and precipitation data for Mount Rainier were acquired from the Paradise cooperative meteorological station (Table 2.421). These data were downloaded from NOAA. For each debris flow date, precipitation amounts were examined for three days on either side (antecedent or subsequent to) of the flow event on each mountain respectively.

Table 2.421 Station specifics for Government Camp, OR and Paradise, WA meteorological stations.

Station	Station ID	Climate Division	Latitude	Longitude	Elevation (m)	Period of Record
Government Camp	353402	OR-04 Northern Cascades	45.3	-121.75	1213.1	1951 – present
Paradise	456898	WA-05 Cascade Mountains West	46.783	-121.75	1654.1	1948 – present

2.43 Orographic Enhancement

Measures of orographic enhancement were calculated by using total daily precipitation at coupled meteorological sites and dividing the precipitation amount at the higher elevation site by the precipitation amount at the lower elevation site (e.g. Dore et al., 2006). The orographic enhancement values for Mount Hood were calculated using data from the Government Camp and Three Lynx cooperative meteorological stations (Table 2.431). Values for Mount Rainier were calculated using data from the Paradise and Longmire cooperative meteorological stations (Table

2.432). The enhancement values computed are for the sum of precipitation falling during a three-day window centered on the debris flow event day.

Table 2.431 Site specifications for the Government Camp and Three Lynx meteorological stations near Mount Hood.

Station	Station ID	Climate Division	Latitude	Longitude	Elevation (m)	Period of Record
Government Camp	353402	OR-04 Northern Cascades	45.3	-121.75	1213.1	1951 – present
Three Lynx	358446	OR-04 Northern Cascades	45.116	-122.066	341.1	1948 – present

Table 2.432 Site specifications for the Paradise and Longmire meteorological stations at Mount Rainier.

Station	Station ID	Climate Division	Latitude	Longitude	Elevation (m)	Period of Record
Paradise	456898	WA-05 Cascade Mountains West	46.783	-121.75	1654.1	1948 – present
Longmire	454764	WA-05 Cascade Mountains West	46.75	-121.816	841.9	1948 – present

2.5 Moisture Transport

Daily integrated water vapor transport composites were accessed through the CDC at NOAA for debris flow day ± 3 days for flow events at both Mount Rainier and Mount Hood. The composites were of the integrated moisture flux at the 850mb analysis level (e.g. Junker et al., 2007) of 10ºN to 60ºN latitude and 160ºE to 110ºW longitude. The plots were created with a transport range of 0 to 1000 kg m^{-1} s^{-1} and an interval of 100 kg m^{-1} s^{-1}. The integrated moisture flux values are calculated by multiplying specific humidity by vector wind integrated from the surface and multiplying the layer by the pressure of that level and dividing by acceleration due to gravity (cdc.noaa.gov). From visual analysis of the created plots, moisture transport values were estimated based on the 100 kg m^{-1} s^{-1} range color overlying the approximate location of the respective mountains. Whether the moisture plume was classified as a PE or AR event and its general spatial and physical characteristics were also noted.

2.6 Antecedent Snow Conditions

Snow water equivalent (SWE) data were gathered from online databases for the Paradise and Mount Hood Test Site SNOTEL stations for Mount Rainier and Mount Hood, respectively (Table 2.61). SWE is calculated as depth*density. This can also be expressed as Depth = SWE/Density. For depth calculations, the Natural Resources Conservation Service (NRCS) estimates for a typical winter Cascades snowpack density of 20-30% are used. Antecedent SWE from one day prior to the debris flow event date was examined for each event at each mountain.

Table 2.61 Site specifications for the Mount Hood Test Site and Paradise SNOTEL stations.

Station	Station ID	Latitude	Longitude	Elevation (m)	Period of Record
Mount Hood Test Site	21d08s	45.316	-121.716	1636.7	WY 1982 – present
Paradise	21c35s	46.783	-121.75	1563.6	WY 1982 – present

Chapter 3: Results

3.1 Relating PE/AR Events to Debris Flows

Over the 58-year record (1948-2006) of combined Pineapple Express and Atmospheric River event catalogues, Mount Hood experienced 24 PE/AR related debris flows on 7 separate dates in 5 years during the later part of the record. This is comparable to 22 debris flows of other origins, occurring on 22 separate dates in 22 years, with the distribution of these dates being more evenly spread over the whole of the record (Figure 3.11). The PE/AR related debris flows appear to be more common in the later record and additionally, these events appear to produce debris flows in multiple drainages as compared to other events which may produce only one, possibly two, debris flows.

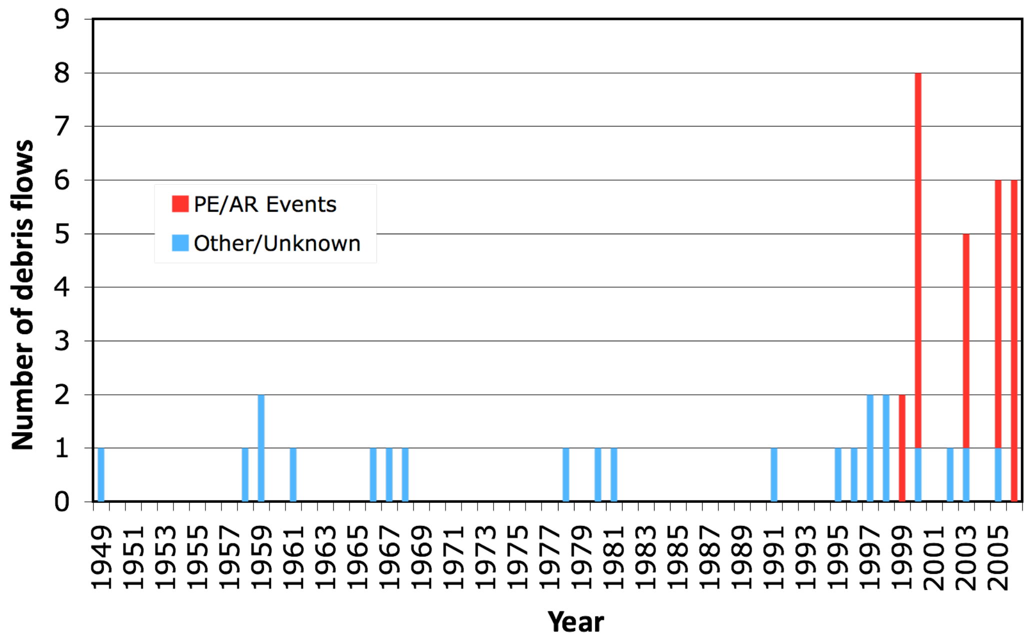

Figure 3.11 Frequency and associated meteorological phenomena of debris flows on Mount Hood between 1948 and 2006. Red bars indicate those flow events associated with Pineapple Express circulations or Atmospheric Rivers while blue bars indicate flow events associated with a non-PE/AR event.

Over this same 58-year period, Mount Rainier experienced 36 non-PE/AR related debris flows on 35 separate days, in 24 discrete years (Figure 3.12). Only 10 debris flows on Mount Rainier were associated with PE/AR events, one occurring in 2003, three occurring on a single date in 2005, and six occurring on a single date in 2006. Many of the debris flows on Mount Rainier were the result of glacial outbursts and occurred in the summer during anomalously hot and dry weather. These outburst events typically produced only one flow in a single drainage whereas rain events could produce multiple flows in multiple drainages.

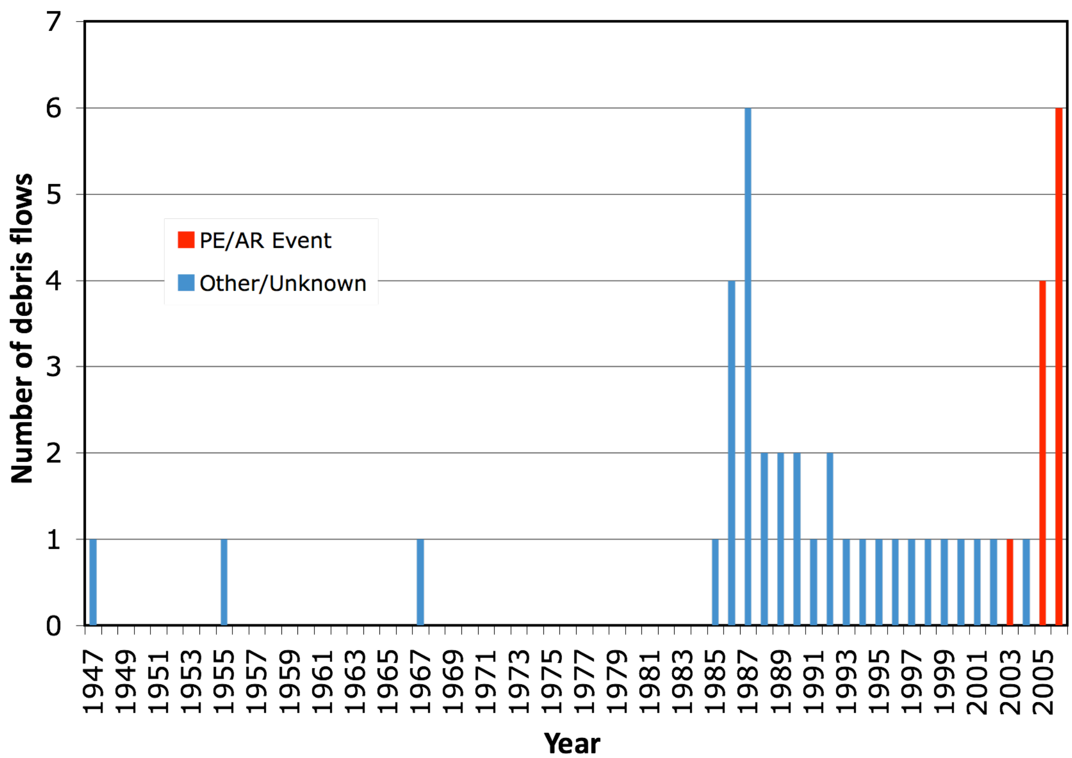

Figure 3.12 Frequency and associated meteorological phenomena of debris flows on Mount Rainier between 1948 and 2006. Red bars indicate those flow events associated with Pineapple Express circulations or Atmospheric Rivers while blue bars indicate flow events associated with either a non-PE/AR rain event or a glacial outburst event.

3.2 Geostrophic Flow

Both Mount Hood and Mount Rainier experienced rain-related debris flows that were associated with both zonal and meridional flow at the 500-hPa pressure level. A time-series view of geopotential heights at this pressure level depicts the development and movement of flow regimes before and after the recorded debris flow event dates. The total time series was considered when determining the coupling of the upper atmosphere flow pattern with each debris flow date, with particular attention paid to the day prior to and the day of the flow. Meridional flow patterns associated with debris flows include 7 troughs (Figure 3.21), a ridge (Figure 3.22) and the broad troughs defined by Dettinger (2004) as Pineapple Express circulations (Figure 3.23). There is some discrepancy between the mountains as to which flow regimes are more commonly associated with debris flows, with troughs being more common at Mount Rainier than at Mount Hood (Tables 3.21 and 3.22) At Mount Hood, all but one of the dates with multiple flows are associated with meridional flow; at Mount Rainier, only two dates produced multiple debris flows and of these two, one is associated with meridional flow. At both Mount Rainier and Mount Hood, the debris flow date that produced multiple debris flows and was not associated with meridional flow – September 29, 2005 and September 30, 2005 respectively – is an upper-level zonal flow system (Figure 3.24). In all instances, the isobars are relatively close together indicating strong flow aloft.

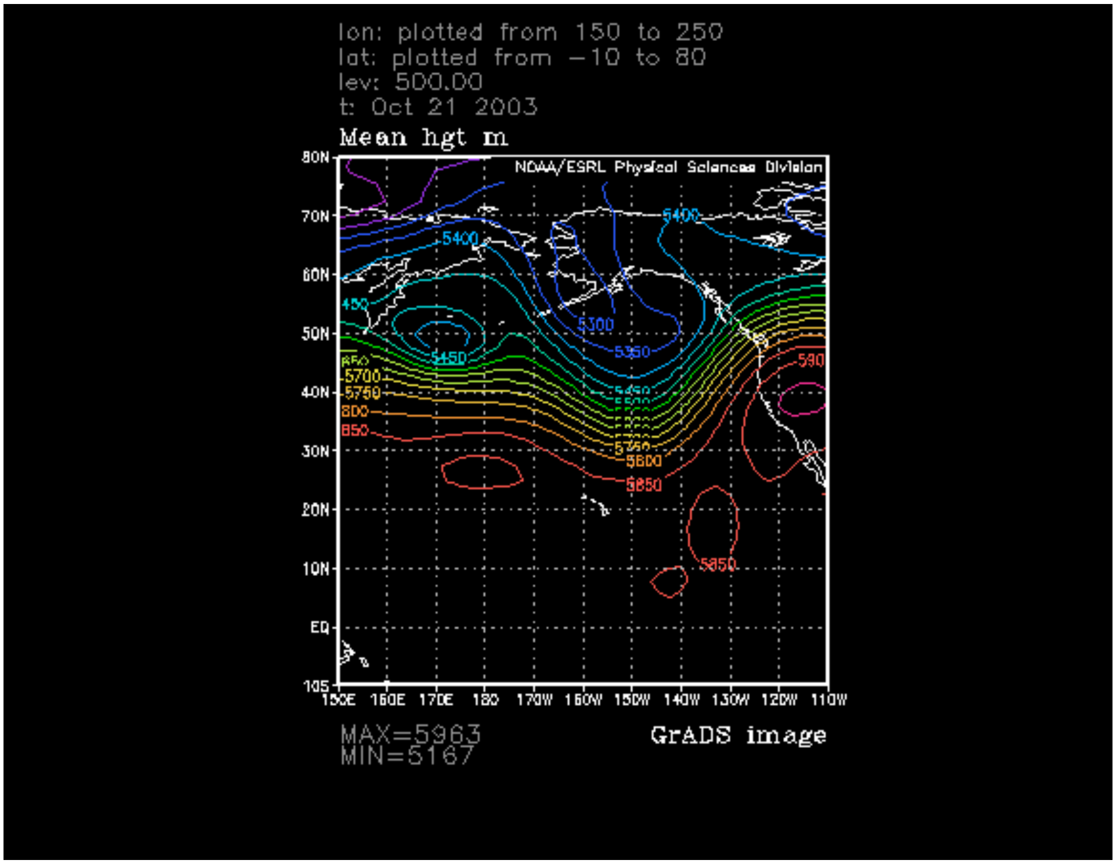

Figure 3.21 500-hPa geopotential heights show an upper atmosphere trough in the mid-latitude eastern Pacific on October 21, 2003, on which Mount Hood experienced one debris flow.

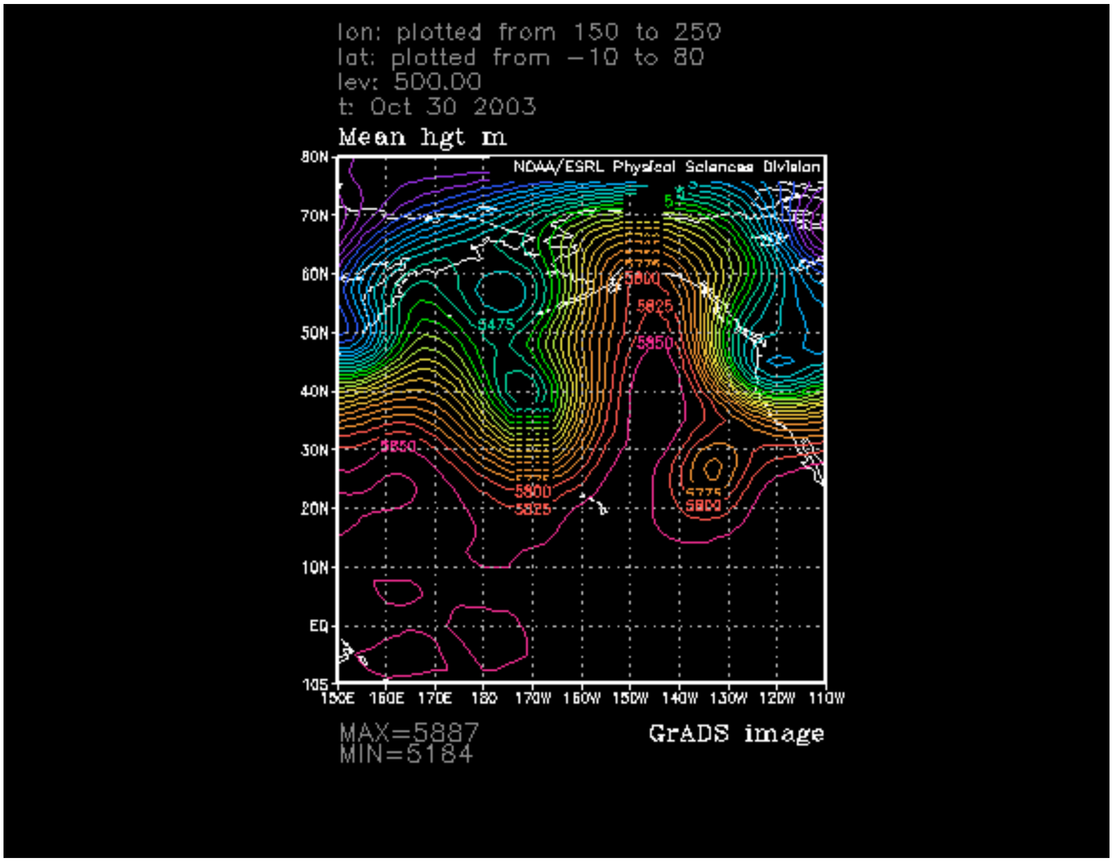

Figure 3.22 A high amplitude ridge extending into the Gulf of Alaska was coupled with a debris flow on Mount Hood on October 30, 2003.

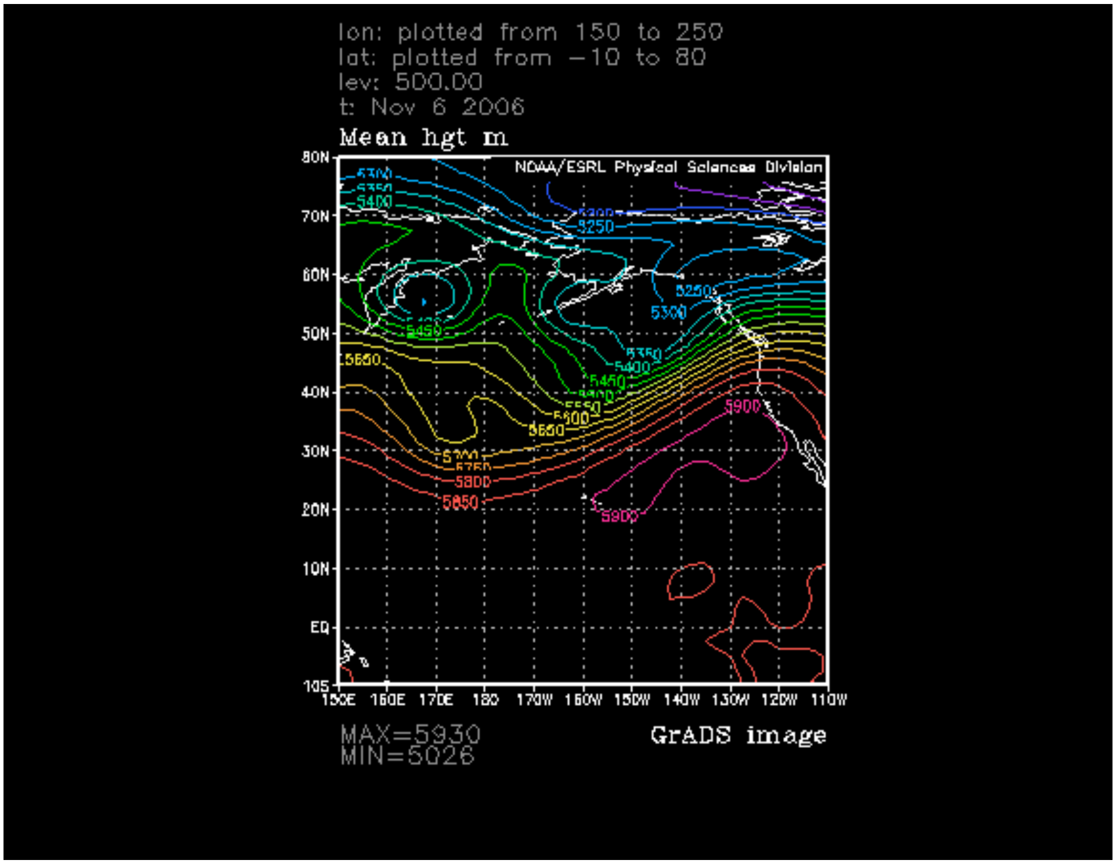

Figure 3.23 Defined by Dettinger (2004) as a Pineapple Express circulation, the flow associated with these isohypses brought a warm and wet storm system to the Northwest which produced 6 debris flows on Mount Rainier on November 6, 2006 (shown) and 7 debris flows on Mount Hood the following day.

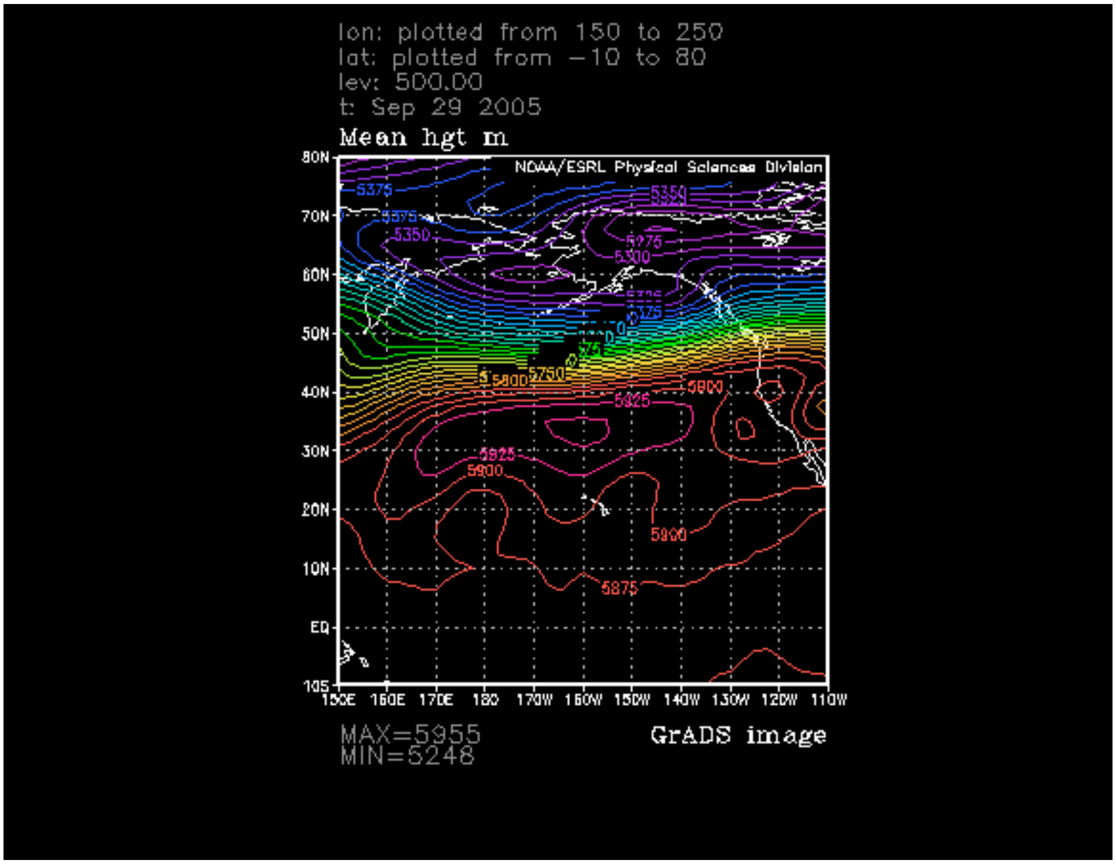

Figure 3.24 High isohypses and zonal flow are coupled with 4 debris flows on Mount Rainier on September 29, 2005 (shown) and 5 flows on Mount Hood on September 30.

Table 3.21 Mount Rainier debris flow dates and associated geostrophic patterns.

YEAR	MONTH	DATE	# OF DEBRIS FLOWS	FLOW PATTERN	FLOW DESCRIPTION
1986	10	26	1	Meridional	Trough
1988	10	16	1	Meridional	Trough (high off SoCal coast)
1989	11	9	1	Meridional	Trough (to 170E)
1990	10	3	1	Zonal	Zonal
1991	11	5	1	Meridional	Broad Trough
1992	9	8	1	Zonal	Zonal
1992	9	20	1	Zonal	Zonal
2003	10	20	1	Meridional	Pineapple Express
2005	9	29	4	Zonal	Zonal
2006	11	6	6	Meridional	Pineapple Express

Table 3.22 Mount Hood debris flow dates and associated geostrophic patterns.

YEAR	MONTH	DATE	# OF DEBRIS FLOWS	FLOW PATTERN	FLOW DESCRIPTION
1958	11	8	1	Zonal	Zonal
1961	9	1	1	Zonal	Zonal
1999	11	26	1	Zonal	Zonal
2000	10	1	7	Meridional	Trough (high off SoCal coast)
2003	10	21	1	Meridional	Trough
2003	10	28	2	Meridional	Trough
2003	10	30	1	Meridional	Ridge
2005	9	30	5	Zonal	Zonal
2005	10	31	1	Zonal	Zonal
2006	11	7	6	Meridional	Pineapple Express

3.3 Temperature

Free air freezing altitudes for both KSLE (Figures 3.31 and 3.32) and KUIL (Figures 3.33 and 3.34) debris flow event dates were found to be, on average, higher than the mean free air freezing altitude for all other significant rainfall events during the fall season at the respective sites. The mean freezing altitude for significant fall season rainfall events at KSLE is 2135 m at 0400 PST and 2028 m at 1600 PST, with a standard deviation of 822 m and 695 m, respectively. At KUIL, the mean freezing altitude for rainfall events is 2227 m at both 0400 PST and 1600 PST, with a standard deviation of 738 m at 0400 PST and 688 m at 1600 PST. At KSLE, 7 of 10 rain-related debris flow event dates had freezing altitudes exceeding one standard deviation than mean freezing levels for all fall season rainfall event dates at both 0400 and 1600 PST. KUIL had 11 of 13 debris flow event dates experience freezing altitudes exceeding one standard deviation than mean at the 0400 PST sounding, however only 5 of 12 debris flow event dates[2] with freezing altitudes that exceed one standard deviation at the 1600 PST sounding, though 10 of these 12 had freezing altitudes higher than the mean of all rainfall event dates.

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[2] Freezing altitude data were missing for one debris flow event date: October 20, 2003. The data missing from the KSLE record are for October 21, 2003 at 0GMT.

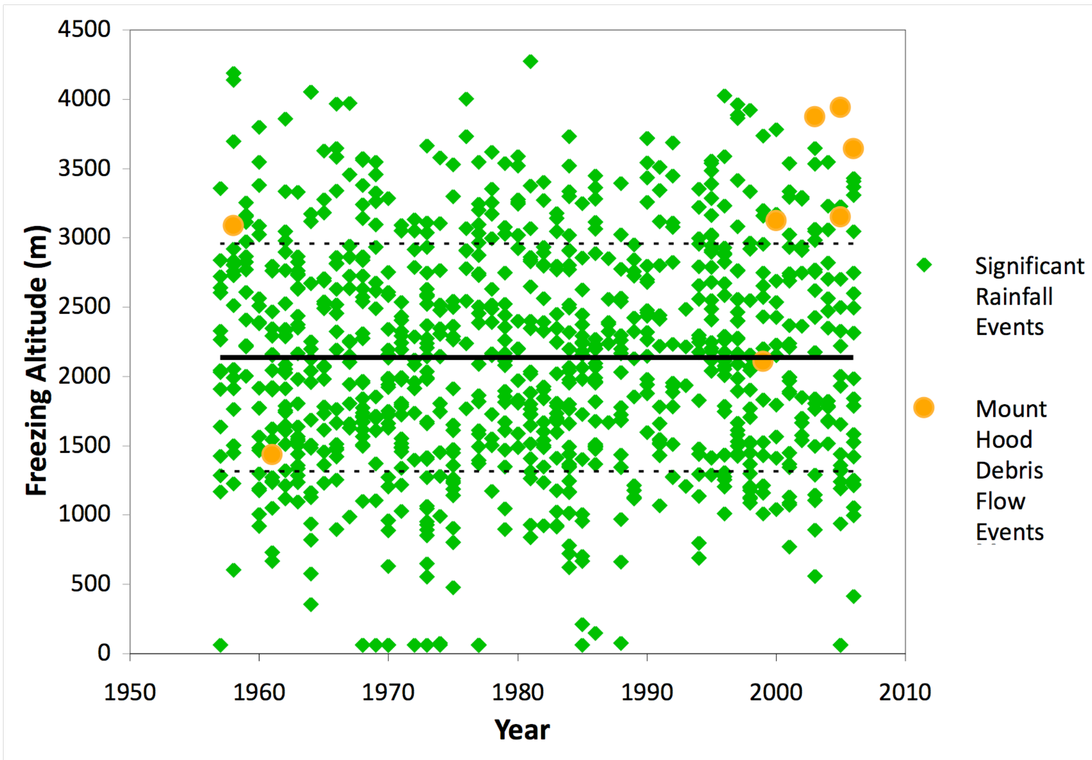

Figure 3.31 At 0400 PST, freezing levels for debris flow event dates on Mount Hood (shown in orange) are generally higher than the freezing levels for other fall dates with significant amounts of rainfall. The mean is shown here as a solid black line, with one standard deviation depicted by the dashed lines.

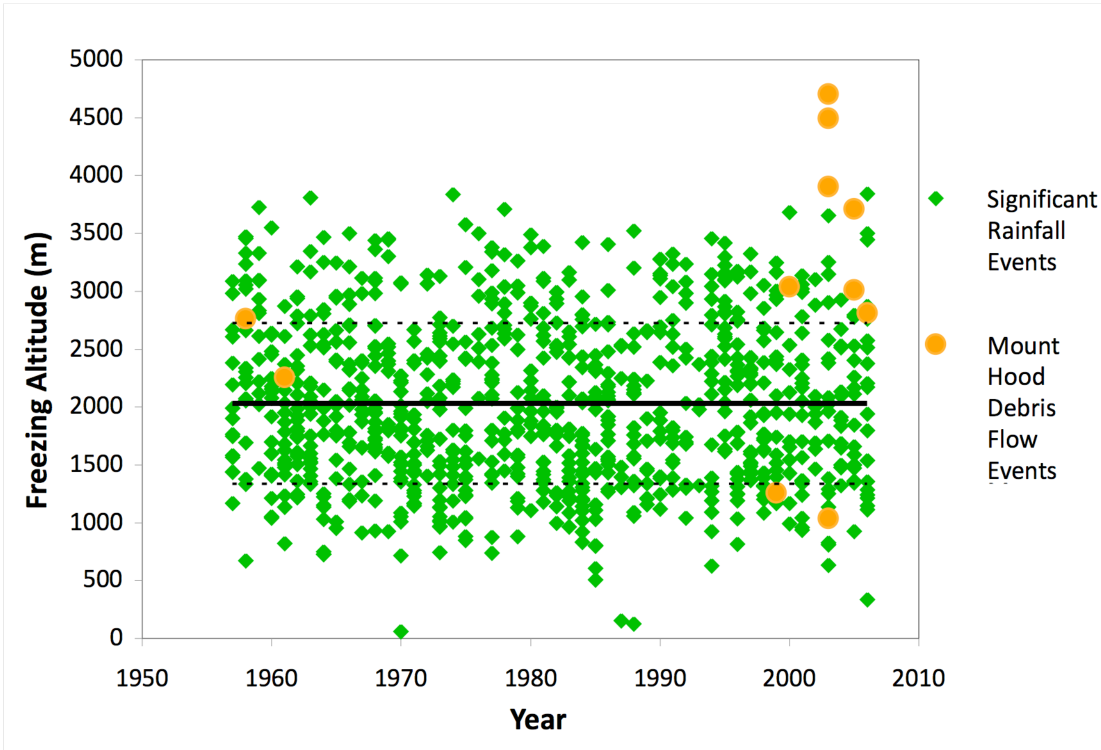

Figure 3.32 At 1600 PST, freezing levels for debris flow events on Mount Hood are generally higher than freezing levels for other fall dates with significant rainfall, though outliers exist.

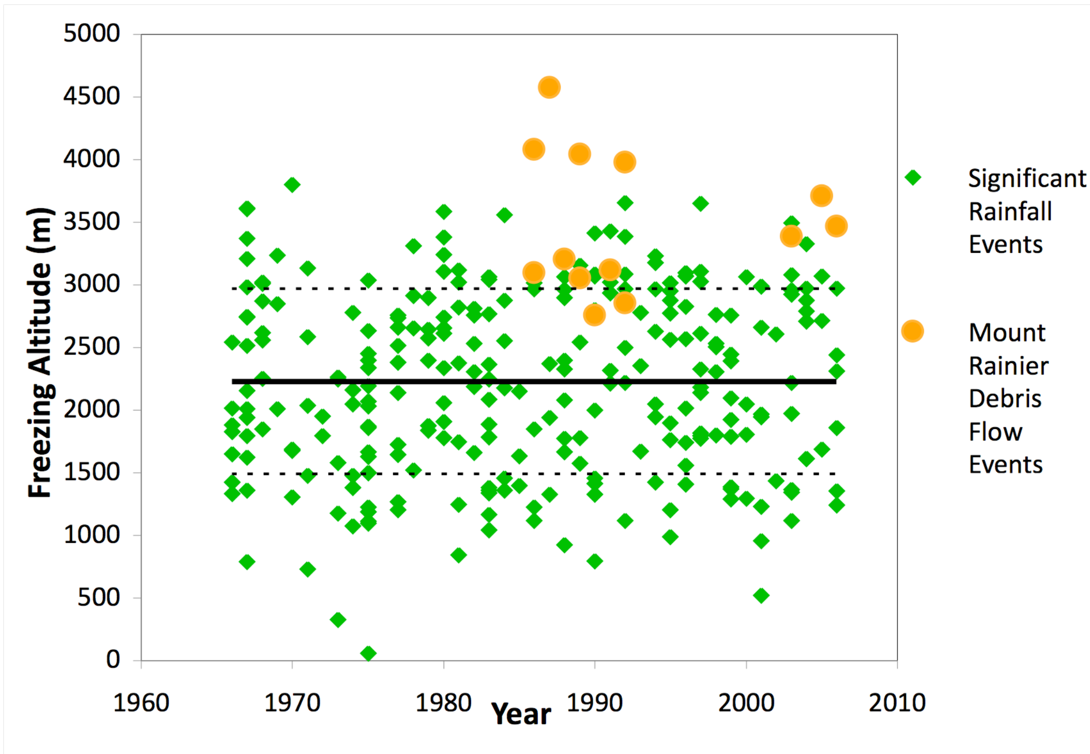

Figure 3.33 At 0400 PST, freezing levels for Mount Rainier debris flow events are generally higher than freezing levels for other fall dates with significant rainfall.

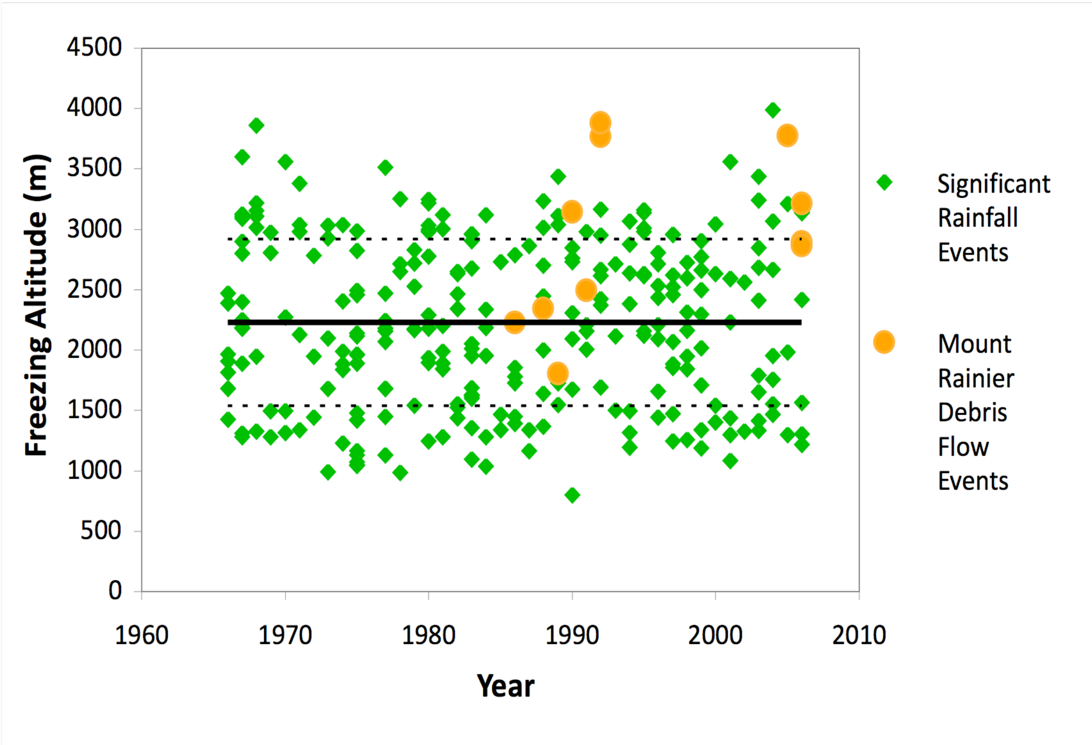

Figure 3.34 At 1600 PST, freezing levels for Mount Rainier debris flow dates are generally higher than freezing levels for other fall dates with significant rainfall, though some more markedly than others.

3.4 Precipitation

3.41 Fall Season Rain Events

Charting total daily precipitation amounts for fall season significant rainfall events over time shows some trend at Salem (Figure 3.411), but linear regression analysis shows this trend to be not statistically significant at 95% confidence (p=0.07). A similar analysis using the Quillayute (Figure 3.412) data shows a less notable trend, which is also statistically non-significant at 95% confidence (p=0.52).

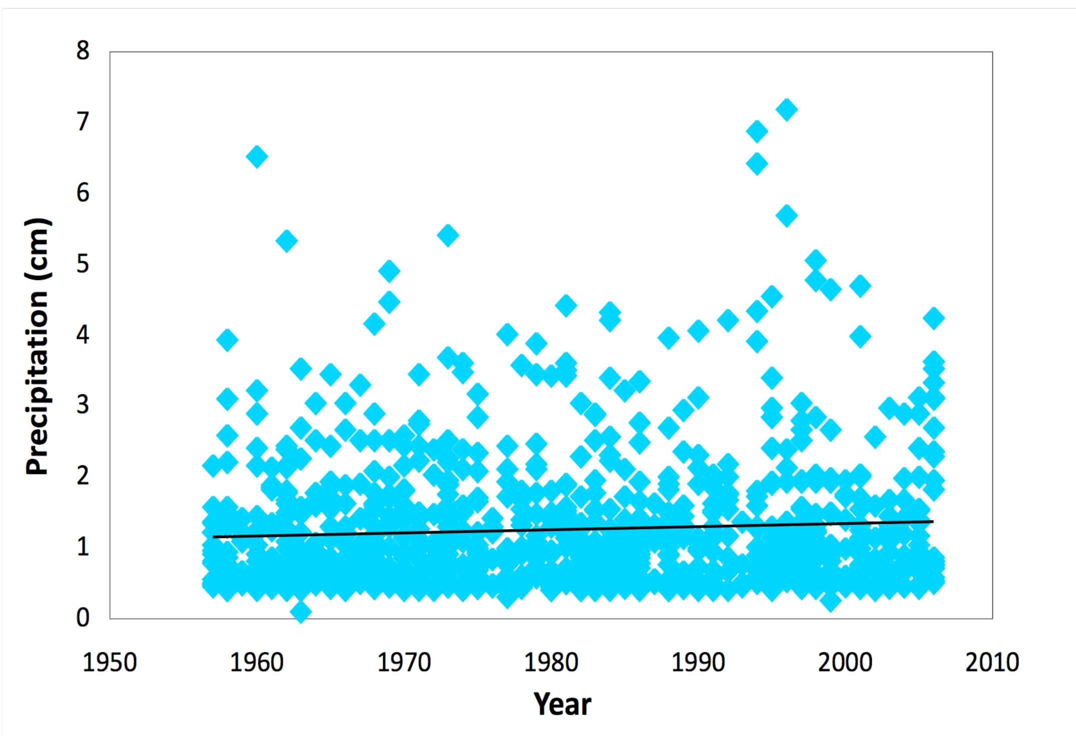

Figure 3.411 Although there appears to be a slight trend over time in the magnitude of fall significant precipitation, linear regression analysis shows that the trend is not statistically significant at 95% confidence.

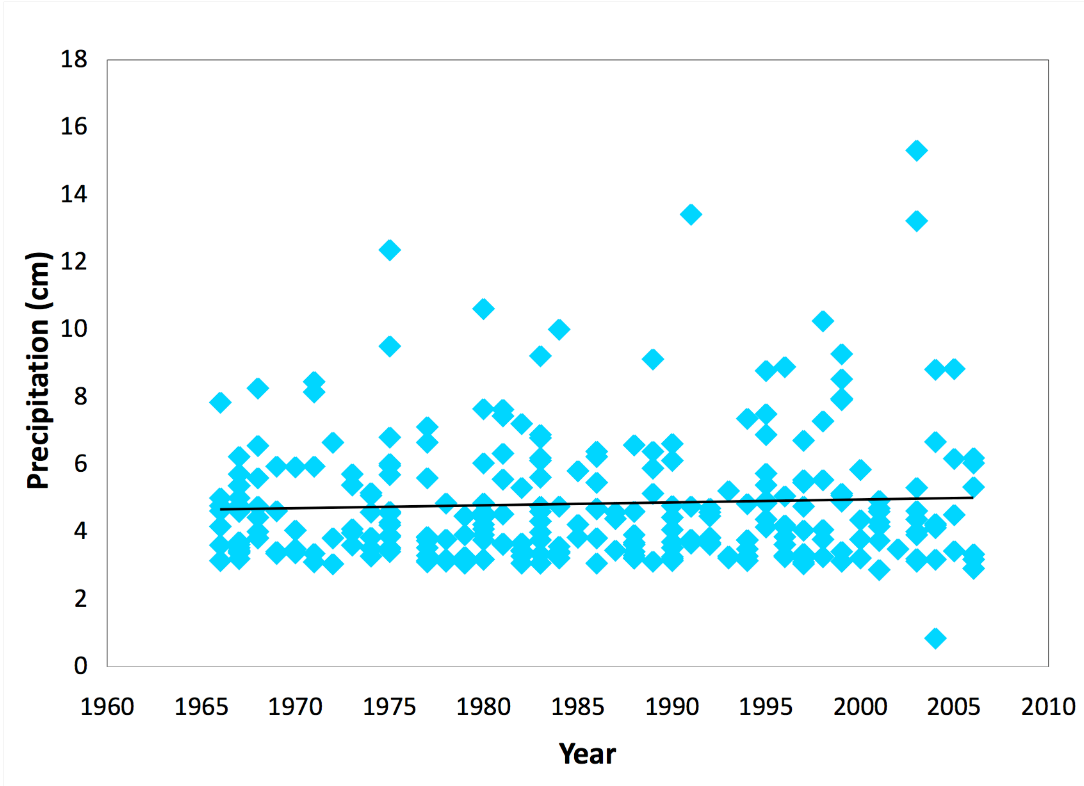

Figure 3.412 There is virtually no trend in precipitation amounts over time for fall season wet days at Quillayute.

3.42 Precipitation Associated with Debris Flow Events

At Mount Hood, precipitation amounts associated with debris flows are variable. Precipitation amounts were examined for the 3-day antecedent time frame, the individual recorded debris flow event date, and the three day window centered on the debris flow date (Table 3.421), as well as the 7-day period including the debris flow event date and the three days both preceding and succeeding the flow event date. Precipitation amounts for the debris flow date ±3 days were also plotted with the associated freezing altitudes. In some instances, the most significant precipitation for the 7-day period surrounding the debris flow event occurred after the recorded debris flow event date (Figure 3.421). Interestingly, there are also instances of similar amounts of both antecedent and same-day precipitation that produce multiple debris flows on one date while producing only one flow on another (Figures 3.422 and 3.423).

Table 3.421 Debris flow event dates at Mount Hood, the number of debris flows occurring in Mount Hood drainages on that date, and the cumulative precipitation (PRECIP) amounts recorded at the Government Camp meteorological station for the 3 days prior to the debris flow event, the day of the debris flow event, and for a three day window, centered on the debris flow event date. Dates with more than 2 debris flows are highlighted with bold font.

YEAR	MONTH	DATE	# OF DEBRIS FLOWS	3-DAY PRIOR PRECIP (CM)	DEBRIS FLOW DAY PRECIP (CM)	DEBRIS FLOW ± 1 DAY PRECIP (CM)
1958	11	8	1	11.96	1.44	7.95
1961	9	1	1	9.52	4.77	13.10
1999	11	26	1	24.38	0.71	13.58
2000	**10**	**1**	**7**	**9.39**	**2.41**	**10.54**
2003	10	21	1	0.07	0	1.52
2003	10	28	2	0.25	3.83	5.25
2003	10	30	1	5.25	0	1.16
2005	**9**	**30**	**5**	**0.05**	**4.74**	**7.67**
2005	10	31	1	2.18	6.22	11.02
2006	**11**	**7**	**6**	**20.44**	**5.28**	**37.85**

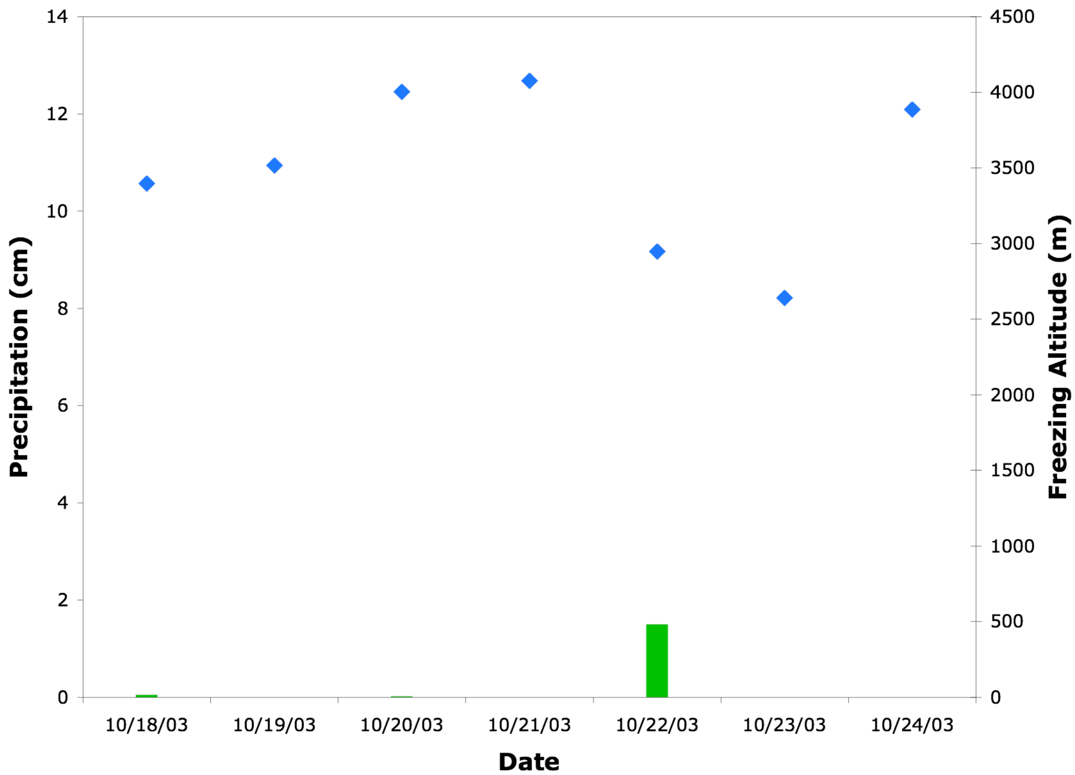

Figure 3.421 A single debris flow was recorded on Mount Hood on October 21, 2003, despite minimal antecedent precipitation and no precipitation recorded on the day of the debris flow event. The only significant precipitation was recorded on the following day. Green bars indicate daily precipitation in centimeters, while blue diamonds indicate daily mean freezing altitudes in meters.

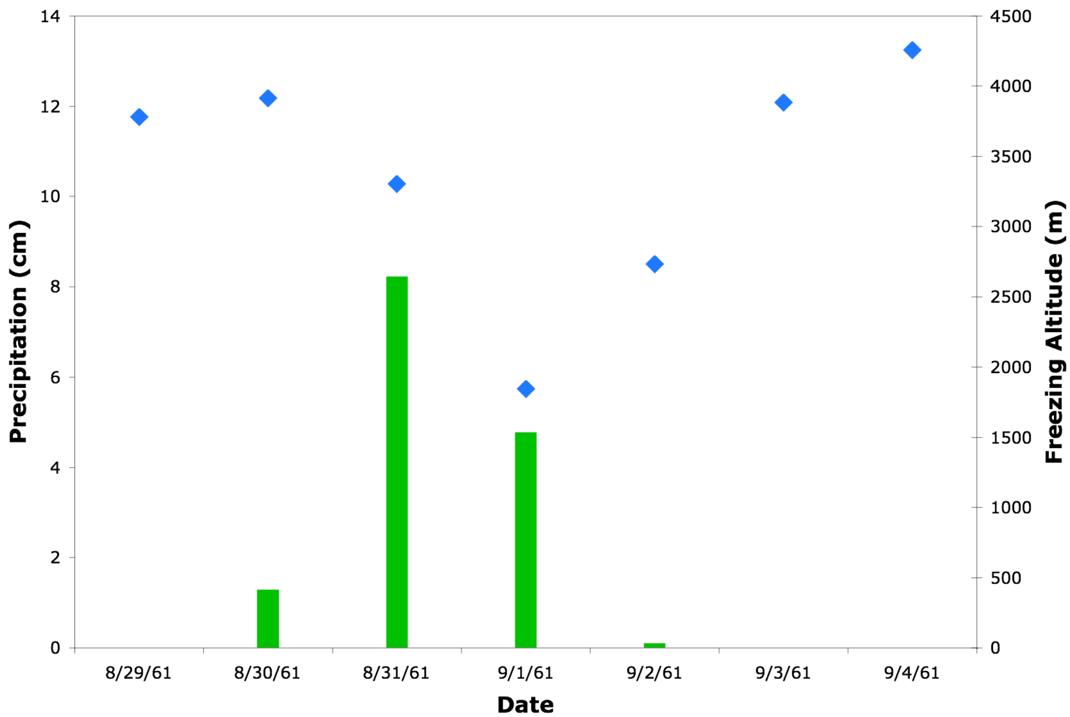

Figure 3.422 Despite significant antecedent and same-day precipitation, this storm system – associated with a zonal flow regime – produced only one debris flow. Green bars indicate daily precipitation in centimeters, while blue diamonds indicate daily mean freezing altitudes in meters.

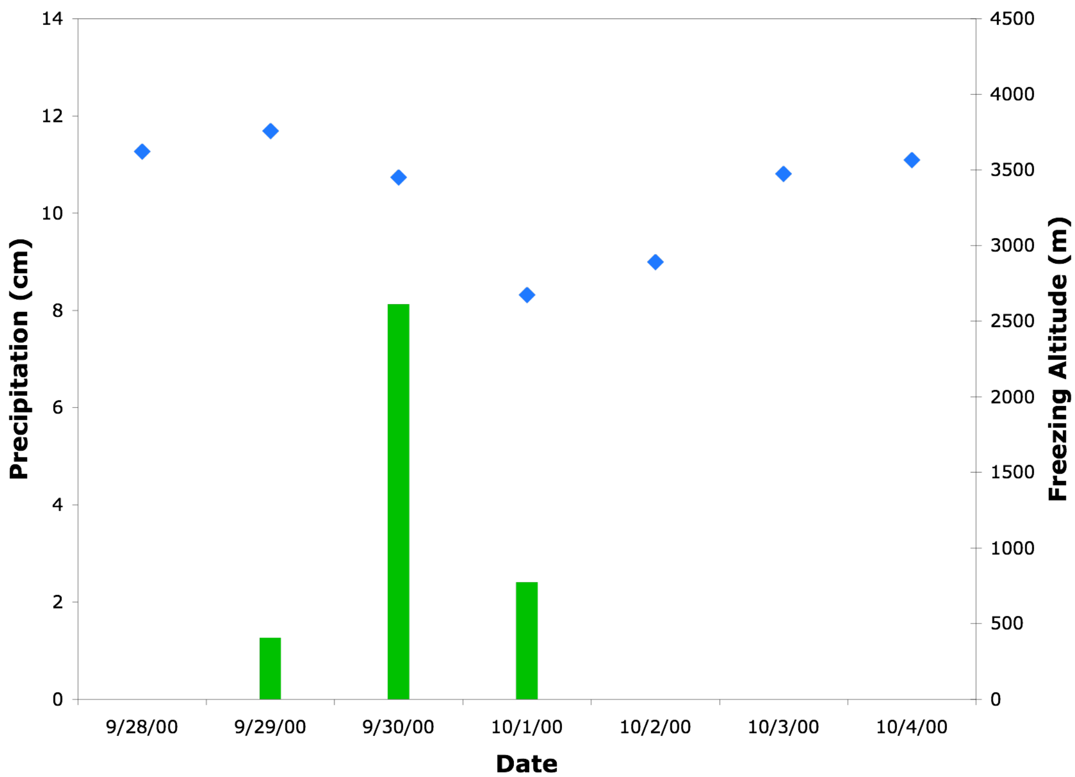

Figure 3.423 Although this storm produced similar amounts of antecedent precipitation as the 1961 storm event (Figure 3.422), and produced less precipitation on the day of the debris flow event, 7 debris flows are associated with this rain event. Green bars indicate daily precipitation in centimeters, while blue diamonds indicate daily mean freezing altitudes in meters.

Mount Rainier precipitation amounts for debris flow events were also variable. Again, precipitation amounts were examined for the 3 days prior to the debris flow, the debris flow event date, the 3-day window centered on the debris flow event date (Table 3.422), and the 7-day period around the debris flow event date. Mount Rainier precipitation totals were generally higher than those on Mount Hood. Additionally, all debris flow dates on Mount Rainier experienced some amount of precipitation, and only one date had notably less antecedent and same-day precipitation relative to other debris flow dates (Figure 3.423). Mount Rainier precipitation totals illustrate both the importance of antecedent precipitation (Figure 3.424) and the importance of same-day precipitation (Figure 3.425) to debris flow generation.

Table 3.422 Debris flow event dates at Mount Rainier, the number of debris flows occurring in Mount Rainier drainages on that date, and the cumulative precipitation (PRECIP) amounts recorded at the Paradise meteorological station for the 3 days prior to the debris flow event, the day of the debris flow event, and for the 3-day window centered on the debris flow event date. Dates with multiple debris flows are highlighted with bold font.

YEAR	MONTH	DATE	# OF DEBRIS FLOWS	3-DAY PRIOR PRECIP (CM)	DEBRIS FLOW DAY PRECIP (CM)	DEBRIS FLOW ± 1 DAY PRECIP (CM)
1986	10	26	1	5.94	6.73	12.72
1988	10	16	1	18.51	3.04	12.21
1989	11	9	1	16.05	1.34	11.09
1990	10	3	1	6.42	7.74	15.64
1991	11	5	1	12.14	0.17	10.54
1992	9	8	1	3.91	0.86	4.26
1992	9	20	1	0.35	1.17	1.95
2003	10	20	1	3.09	6.85	10.26
2005	**9**	**29**	**4**	**2.28**	**13.05**	**17.78**
2006	**11**	**6**	**6**	**39.85**	**16.76**	**45.46**

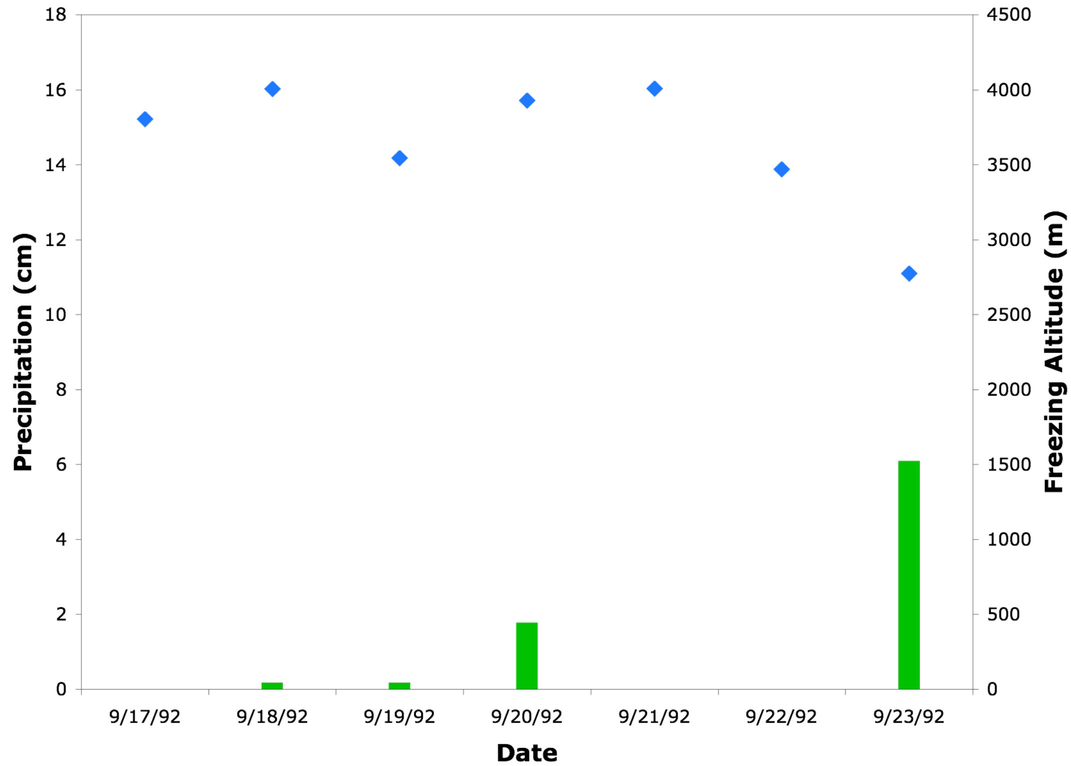

Figure 3.424 Although this storm event – associated with zonal flow – had very little antecedent precipitation and same-day precipitation amounts that are unimpressive relative to precipitation totals associated with other debris flow events, the conditions nonetheless produced a debris flow. Green bars indicate daily precipitation in centimeters, while blue diamonds indicate daily mean freezing altitudes in meters.

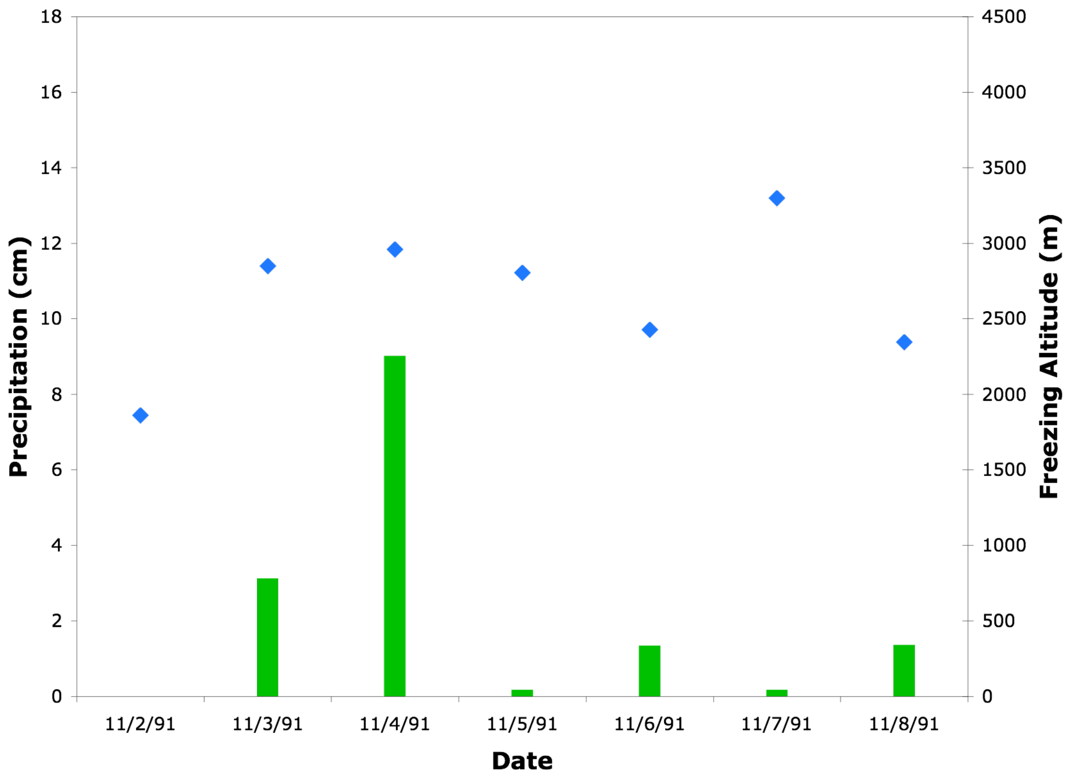

Figure 3.425 The November 1991 debris flow event illustrates how antecedent precipitation may be an important factor in the absence of heavy same-day precipitation. This rain event, associated with a broad trough, produced more than 12 cm of antecedent precipitation, though less than one half of a centimeter precipitation on the day of the debris flow. Green bars indicate daily precipitation in centimeters, while blue diamonds indicate daily mean freezing altitudes in meters.

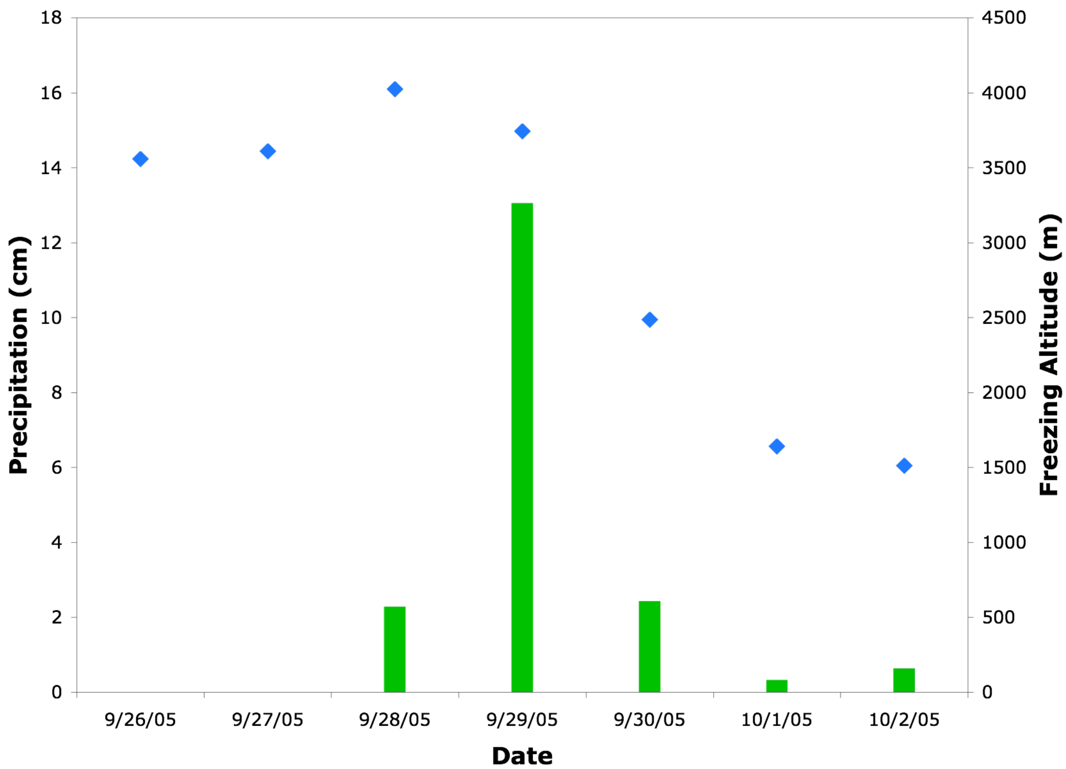

Figure 3.426 Contrary to the November 1991 debris flow event, the September 2005 debris flows were associated with very little antecedent precipitation, but heavy same-day (>13 cm) precipitation. This rain event is linked with zonal flow and the resulting debris flows on Mount Rainier occurred in four drainages.

3.43 Orographic Enhancement

Mount Hood orographic enhancement values, calculated between Three Lynx and Government Camp, range from 0.7 to 2.0 (Figure 3.431) on dates coinciding with debris flows. Where data are available, the relationship between orographic enhancement values and both total precipitation and number of linked debris flows is variable (Table 3.431). Further, there appears to be little or no relation between enhancement values and upper level flow patterns (Table 3.432), though data dropouts yield inconclusive results for 3 of the 10 debris flow dates.

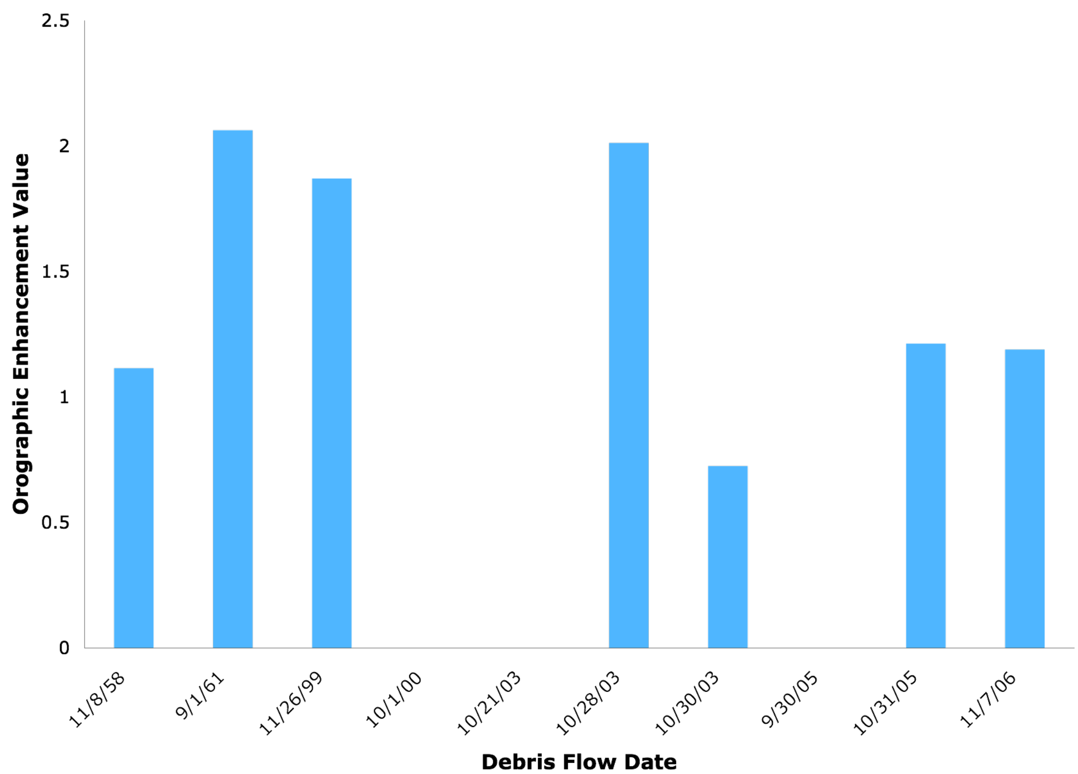

Figure 3.431 Orographic enhancement values were calculated by dividing the precipitation at Government Camp (1213m) by the precipitation at Three Lynx (341m). Three Lynx data were missing for 9/30/2005.

Table 3.431 The enhancement value for days producing multiple debris flows (highlighted in bold font) varies. These same dates are also associated with variable total precipitation for the three-day window.

YEAR	MONTH	DATE	# OF DEBRIS FLOWS	GOVT. CAMP 3-DAY PRECIPITATION (CM)	ENHANCEMENT VALUE
1958	11	8	1	7.95	1.1
1961	9	1	1	13.1	2.0
1999	11	26	1	13.58	1.8
2000	**10**	**1**	**7**	**10.54**	
2003	10	21	1	1.52	
2003	**10**	**28**	**2**	**5.25**	**2.0**
2003	10	30	1	1.16	0.7
2005	**9**	**30**	**5**	**7.67**	
2005	10	31	1	11.02	1.2
2006	**11**	**7**	**6**	**17.85**	**1.1**

Table 3.432 Mount Hood enhancement values cannot be clearly attributed to flow regimes. Zonal and meridional flow both experience relatively high and low enhancement values. Data dropouts produce inconclusive results.

YEAR	MONTH	DATE	FLOW PATTERN	ENHANCEMENT VALUE
1958	11	8	Zonal	1.1
1961	9	1	Zonal	2.0
1999	11	26	Zonal	1.8
2000	10	1	Meridional	
2003	10	21	Meridional	
2003	10	28	Meridional	2.0
2003	10	30	Meridional	0.7
2005	9	30	Zonal	
2005	10	31	Zonal	1.2
2006	11	7	Meridional	1.1

Mount Rainier enhancement values, calculated between Longmire (841m) and Paradise (1643m), range from approximately 0.7 to 2.8 (Figure 3.432) and do not appear to be linked with the precipitation at Paradise or the number of debris flows that the conditions produced (Table 3.433). As with Mount Hood, there is no significant correlation between the precipitation at Longmire and precipitation at Paradise for the debris flow dates. Enhancement values for debris flow dates between Longmire and Paradise also appear to have a variable relationship to the upper air flow patterns (Table 3.434). Although the two dates with the highest enhancement values are associated with the highest mean daily freezing levels, the lowest orographic enhancement values are still associated with free air freezing levels that should produce rainfall at Paradise.

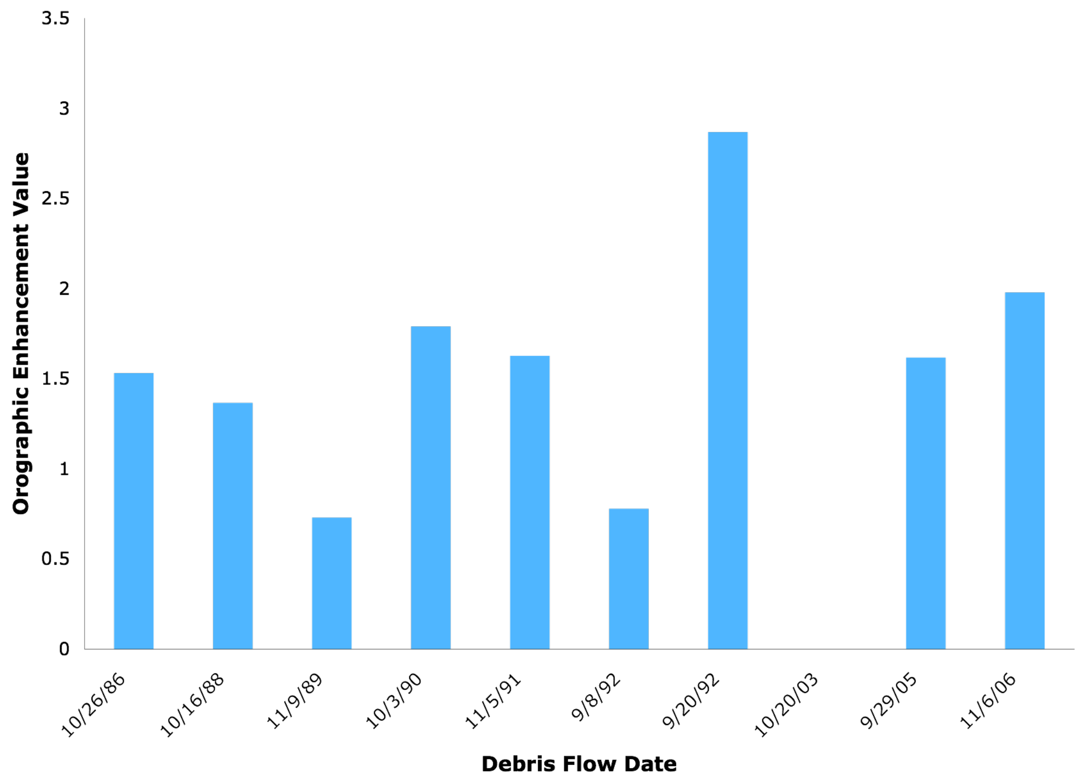

Figure 3.432 Orographic enhancement values between Longmire and Paradise. Data were missing at Longmire on 10/20/2003.

Table 3.433 High enhancement values do not necessarily produce multiple debris flows.

YEAR	MONTH	DATE	# OF DEBRIS FLOWS	PARADISE 3-DAY PRECIPITATION (CM)	ENHANCEMENT VALUE
1986	10	26	1	12.72	1.5
1988	10	16	1	12.21	1.3
1989	11	9	1	11.09	0.7
1990	10	3	1	15.64	1.7
1991	11	5	1	10.64	1.6
1992	9	8	1	4.26	0.7
1992	9	20	1	1.95	2.8
2003	10	20	1	10.26	
2005	**9**	**29**	**4**	**17.78**	**1.6**
2006	**11**	**6**	**6**	**45.46**	**1.9**

Table 3.434 Relationships between geostrophic flow and enhancement values at Mount Rainier on debris flow dates.

YEAR	MONTH	DATE	FLOW PATTERN	ENHANCEMENT VALUE
1986	10	26	Meridional	1.5
1988	10	16	Meridional	1.3
1989	11	9	Meridional	0.7
1990	10	3	Zonal	1.7
1991	11	5	Meridional	1.6
1992	9	8	Zonal	0.7
1992	9	20	Zonal	2.8
2003	10	20	Meridional	
2005	9	29	Zonal	1.6
2006	11	6	Meridional	1.9

3.5 Moisture Transport

Reviewing 850 mb integrated moisture flux composites for the dates of the debris flows shows the transport vectors and intensity of atmospheric water vapor (Figure 3.51). Integrated water vapor (IWV) transport for debris flow event dates on Mount Hood were typically between 300-400 kg m^{-1} s^{-1}, though one date had values of 0-100 kg m^{-1} s^{-1}, three dates saw values of 400-500 kg m^{-1} s^{-1} and the November 2006 event experienced an integrated moisture flux of 700-800 kg m^{-1} s^{-1} (Table 3.51). IWV transports for Mount Rainier debris flow event dates range from 200 to 900 kg m^{-1} s^{-1}, with the highest values again being associated with the November 2006 Pineapple Express event (Table 3.52). Often the IWV image from the day prior to the debris flow shows a plume with a stronger flux off of the coast, which then weakens as it makes landfall (Figures 3.52 and 3.53). Virtually all debris flow dates are associated with a plume of integrated moisture flux that is high relative to the surrounding region, and the center of these plumes typically has a flux approximately 100-200 kg m^{-1} s^{-1}

higher than the portion of the plume impacting the mountains, which is recorded in Tables 3.51 and 3.52. Further, the majority of these plumes are AR-*like* in that they are 'longer than they are wide' regions of strong moisture flux.

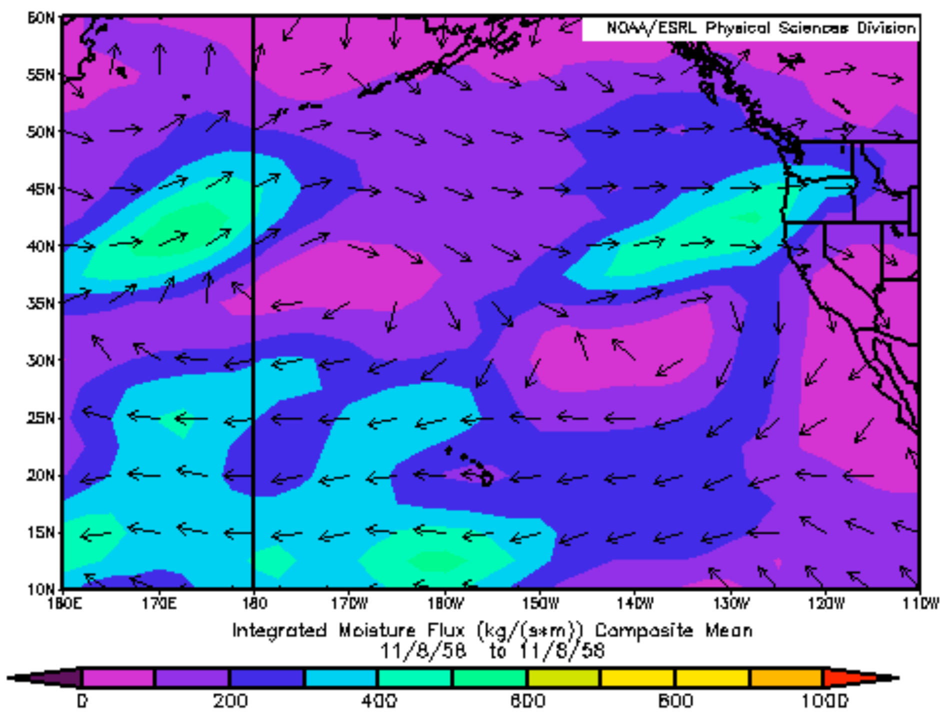

Figure 3.51 A plume of integrated moisture flux of ~300-400 kg m^{-1} s^{-1} impacts the Northwest coast on November 8, 1958 when a debris flow event occurred on Mount Hood.

Table 3.51 Mount Hood debris flow associated integrated water vapor values.

YEAR	MONTH	DATE	# OF DEBRIS FLOWS	IWV (kg m^{-1} s^{-1})
1958	11	8	1	400-500
1961	9	1	1	300-400
1999	11	26	1	300-400
2000	10	1	7	300-400
2003	10	21	1	300-400
2003	10	28	2	400-500
2003	10	30	1	0-100
2005	9	30	5	400-500
2005	10	31	1	300-400
2006	11	7	6	700-800

Table 3.52 Mount Rainier debris flow dates and associated IWV.

YEAR	MONTH	DATE	# OF DEBRIS FLOWS	IWV (kg m^{-1} s^{-1})
1986	10	26	1	400-500
1988	10	16	1	500-600
1989	11	9	1	500-600
1990	10	3	1	300-400
1991	11	5	1	400-500
1992	9	8	1	200-300
1992	9	20	1	200-300
2003	10	20	1	500-600
2005	9	29	4	500-600
2006	11	6	6	800-900

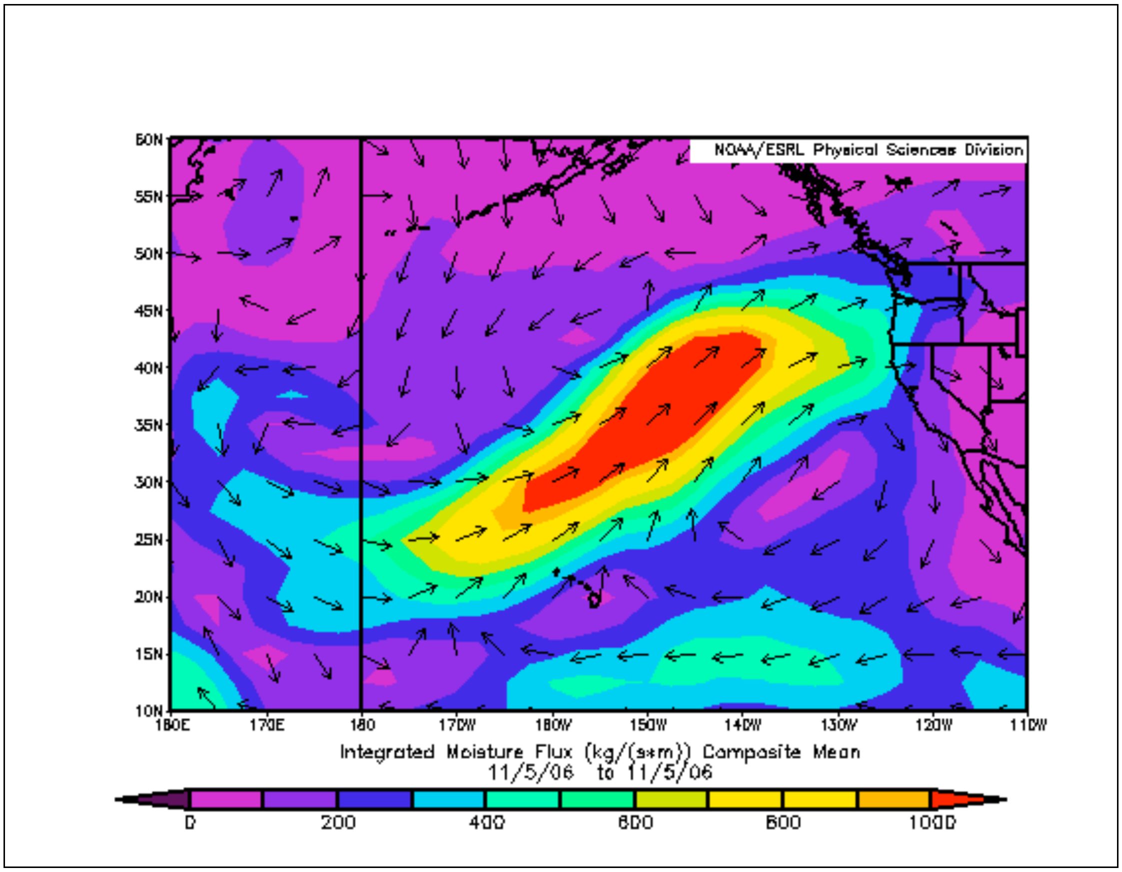

Figure 3.52 The day prior to the November 6, 2006 debris flows on Mount Rainier, an Atmospheric River (to which a Pineapple Express circulation was also attributed) moves toward the northwest coast, with a large and broad band of $\geq$1000 kg m^{-1} s^{-1} IWV flux.

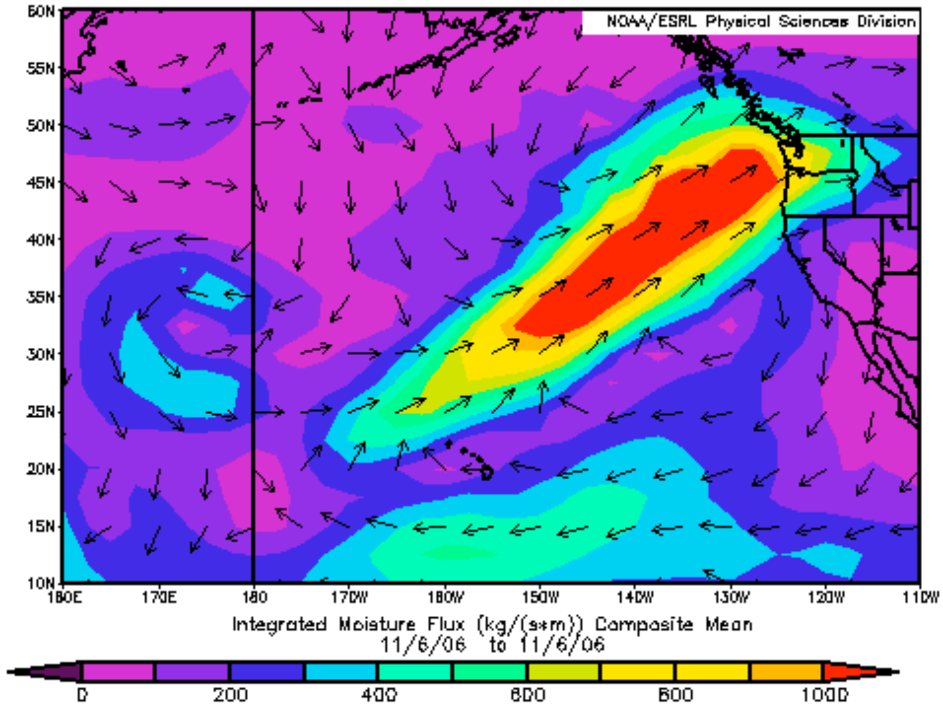

Figure 3.53 The AR-like plume makes landfall on November 6, having a narrowed and potentially weaker core.

3.6 Snow Water Equivalent

Mount Hood antecedent snow water equivalent (SWE) conditions ranged from 0 to 104 mm on the day prior to the recorded debris flow event date (Figure 3.61). These SWE values equate to snow depths of 0.0 to approximately 0.416 m. Of the dates in the debris flow record that contain multiple debris flows on one date, three have no antecedent snowpack and one date has only a trace amount of snow present at the SNOTEL site (Table 3.61).

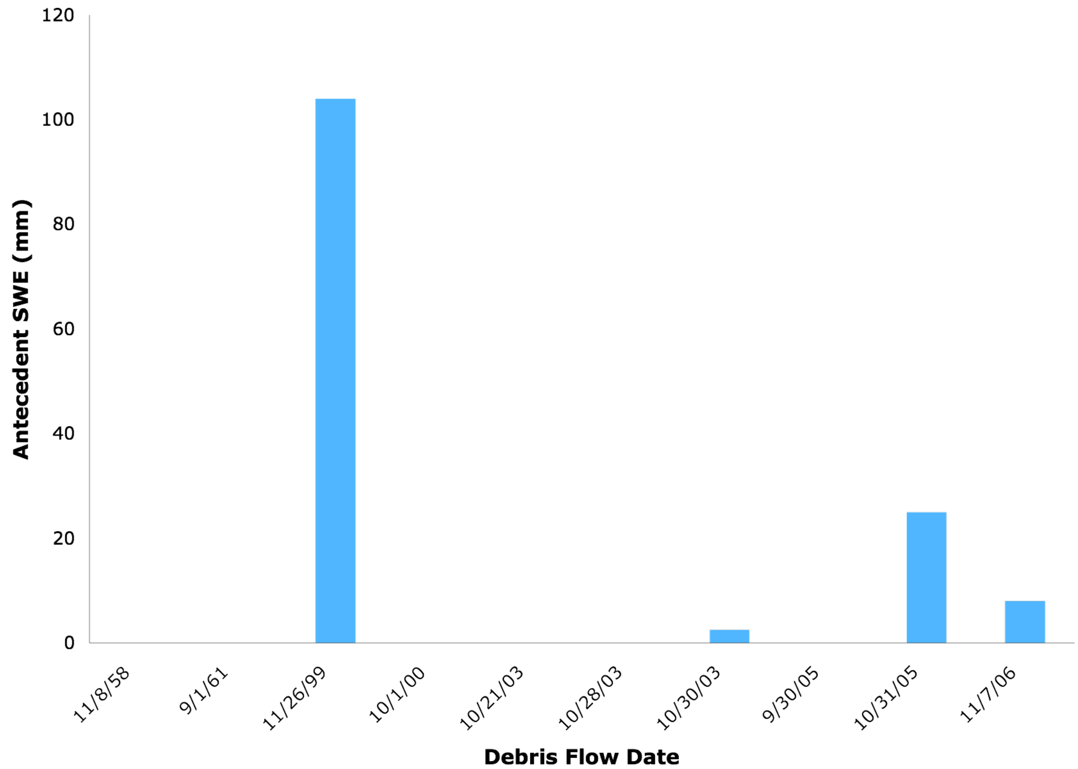

Figure 3.63 SWE values for the day prior to the debris flow events on Mount Hood.

Table 3.61 Dates associated with multiple debris flows, highlighted in bold font, are associated with low SWE values.

YEAR	MONTH	DATE	# OF DEBRIS FLOWS	0Z FL (M)	12Z FL (M)	SWE (MM)
1958	11	8	1	2760.1	3086.8	
1961	9	1	1	2254	1436.8	
1999	11	26	1	1258	2106.5	104
2000	**10**	**1**	**7**	**3035.8**	**3122**	**0**
2003	10	21	1	4494.8	4020.4	0
2003	**10**	**28**	**2**	**3904.3**	**3872.7**	**0**
2003	10	30	1	1033.9	1062.8	2.5
2005	**9**	**30**	**5**	**3709.9**	**3939.8**	**0**
2005	10	31	1	3008.5	3148.3	25
2006	**11**	**7**	**6**	**2811.7**	**3641.8**	**8**

Mount Rainier antecedent SWE for the day prior to debris flow events ranged from 0 to 102 mm (Figure 3.62). Unlike Mount Hood, Mount Rainier's two highest antecedent SWE dates were not associated with multiple flows, but were associated with only one flow event (Table 3.62). The dates associated with multiple flows on Mount Rainier had no antecedent SWE.

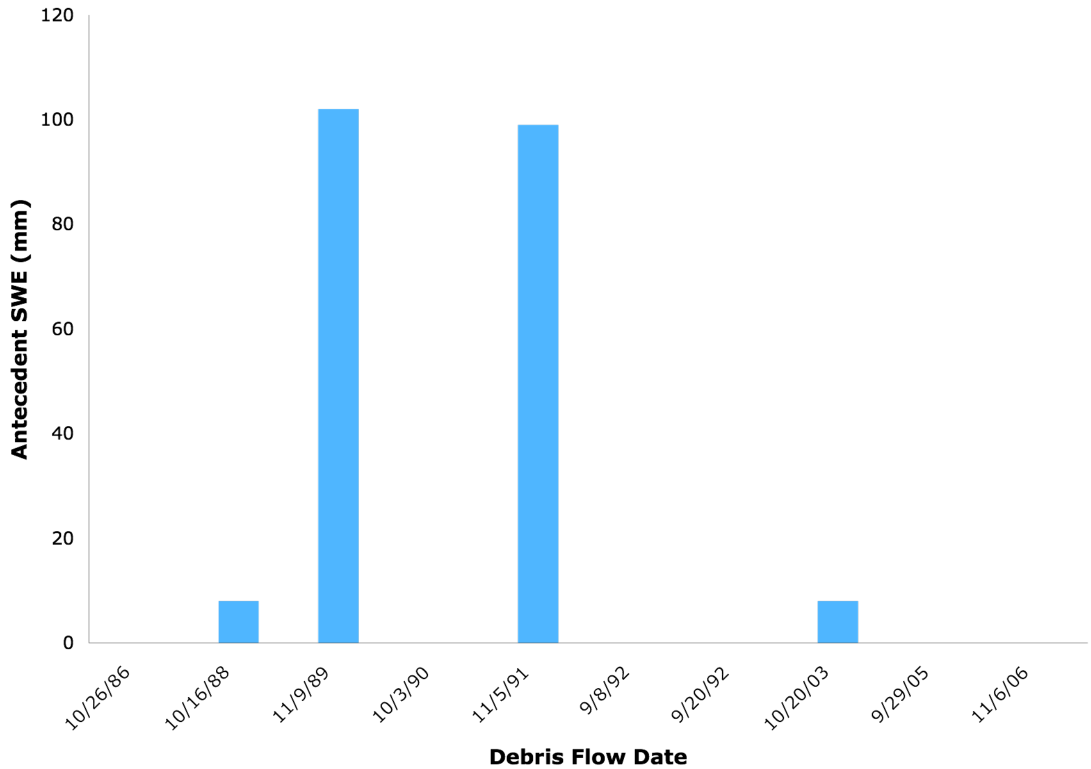

Figure 3.64 SWE values for the day prior to debris flow event dates on Mount Rainier.

Table 3.62 Dates associated with multiple debris flows, highlighted in bold font, are associated with warm temperatures and no antecedent SWE.

YEAR	MONTH	DATE	# OF DEBRIS FLOWS	0Z FL (M)	12Z FL (M)	SWE (MM)
1986	10	26	1	2225.5	3095.9	0
1988	10	16	1	2344.3	3204.3	8
1989	11	9	1	1802.5	3052.2	102
1990	10	3	1	3141.7	2758.2	0
1991	11	5	1	2490.8	3117.2	99
1992	9	8	1	3771.8	2853.8	0
1992	9	20	1	3877	3981.1	0
2003	10	20	1		3388.7	8
2005	**9**	**29**	**4**	**3774.8**	**3710.9**	**0**
2006	**11**	**6**	**6**	**2892.5**	**3466.8**	**0**

Chapter 5: Discussion

5.1 Relating PE/AR Events to Debris Flows

Cross-referencing a catalogue of combined PE and AR events with a catalogue of debris flow events suggested that many of the debris flow event dates on both mountains are the result of processes or triggering mechanisms that are not PE/AR related, that those dates that are PE/AR related appear more frequently in the later record, and that the PE/AR debris flow dates appear more apt to produce multiple debris flows. While it does appear from this study and others (e.g. Walder and Driedger, 1994) that Mount Hood and Mount Rainier debris flows can occur without precipitation, the catalogues of PE and AR events used for this initial analysis may not fully capture these atmospheric phenomena.

The PE catalogue is based on NCEP/NCAR reanalysis data, which is derived at a coarse 2.5°x2.5° spatial resolution, which will likely overlook any PE circulations that are not large enough – particularly wide enough – to be detected by this method (Dettinger, 2004). Further, the AR catalogue, while capable of detecting smaller, or narrower, incidents of poleward water vapor transport, is limited in its temporal resolution, only extending back to 1997. However, the higher spatial resolution of the AR catalogue (0.25°x0.25°) yields 301 dates on which an AR impacted the West Coast between 41.0°N and 52.5°N in only 8 years of record (Neiman et al., 2008) as compared to 382 dates that were classified as having a PE impact the west coast between 30°N and 52.5°N over 58 years (M. Dettinger, personal communication). These resolution discrepancies may produce the apparent trend in more frequent

PE/AR events in the later record, and may also result in some events – particularly PE events – being omitted from the record.

Moreover, the integrated water vapor (IWV) transport metrics used for classifying PE and AR events do not capture all instances of atmospheric moisture plumes. Dettinger (2004) only captures days where the average IWV transport averaged 500 kg $m^{-1}s^{-1}$ and Neiman et al. (2008) only catalogues dates where the SSM/I plumes were >2000km in length, <1000km in width, and had IWV values >2cm. These thresholds exclude less strong events that, despite their reduced intensity, may be associated with rain-related debris flows.

Lastly, it should be noted that the debris flow records for Mount Hood and Mount Rainier are incomplete. Additionally, for those portions of the debris flow records that are complete, it is assumed that the records are accurate. This assumption may result in significantly different results for virtually all analysis in this project if it does not hold true. Yet, these catalogues are, to the author's knowledge, the best and only compiled catalogues of all debris flow events on the mountains.

Given the limitations of the data resolution and the technological limitations to improving this obstacle and the improbability of retroactively recording debris flow events, this analysis could potentially be improved upon by expanding the PE and AR indices to include a more liberal classification scheme.

5.2 Exploring Meteorological Parameters

This study has found debris flows to be associated with variable atmospheric conditions. Upper airflow patterns range from strongly zonal to strongly meridional, and bring southwesterly winds from deep troughs as well as northwesterlies from weak ridges. These flow patterns drive many of the other meteorological parameters explored in this work, and yet they prove to be as variable as the weather.

As a driving mechanism, it is expected that steering winds would affect storm temperature – with southwesterly winds being generally warmer than zonal or northwesterly winds. For debris flow dates, this does appear to hold true and in instances where it does not, other variables such as the time of year, the depth of the trough, or variation in surface wind direction may prove to be confounding factors. Regardless of the origin of the air mass or other confounding variables, this study has shown that rain-related debris flows are generally associated with significantly warm temperatures. The freezing altitudes associated with these wet season debris flows suggest that precipitation on nearly all of these dates fell as rain at the altitude at which debris flow initiation sites lie (~1800m).

Although precipitation may be falling as rain, the precipitation amounts associated with debris flows – both antecedent and same-day – are variable. Higher amounts of precipitation are not correlated with increased numbers of debris flows, nor are they correlated with particular patterns of geostrophic airflow or atmospheric moisture plumes. However, precipitation data were acquired at meteorological stations at lower elevations than the debris flow initiation sites and this work suggests that orographic enhancement may play an ancillary role in debris flow generation. Debris flows occur on days that experience significant orographic enhancement between high and low elevation sites, as well as on days with lower amounts of precipitation recorded at higher elevation; however, in nearly all cases for which data were available, the higher elevation sites received up to twice as much rainfall as the lower elevation sites.

Further, this work does not show conclusive evidence of a correlation between orographic enhancement values and the atmospheric flow regime, the free air freezing levels, or the atmospheric integrated moisture flux. Although orographic enhancement values were highest at Rainier on days with zonal flow regimes, on of the lowest values was also associated with a zonal flow pattern. Similarly, the highest enhancement value at Mount Rainier (2.8) was associated with relatively low IWV (200-300 kg $m^{-1}s^{-1}$), while the next highest enhancement value (1.9) was associated with high IWV (800-900 kg $m^{-1}s^{-1}$). Interestingly, at Mount Hood, the highest enhancement values (both 2.0) were associated with both zonal and meridional flow, and with moderate IWV (300-400 kg $m^{-1}s^{-1}$ and 300-400 kg $m^{-1}s^{-1}$respectively).

For both the precipitation and orographic enhancement analysis, potential errors include attribution of the total daily precipitation to a single calendar date, rather than apportioning it to the date in which it fell. This potential error is a result of the 0800 PST reporting time of the meteorological stations, which report the amount of precipitation that fell in the previous 24 hours – the result being that without hourly data analysis, the rainfall may be attributed to the incorrect calendar date. This may be a possible explanation for the unusual precipitation pattern associated with the October 21, 2003 Mount Hood debris flow (Figure 3.421). Using a three-day window centered on the debris flow date for the orographic enhancement analysis is an attempt to mitigate this potential error.

This work does show a connection between atmospheric moisture plumes and debris flow events. For all rain-related debris flow events with the exception of one (Mount Hood, October 30, 2003), a plume of high integrated moisture flux exists off of the Northwest coast the day prior to the event and makes landfall on the day of the debris flow event. In the case of October 30, 2003, a plume exists off of the coast 2 days prior and makes land fall on the day prior to the debris flow. The presence of these plumes supports the need for exploration beyond the established indices, as has been presented. Additionally, it suggests the need for new work investigating the potential for alternate methodologies of capturing these events.

In addition to finding atmospheric moisture similarities across all debris flow dates, antecedent snowpack conditions were found to be relatively similar for all debris flow dates. In all instances, the snowpack was non-exisistent or negligible. Snowpack melting is a primary source of soil-moisture (e.g. Manabe and Wetherald, 1986) and may provide a supplemental water source for debris flow generation. However, the simple approach undertaken here of examining solely the antecedent snowpack conditions does not provide a complete quantification of the importance of snowpack – or lack thereof – to debris flow processes. Ideally, a surface energy balance calculation or a distributed model such as SnowModel (Liston and Elder, 2006) could be used to better quantify the amount of melting occurring on these dates and the subsequent amount of water being added to the system. However, even these models may be limited by the availability of input parameters.

Regardless of the meteorological parameter, the accuracy of the analysis performed in this study hinges on the accuracy of the debris flow catalogue. Although many of the recorded debris flow dates have been confirmed by field work, the precipitation record suggests that some of the recorded dates for debris flows may be inaccurate on those dates with negligible precipitation on the recorded debris flow date and on those days prior but significant precipitation in the days following the recorded date.

In addition to accurate debris flow records, this study could be further improved with an expanded debris flow record for other Cascade mountains, though such a record is difficult to compile given the remote locations of some of these flows. With only 20 established dates of rain-related debris flow occurrence, it may not be appropriate to make inferences of the effects of specific meteorological parameters at a broader scale.

Chapter 6: Conclusions

Questions concerning the effects of climate dynamics on natural hazards have come to the forefront of discussion as awareness of climate change increases. This study was motivated by a need for increased understanding of the interactions between climate and the natural hazard that debris flows present, and as a means towards understanding climatological trends the study addressed meteorological conditions. However, the atmosphere is a dynamic system with interconnections at both synoptic and micro scales, making it difficult to isolate the effects of the independent variables addressed in this work.

Despite the data limitations in this study, the most valuable conclusion drawn from this work is that the meteorological conditions associated with debris flow events cannot be neatly classified. It appears that several factors contribute to rain-related debris flow generation: temperature, precipitation and antecedent conditions, all of which are driven by larger scale atmospheric dynamics. The complex nature of debris flow mechanics, meteorology, and the small population of events examined here make it difficult to attribute any perceived recent increase in debris flow frequency to particular changes in meteorology or climate.

This study points to the need for additional research, for which the work presented here may serve as a foundation. As mentioned in chapter 5, extensions of this study may include a re-analysis of Atmospheric River characterization and classification, and a quantification of the effects of snowpack on debris flow initiation which may include the development of snowpack depth or heterogeneity thresholds (e.g. Singh et al., 1997). Additionally, future research may attempt to establish rainfall thresholds for debris flow initiation as has been done in the Dolomites (Bacchini and Zannoni, 2003) and in doing so it may be beneficial to explore other datasets not used here, such as AgriMet – a network of automated weather stations in the Pacific Northwest. The precipitation analysis in this work suggests that developing rainfall thresholds for debris flow generation and better understanding the effects of orographic enhancement, considering both precipitation totals precipitation intensity, may be a promising first step in establishing a means of forecasting debris flow generating conditions. Using storm characterization as a predictive tool for site-specific debris flow initiation may be possible when considering the meteorological conditions addressed in this work (rainfall, freezing temperatures, storm direction), but to develop and validate such methods would require a larger population of data points than was available to this study.

In addition to further exploration of these standalone variables, other future work may include exploring the relationship between rainwater input and the rapid drainage of englacial cavities specific to those Mount Hood and Mount Rainier glaciers whose drainages have experienced debris flows initiating near the glacier toe (Walder and Fountain, 1997), and the investigation of the role of the melting of ice cored moraines and ice lenses in the thermokarst-like environment (Krüger and Kjær, 2000) and how this de-icing is coupled with potential meteorological priming mechanisms or climatological trends.

Future studies, regardless of the research path they take, will benefit from a continued accurate and detailed cataloguing of debris flows on both Mount Hood, Mount Rainier, and where possible, other Cascade mountains.

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Appendices

Appendix A. Catalogue of PE circulations based on reanalysis data, courtesy Michael Dettinger, USGS.

Year	Month	Date	Transport Rate (kg/m/s)	Path Length (cells)	West Coast Crossing Latitude	Southern Limit Latitude
1948	1	20	501	13	52.5	25
1949	1	16	570	14	52.5	20
1949	10	29	546	16	52.5	25
1949	11	23	541	13	52.5	25
1950	11	1	600	17	40	22.5
1950	11	17	510	12	35	22.5
1950	11	20	590	9	37.5	22.5
1950	12	2	506	14	42.5	25
1950	12	3	592	9	37.5	20
1950	12	5	705	14	52.5	20
1950	12	6	615	11	42.5	20
1950	12	10	536	12	50	22.5
1951	2	5	530	13	37.5	22.5
1951	2	8	526	13	50	20
1951	12	28	591	8	35	20
1952	1	23	572	16	50	22.5
1952	3	23	693	21	52.5	25
1952	12	12	732	13	50	22.5
1953	1	1	538	14	40	20
1953	1	8	718	11	42.5	22.5
1953	1	9	688	9	40	20
1953	1	16	767	21	40	20
1953	1	22	589	13	42.5	25
1953	1	30	542	15	45	22.5
1953	12	19	629	11	40	22.5
1954	3	7	662	8	35	20
1954	3	8	763	8	37.5	20
1954	11	4	598	13	52.5	22.5
1954	11	13	527	12	50	22.5
1954	11	20	885	13	52.5	25
1955	11	7	618	12	52.5	25
1955	11	26	547	13	42.5	25
1955	12	19	629	8	37.5	20
1955	12	20	513	13	45	20
1955	12	21	920	11	45	20

Year	Month	Date	Transport Rate (kg/m/s)	Path Length (cells)	West Coast Crossing Latitude	Southern Limit Latitude
1956	1	13	548	12	42.5	20
1956	1	14	920	14	37.5	20
1956	1	18	529	16	52.5	20
1956	1	19	656	21	40	22.5
1956	1	20	551	19	52.5	20
1956	11	2	669	16	52.5	25
1956	12	9	817	17	47.5	22.5
1956	12	15	536	21	50	25
1956	12	25	514	12	52.5	25
1956	12	26	534	14	52.5	20
1957	1	12	560	6	32.5	20
1957	2	22	593	10	42.5	20
1957	2	24	560	9	40	20
1957	2	25	708	10	42.5	20
1957	2	26	609	9	40	20
1957	6	10	524	14	52.5	22.5
1958	1	21	533	16	52.5	20
1958	1	22	668	14	52.5	20
1958	2	17	512	13	50	20
1958	2	18	576	10	35	25
1958	2	21	556	16	50	25
1958	3	20	661	11	40	22.5
1958	3	21	526	10	30	25
1958	12	1	580	9	45	25
1959	1	15	665	12	45	20
1959	1	16	505	11	45	25
1959	2	14	519	9	40	20
1959	2	15	859	13	42.5	22.5
1959	2	16	821	9	30	25
1959	11	22	747	17	45	25
1960	1	28	618	10	42.5	20
1960	1	29	542	11	45	25
1960	2	5	602	13	50	20
1960	2	6	501	9	45	25
1960	12	12	604	11	47.5	25
1961	1	10	503	12	47.5	22.5
1961	1	15	523	11	50	25
1961	2	1	517	12	47.5	20
1961	2	4	586	13	50	20
1961	2	5	511	11	47.5	22.5

Year	Month	Date	Transport Rate (kg/m/s)	Path Length (cells)	West Coast Crossing Latitude	Southern Limit Latitude
1961	10	13	672	12	52.5	25
1961	11	25	533	6	32.5	20
1962	1	4	600	12	52.5	25
1962	1	7	648	19	52.5	22.5
1962	2	9	626	7	35	25
1962	10	27	638	14	52.5	25
1963	1	30	826	8	37.5	20
1963	1	31	861	8	37.5	20
1963	2	1	826	12	35	20
1963	2	2	794	10	42.5	20
1963	2	3	690	11	47.5	22.5
1963	2	4	548	21	50	25
1963	2	6	531	13	50	20
1963	3	27	578	7	35	20
1963	11	24	638	17	52.5	20
1963	11	25	587	14	45	25
1963	12	22	727	14	52.5	22.5
1963	12	24	537	10	47.5	25
1964	12	21	627	10	42.5	20
1964	12	22	792	13	35	20
1965	1	12	520	14	52.5	22.5
1965	10	20	500	13	52.5	22.5
1965	11	12	507	9	42.5	22.5
1965	11	15	516	6	32.5	20
1965	11	22	543	6	30	20
1965	11	23	657	6	32.5	20
1966	3	29	520	12	52.5	25
1966	12	4	691	21	32.5	22.5
1967	1	26	521	12	40	25
1967	2	2	569	21	47.5	25
1967	2	8	543	16	52.5	22.5
1967	3	16	544	7	35	20
1968	1	13	590	13	50	20
1968	1	14	595	10	40	25
1968	1	17	562	14	50	20
1968	1	18	625	12	47.5	20
1968	1	19	520	12	47.5	20
1968	1	20	551	13	50	20
1968	1	21	570	15	50	20
1968	1	22	898	14	52.5	20

Year	Month	Date	Transport Rate (kg/m/s)	Path Length (cells)	West Coast Crossing Latitude	Southern Limit Latitude
1968	2	17	699	11	42.5	20
1968	2	18	513	9	40	20
1968	2	20	628	18	40	22.5
1968	2	21	545	16	42.5	25
1968	11	7	692	16	45	22.5
1968	11	8	599	16	45	22.5
1969	1	3	597	14	52.5	20
1969	1	4	524	14	45	25
1969	1	11	525	10	35	20
1969	1	12	599	7	35	20
1969	1	13	515	6	32.5	20
1969	1	18	590	8	35	20
1969	1	24	541	9	35	20
1969	1	25	503	6	32.5	20
1969	6	1	512	14	52.5	22.5
1969	12	20	590	10	42.5	25
1970	1	8	542	9	37.5	25
1970	1	13	514	21	45	22.5
1970	1	14	604	15	35	20
1970	1	15	631	13	40	22.5
1970	1	17	510	19	37.5	22.5
1970	1	18	592	17	47.5	25
1970	1	21	534	10	45	22.5
1970	1	22	622	11	45	22.5
1970	2	15	558	10	42.5	20
1970	11	22	646	10	42.5	20
1970	11	23	630	10	42.5	20
1970	11	24	506	10	42.5	20
1971	1	15	615	10	42.5	20
1971	1	16	716	12	47.5	20
1971	1	17	746	12	45	20
1971	1	18	590	12	42.5	20
1971	1	29	589	15	52.5	25
1971	1	30	576	15	50	25
1971	3	22	546	13	40	20
1972	3	9	531	15	50	25
1972	3	14	599	15	52.5	25
1972	10	31	579	11	50	25
1972	12	16	672	10	42.5	20
1972	12	19	557	15	40	25

Year	Month	Date	Transport Rate (kg/m/s)	Path Length (cells)	West Coast Crossing Latitude	Southern Limit Latitude
1972	12	20	633	12	42.5	25
1973	2	15	560	13	50	25
1973	11	8	538	9	40	22.5
1973	11	11	526	9	37.5	25
1973	12	15	547	9	45	25
1974	1	14	717	11	45	20
1974	1	15	964	11	42.5	25
1974	1	16	629	9	37.5	25
1974	1	17	550	20	35	25
1974	3	14	563	12	40	25
1975	1	17	542	19	47.5	25
1975	12	23	515	13	45	22.5
1975	12	25	567	11	50	25
1975	12	27	566	14	52.5	22.5
1976	1	26	683	14	52.5	20
1976	1	27	514	12	50	22.5
1977	1	16	695	14	52.5	20
1977	1	17	688	14	52.5	20
1977	2	10	505	17	47.5	20
1977	11	23	590	15	42.5	20
1977	11	24	654	14	42.5	20
1977	11	25	531	10	47.5	25
1977	11	27	510	20	45	22.5
1977	12	26	679	6	32.5	20
1977	12	27	657	6	32.5	20
1978	1	7	500	13	50	20
1978	11	27	556	16	52.5	22.5
1979	1	9	514	13	40	20
1979	1	10	650	13	40	20
1979	2	12	917	9	40	20
1979	2	13	634	7	35	22.5
1979	3	5	511	13	50	22.5
1979	4	25	592	8	35	20
1979	12	16	564	19	45	25
1979	12	17	708	11	45	20
1980	1	11	947	18	32.5	20
1980	2	1	539	11	45	20
1980	2	14	571	12	30	20
1980	2	15	737	7	35	20
1980	11	3	615	12	50	25

Year	Month	Date	Transport Rate (kg/m/s)	Path Length (cells)	West Coast Crossing Latitude	Southern Limit Latitude
1980	12	10	680	14	52.5	25
1980	12	24	641	11	45	20
1980	12	25	797	10	45	22.5
1981	1	18	641	13	50	20
1981	1	19	633	20	50	25
1981	1	21	586	9	40	20
1981	2	12	657	11	45	20
1981	2	13	618	8	40	22.5
1981	2	14	722	19	42.5	20
1981	2	15	761	16	47.5	20
1981	2	17	547	16	42.5	22.5
1981	2	18	559	11	42.5	25
1981	11	15	543	9	40	20
1982	1	7	604	18	50	22.5
1982	1	8	603	15	52.5	25
1982	1	24	505	13	42.5	22.5
1982	2	12	700	12	47.5	20
1982	2	13	741	11	45	20
1982	2	17	525	21	50	22.5
1982	2	18	671	13	47.5	22.5
1982	2	19	534	13	40	20
1982	4	9	557	7	35	20
1982	4	10	810	7	35	20
1982	4	11	512	7	32.5	20
1982	10	28	565	13	50	20
1983	1	2	537	20	42.5	22.5
1983	1	6	635	21	40	25
1983	1	25	584	10	42.5	20
1983	1	26	733	10	40	25
1983	2	10	629	13	50	25
1983	2	11	537	12	52.5	25
1983	2	17	642	11	45	25
1983	2	28	545	8	35	25
1983	3	1	557	6	35	25
1983	3	8	724	12	45	25
1983	12	23	599	11	37.5	20
1983	12	24	689	9	40	20
1983	12	28	521	13	45	25
1983	12	29	542	12	45	25
1983	12	31	592	18	50	25

Year	Month	Date	Transport Rate (kg/m/s)	Path Length (cells)	West Coast Crossing Latitude	Southern Limit Latitude
1984	1	1	703	14	52.5	20
1984	1	2	534	14	52.5	20
1984	1	3	687	17	52.5	22.5
1984	1	4	580	13	47.5	22.5
1984	1	26	764	19	52.5	20
1984	1	27	540	18	50	25
1984	3	24	620	21	52.5	22.5
1985	12	1	535	9	37.5	25
1986	1	17	595	14	45	20
1986	1	18	734	12	47.5	20
1986	1	29	582	9	40	20
1986	2	13	548	8	37.5	20
1986	2	14	681	9	40	20
1986	2	16	601	13	35	20
1986	2	17	712	10	37.5	20
1986	2	18	645	9	35	20
1986	2	22	645	18	45	22.5
1986	2	23	780	16	45	25
1987	2	1	574	11	42.5	22.5
1987	3	3	574	11	45	20
1987	3	4	857	13	50	20
1987	3	5	625	7	35	20
1988	1	3	542	8	37.5	20
1988	1	14	575	9	45	25
1988	12	10	549	14	52.5	25
1989	3	5	578	9	40	22.5
1989	12	4	512	10	47.5	25
1990	11	9	632	17	45	25
1990	11	11	545	11	50	25
1990	11	12	524	11	47.5	22.5
1991	2	1	588	19	52.5	25
1991	2	3	520	11	45	20
1991	2	12	578	17	45	25
1991	2	18	503	14	50	25
1991	2	27	505	9	30	22.5
1991	3	3	557	11	40	22.5
1991	3	4	511	10	37.5	22.5
1991	10	18	541	18	52.5	25
1992	1	23	567	13	50	25
1992	1	29	616	12	47.5	20

Year	Month	Date	Transport Rate (kg/m/s)	Path Length (cells)	West Coast Crossing Latitude	Southern Limit Latitude
1992	1	30	560	11	45	20
1993	1	5	520	6	32.5	20
1993	1	7	561	14	30	20
1993	2	26	527	17	52.5	25
1993	3	16	548	9	40	20
1994	1	11	515	16	52.5	25
1995	1	9	525	12	42.5	22.5
1995	1	13	523	10	40	25
1995	1	27	554	21	37.5	25
1995	1	28	683	21	42.5	25
1995	1	29	553	11	42.5	20
1995	1	30	681	14	52.5	20
1995	1	31	673	10	45	22.5
1995	2	17	602	19	47.5	25
1995	2	18	694	13	50	20
1995	2	19	515	12	47.5	20
1995	3	9	589	10	35	22.5
1995	3	10	622	8	35	25
1995	4	30	525	10	35	20
1995	12	9	614	21	47.5	25
1995	12	29	698	16	40	22.5
1996	1	6	564	13	47.5	25
1996	1	30	557	8	35	22.5
1996	2	2	592	10	35	20
1996	2	3	549	11	40	22.5
1996	2	5	730	15	47.5	20
1996	2	6	636	10	45	25
1996	4	5	614	14	52.5	20
1996	11	10	528	13	52.5	25
1996	11	18	752	12	40	20
1996	11	19	719	9	40	20
1996	11	26	529	14	52.5	25
1996	12	9	522	7	35	25
1996	12	24	511	12	45	25
1996	12	28	654	12	42.5	25
1996	12	29	673	13	40	25
1996	12	30	755	20	35	25
1996	12	31	856	9	40	20
1997	1	1	899	9	40	20
1997	1	17	616	11	45	22.5

Year	Month	Date	Transport Rate (kg/m/s)	Path Length (cells)	West Coast Crossing Latitude	Southern Limit Latitude
1997	1	28	550	15	47.5	20
1997	1	29	954	14	52.5	20
1997	1	30	636	15	50	22.5
1997	3	19	552	9	42.5	25
1997	12	13	631	14	52.5	20
1997	12	28	591	17	50	22.5
1998	1	17	591	12	40	22.5
1998	1	22	555	16	50	25
1998	2	2	602	8	35	25
1998	2	5	541	10	37.5	22.5
1998	2	11	534	14	40	20
1998	3	22	675	9	40	20
1998	11	12	552	13	45	25
1998	12	28	652	15	42.5	25
1999	11	11	570	10	42.5	20
1999	11	12	550	9	45	25
1999	12	14	675	19	45	22.5
2000	1	18	582	7	35	20
2000	1	23	543	8	37.5	20
2000	1	24	682	7	35	20
2000	9	29	608	18	45	25
2000	11	2	520	18	52.5	22.5
2001	11	14	515	10	47.5	25
2001	12	29	563	17	30	25
2001	12	31	502	10	40	20
2002	1	1	544	9	40	20
2002	1	6	707	9	42.5	22.5
2002	1	7	719	10	42.5	25
2002	4	9	549	21	37.5	25
2002	4	12	626	18	42.5	20
2003	1	1	543	12	50	22.5
2003	1	2	582	10	45	22.5
2003	1	22	586	10	42.5	20
2003	1	24	527	12	47.5	20
2003	1	25	694	15	50	22.5
2003	1	26	514	10	45	22.5
2003	1	30	580	12	42.5	22.5
2003	10	17	561	10	47.5	25
2003	10	20	656	9	45	25
2003	12	4	505	8	40	22.5

Year	Month	Date	Transport Rate (kg/m/s)	Path Length (cells)	West Coast Crossing Latitude	Southern Limit Latitude
2004	1	5	529	12	45	20
2004	2	15	632	11	42.5	25
2004	2	16	549	7	37.5	22.5
2004	10	11	527	16	50	25
2004	11	6	532	15	47.5	25
2004	11	13	512	14	52.5	20
2004	11	14	526	11	47.5	25
2004	12	9	641	13	40	20
2004	12	10	744	10	47.5	25
2005	1	16	566	13	50	20
2005	1	17	768	13	50	20
2005	1	18	785	13	47.5	20
2005	1	19	701	12	47.5	20
2005	1	22	537	14	52.5	20
2005	1	23	507	13	52.5	22.5
2005	3	5	547	13	50	20
2005	3	26	570	12	47.5	20
2005	12	19	768	10	42.5	20
2005	12	20	592	15	50	22.5
2005	12	23	640	11	47.5	25
2006	2	26	509	12	47.5	20
2006	2	27	671	10	40	22.5
2006	11	5	705	16	47.5	20
2006	11	6	925	11	50	25
2006	11	15	578	10	47.5	25
2006	12	25	537	8	42.5	25
2006	12	31	553	19	50	22.5

Appendix B. Mount Hood debris flow catalogue provided by Tom DeRoo (USFS).

Year	Month	Drainage
1949	*?*	*White*
1958	8-Nov	Coe
1959	*September*	*White*
1959	*October*	*White*
1961	1-Sep	Ladd
1961	*September*	*White*
1966	*January*	*White*
1967	*January*	*White*
1968	*September*	*White*
1978	*August*	*Newton*
1980	25-Dec	Polallie
1981	*September*	*White*
1991	*November*	*Newton*
1995	*?*	*Newton*
1996	*?*	*Ladd*
1997	*October*	*Polallie*
1997	*?*	*Clark*
1998	*July*	*Newton*
1998	*September*	*White*
1999	26-Nov	Eliot
1999	26-Nov	Clark
2000	*January*	*Eliot*
2000	1-Oct	Newton
2000	1-Oct	Clark
2000	1-Oct	Eliot
2000	1-Oct	Sandy
2000	1-Oct	Muddy Fork
2000	1-Oct	Coe
2000	1-Oct	White
2002	14-Jun	Muddy Fork
2003	2-Sep	White
2003	21-Oct	Newton
2003	28-Oct	White
2003	28-Oct	Sandy
2003	30-Oct	Clark
2005	30-Sep	W. Compass
2005	30-Sep	Newton
2005	30-Sep	Clark
2005	30-Sep	White
2005	30-Sep	Sandy
2005	31-Oct	White
2006	7-Nov	White
2006	7-Nov	Clark
2006	7-Nov	Newton
2006	7-Nov	Eliot
2006	7-Nov	Ladd
2006	7-Nov	Sandy

Appendix C. Mount Rainier debris flow catalogue provided by Elizabeth Copeland.

Source(s)	Date	Year
OF 93-124	?	1926
OF 93-124	?	1932
OF 93-124	?	1934
OF 93-124	?	1955
OF 93-124	?	1961
93-4093	August	1967
93-4093	August	1967
OF 93-124	?	1968
Kennard		1968
93-4093		1970
93-4093		1971
93-4093		1992
Kennard	2-3 Oct	1947
93-4093		1967
93-4093		1979
93-4093		1981
93-4093	18 July	1985
93-4093	4 Sept	1986
Kennard	?	1986
93-4093	26 Oct	1986
93-4093		1986
93-4093	9 Aug	1987
93-4093	9 August	1987
93-4093	29 June	1987
93-4093	28 August	1987
93-4093	31 August	1987
93-4093	23 Sept	1987
93-4093	14 July	1988
93-4093	26 July	1988
93-4093	16 Oct	1988
93-4093	23 Sept	1989
93-4093	9 Nov	1989
93-4093	4 Aug	1990
93-4093	3 Oct	1990
93-4093	5 Nov	1991
93-4093	8 Sept	1992
93-4093	20 Sept	1992
Kennard		1993
Kennard		1994
Kennard		1995
Kennard		1996
Kennard		1997
Kennard		1998
Kennard		1999
Kennard		2000
Vallance 2002	14 Aug	2001
Kennard		2001
Kennard	Aug 14	2001

Source(s)	Date	Year
Kennard		2002
Kennard		2003
Kennard	Oct 20	2003
Kennard		2004
Kennard	29 Sept	2005
Kennard	29 Sept	2005
Kennard		2005
Kennard	29 Sept	2005
Kennard	5-7 Nov	2006
Fieldwork	5-7 Nov	2006
Fieldwork	5-7 Nov	2006
Fieldwork	5-7 Nov	2006
Fieldwork	5-7 Nov	2006
Fieldwork	5-7 Nov	2006

Appendix D. Tables showing the dates used for analysis of rain-related debris flows for both Mount Hood and Mount Rainier.

Table D1 List of rain-related debris flow dates for Mount Hood

YEAR	MONTH	DATE
1958	11	8
1961	9	1
1999	11	26
2000	10	1
2003	10	21
2003	10	28
2003	10	30
2005	9	30
2005	10	31
2006	11	7

Table D2 List of rain-related debris flow dates for Mount Rainier

YEAR	MONTH	DATE
1986	10	26
1988	10	16
1989	11	9
1990	10	3
1991	11	5
1992	9	8
1992	9	20
2003	10	20
2005	9	29
2006	11	6