The Sensitivity of Orographic Precipitation to Flow Direction:  
An Idealized Modeling Approach

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A thesis

submitted in partial fulfillment of the

requirements for the degree of

Master of Science

University of Washington

2015

Committee:

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Program Authorized to Offer Degree:

Atmospheric Sciences
A method is developed for forcing a full-physics, full-terrain model with an idealized, balanced atmosphere determined by an input sounding. The initialization technique is applied to investigate the sensitivity of orographic precipitation in Pacific Northwest terrain to wind direction under both barotropic and sheared flow conditions approximating an atmospheric river. The model results agree well with previous studies that considered typical conditions resulting in heavy precipitation, with the precipitation sensitivity to wind direction less than is estimated for similar deterministic cases. To explore the causes of sensitivity in the Olympic Mountains of western Washington State, additional experiments are carried out using modified terrain fields with smoothed or idealized Olympic Mountains, or with nearby orography removed. Model
simulations suggest that the sensitivity of Olympic Mountain precipitation to wind direction is more strongly modulated by the presence of surrounding orography than by the specific Olympic geometry.
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ACKNOWLEDGEMENTS

The author would like to thank his family for their endless support and unwavering love.
Chapter 1. INTRODUCTION

The geographical variation of the amplitude and distribution of orographic rain has substantial impacts on real-world applications such as streamflow prediction, hydropower generation, and flood warning. It is therefore important to thoroughly explore how varying incoming flows can impact the distribution of precipitation in real terrain and to explore the sensitivity of orographic precipitation to small variations in wind direction and other parameters. This is the goal of the present thesis.

The ascent of moist air over terrain is an important mechanism for precipitation formation, with topographic features greatly modulating the global distribution of rain and snow. A number of studies have examined the sensitivity of precipitation amounts and distribution to varying wind speed and directions, atmospheric stability, surface temperatures and freezing levels, model microphysics, and barrier geometry, among other parameters. While variations of these factors have been explored using models for idealized terrain, their effects on the distribution of precipitation over real three-dimensional terrain has received relatively little study.

Dry orographic flow has been examined through the use of linear theory (e.g., Scorer 1949), with some nonlinear aspects of flow, such as flow blocking and wave breaking, accurately modeled using analytic approaches (e.g., Smith 1980). Other studies have examined the impacts of moisture, including reducing the effective atmospheric stability (Fraser et al. 1973), and attenuating effective mountain drag (Barcilon et al. 1979). Lalas and Einaudi (1974) and Durran and Klemp (1982) extended the Brunt-Väisälä frequency $N$, an important linear parameter for dry mountain waves, to the moist case with the moist Brunt-Väisälä frequency, $N_m$. $N_m$ quantifies the stability of a saturated column to small vertical perturbations while accounting for virtual temperature corrections and latent heating, and is considered an important control on the behavior of moist mountain waves.

Recent modeling studies have considered two- or three-dimensional flows over idealized terrain, and investigated how precipitation varies for differing orography or upstream flow. Among the variables considered are terrain geometry (e.g., Rotunno and Ferretti 2001; Jiang 2003, 2006; Colle 2004, 2008; Miglietta and Rotunno 2005, 2006; Kirshbaum and Smith 2008;
Kunz and Wassermann 2011), atmospheric stability (e.g., Jiang 2003; Colle 2004, 2008; Reeves and Rotunno 2008; Kunz and Wassermann 2011), surface temperature or freezing level altitude (e.g., Colle 2004; Miglietta and Rotunno 2006; Kirshbaum and Smith 2008), wind speed (e.g., Jiang 2003; Colle 2004, 2008; Reeves and Rotunno 2008; Kunz and Wassermann 2011), humidity (e.g., Miglietta and Buzzi 2001; Reeves and Rotunno 2008; Kunz and Wassermann 2011), and model microphysics (e.g., Colle 2004; Miglietta and Rotunno 2006; Reeves and Rotunno 2008). These studies have revealed substantial sensitivities of the precipitation distribution to the characteristics of incoming flow. For moist flows, $N_m$ provides a strong control over whether flow moves around or over terrain and whether precipitation is stratiform or convective in nature. Freezing level and microphysical parameterizations play an especially important role in the distribution of precipitation due to the advection of ice species into the lee of terrain. Rotunno and Ferretti (2001) and Jiang (2003) investigated the impacts of ridge concavity or convexity on the distribution of precipitation along the ridge, finding that concave geometry favors heavy local precipitation due to increased upslope winds and low-level blocking.

A major unresolved question deals with the sensitivity of precipitation to the nature of incoming flow, an issue that requires the use of real three-dimensional topography. Nuss and Miller (2001) investigated the sensitivity of coastal California precipitation to small variations in wind direction in order to quantify errors due to imperfect mesoscale model initializations. Rotating the model terrain by one degree clockwise and counterclockwise, they found 20-40% differences in model-calculated area-average 4-hour precipitation totals for a cold frontal event. However, only three model runs were conducted, limiting the analysis to a very specific set of wind directions and events; thus broad conclusions about the sensitivity to larger ranges of wind direction cannot be made. In addition, by rotating the terrain, not only was the wind direction in relation to the terrain altered, but so was the orientation of the associated synoptic-scale midlatitude cyclone. Third, by rotating the terrain, the model grid points in each run resampled the true terrain and thus did not represent the same features across all three runs. These inconsistencies were further exacerbated when the model precipitation was interpolated to the control grid for analysis, as precipitation in complex terrain is rarely a smoothly-varying field. Nonetheless, this study suggests that even small changes in wind direction can greatly impact the distribution of orographic rainfall in complex terrain.
Atmospheric river events (ARs) potentially represent an extreme case of precipitation sensitivity. ARs are plumes of large integrated water vapor transport (IVT) extending from the subtropics into the midlatitudes (Newell et al. 1992). They are often narrow and are usually associated with the pre-cold frontal low-level jet in the warm sector of midlatitude cyclones (Ralph et al. 2004). Globally, despite covering only about 10% of the circumference of any latitude circle, ARs are responsible for over 90% of poleward moisture transport in the midlatitudes (Zhu and Newell 1998). Associated with a layer of warm, saturated air with near-neutral moist stability extending from the surface to an altitude of two to three kilometers, ARs can produce heavy precipitation upon interacting with topography (Ralph et al. 2004; 2005). The connection between AR landfalls and extreme rainfall or flooding events has been well established over the west coast of North America (e.g., Ralph et al. 2006; Neiman et al. 2011), elsewhere in the United States (e.g., Nakamura et al. 2013; Lavers and Villarini 2013a), in western Europe (e.g., Stohl et al. 2008; Lavers et al. 2011; Lavers and Villarini 2013b, Ramos et al. 2015), as well as on the west coast of South America (e.g., Viale and Nuñez 2011). Wind direction has been shown to be a major factor in determining the susceptibility of particular river drainages to these events (e.g., Neiman et al. 2011; Hughes et al., 2014).

The Pacific coast of North America has been of special interest to researchers studying orographic precipitation due to the frequency and consistency of wet season (wintertime) precipitation in the coastal and inland ranges from northern California to southeastern Alaska. Field campaigns focused on the influence of orography on dynamics and cloud physics include the Cascade Project (Hobbs 1975), the Coastal Observation and Simulation with Topography (COAST) Experiment (Bond et al. 1997), the Improvement of Microphysical Parameterization through Observational Verification (IMPROVE) Experiment (Stoelinga et al. 2003), and the Olympic Mountain Experiment (OLYMPEX; Houze et al. 2015). The Olympic Mountains of Washington State receive some of the largest annual precipitation in the continental United States under moist southwesterly flow off the Pacific Ocean, with large differences in precipitation totals between windward ridges and leeside valleys, and between the southwest face of the Olympics and the leeside rainshadow to the northeast (Anders et al. 2007; Minder et al. 2008).

ARs in the Pacific Northwest present an important phenomenon for exploring the sensitivity of orographic precipitation to upstream flow. Using reanalysis data, Warner et al.
(2012) showed that between northern California and Vancouver Island, narrow bands of integrated water vapor transport associated with atmospheric rivers contribute significantly to annual total precipitation. Roberge et al. (2009), considering a domain over the west coast of Canada, concluded that a majority of poleward vapor transport in these higher latitudes was associated with atmospheric rivers. Despite being predominantly warm sector events, Guan et al. (2010) showed that ARs also contribute appreciably to snow water equivalent (SWE) totals in the high mountains of western North America.

Neiman et al. (2011) considered the synoptic-scale conditions leading to flooding in four river basins across the Cascade Range and Olympic Mountains of western Washington. They considered the annual peak daily flows (APDFs) from streamflow gauges on the Green and Sauk Rivers draining the Cascades and the Queets and Satsop Rivers flowing off the Olympic Mountains over twelve years from 1998 to 2009. In 46 of 48 cases, they found that the APDFs corresponded to landfalling ARs in the warm sector of midlatitude cyclones, as determined by assessing satellite-based estimates of IWV. They created composites using the North American Regional Reanalysis (NARR) of the synoptic conditions associated with the top ten APDFs for each river in the 30-year period from 1980-2009. The composites confirmed the connection between APDFs and AR events and showed that despite the varying size of river basins and the different distributions of elevation within each watershed, the most significant difference between cases leading to flooding in the different drainages was the low-level wind direction. The authors posit that the specific topography of western Washington leads certain drainages to be susceptible to the moist, saturated AR flow from specific directions (cf. their Fig. 15) based on terrain orientation and their relationship to upstream terrain. In the presence of a landfalling AR, wind direction determines which rivers are most likely to experience heavy rainfall, with large shifts in precipitation possible over minor changes in direction.

This study examines the influences of varying incoming flow on the precipitation distribution over the Olympic and western Cascade Mountains of Washington state using a full physics model and realistic terrain driven by idealized soundings. This set-up allows the exploration of changing wind direction and other parameters on the precipitation distribution over the regional barriers. In addition, this research explores the impacts of nearby terrain and land-water contrasts on the precipitation distribution across the Olympic Mountains.
Chapter 2. DATA AND METHODS

2.1 MODEL CONFIGURATION

Idealized numerical weather simulations were performed on a single domain covering the northwestern United States and the northeast Pacific Ocean, spanning approximately 38 to 52 degrees north and 117 to 135 degrees west, with 4 km horizontal gridspacing, 305 x 390 grid points, and 37 vertical levels. This domain, shown in Figure 2.1, includes the Cascade Range, as well as the coastal mountains of Washington, Oregon and California, and the high terrain of Vancouver Island and southern mainland British Columbia. At 4-km horizontal resolution, the major river valleys are adequately resolved, including the Hoh, Queets, and Quinault Rivers on the Olympic Peninsula and the Skagit, Stillaguamish, and Duwamish/Green Rivers draining the western slopes of the Washington Cascades, among others. Model runs were forced by an idealized sounding that was used to create the initial and boundary conditions, in a manner discussed in the next section.

For experiments completed using real terrain, the impacts on different river drainages were determined using the Watershed Boundary Dataset (WBD) developed in conjunction by the US Department of Agriculture-Natural Resources Conservation Service, US Geological Survey, and the Environmental Protection Agency to isolate grid points within the selected basin.

Another interesting question regards the role of regional terrain features, such as the mountains of Vancouver Island and the Cascade Range, in modulating precipitation over the Olympic Mountains. To address this question, a series of experiments with modified terrain was carried out, including smoothing the Olympic Mountains, replacing the Olympic Mountains with an idealized symmetric dome, the removal of one or more sections of high terrain in the region (i.e., Cascade Range, coastal mountains, Vancouver Island), and removing the frictional contrasts along the coast.
Figure 2.1. WRF-ARW 4-km resolution model domain used in all experiments. Terrain elevation is shown by color shading.

All experiments were conducted using the Advanced Research Weather Research and Forecasting Model version 3.5 (WRF-ARW V3.5; Skamarock et al. 2008). WRF was run in a fully-compressible, non-hydrostatic mode with the Thompson microphysics (Thompson et al. 2008), Rapid Radiative Transfer Model (RRTMG) shortwave and longwave radiation (Iacono et al. 2008), Yonsei University planetary boundary layer (YSU PBL; Hong et al. 2006), and Old Simplified Arakawa-Schubert (SAS) cumulus (Pan and Wu 1995) parameterizations. A full ice microphysics scheme was chosen since sensitivities to this parameterization have been found as windward precipitation can be heavily influenced by the advection of ice species into the lee (Colle 2004, 2008; Miglietta and Rotunno 2006; Kirshbaum and Smith 2008). The other choices of schemes were motivated by work done by David Ovens (personal communication 2014) at the University of Washington to determine which physics packages are best suited to simulating
conditions in the Pacific Northwest in WRF. Surface heat fluxes were disabled to avoid the influence of varying surface temperatures. The time step was 12 seconds and integration was carried out under constant boundary conditions, as prescribed by the initial sounding, to be discussed in the next section. The model was run for 48 hours, the first 24 of which were reserved for model spin-up, although a near-steady state was reached much sooner. The final 24 hours of each run were used for analysis.

2.2 INITIALIZATION TECHNIQUE

A single hydrostatically-balanced idealized sounding, shown in Figure 2.2, was used to specify a balanced initial state and to create the steady boundary conditions. The vertical thermodynamic structure was chosen to approximate the conditions during an atmospheric river event: relatively warm and near saturation at low levels, and slightly stable with respect to moist processes. To this end, a sounding from an AR event at 1200 UTC 07 January 2009 from Quillayute Airport (KUIL) on the Washington coast was smoothed and slightly modified. The sounding is characterized by a shallow stable layer below 925 hPa with a slightly stable temperature profile extending to the tropopause near 250 hPa, corresponding to an increase in \( \theta_e \) from 295 K at 925 hPa to 301 K at the tropopause. The profile was near saturation (RH > 95%) from the surface up to 600 hPa, followed by a smooth decrease with increasing height. The vertical and horizontal distribution of winds in the domain, to be discussed in section 3, varied for different experiments.

To determine the state of the entire 3-D domain, a point (47.5°N, 123.75°W) on Washington's Olympic Peninsula was chosen for the prescribed sounding and a single wind direction was selected. In all cases, initial winds were then assumed to be horizontal and unidirectional everywhere in the domain, and relative humidity was set to be constant on pressure levels and could vary with height. Geopotential heights were calculated horizontally away from the sounding location assuming geostrophic balance. Temperatures on each level were also calculated by determining the temperature gradient on pressure levels through thermal wind balance. After these variables were determined everywhere in the domain, values at heights lower than the topography at each point were removed and surface values were set equal to the first vertical level above the surface. Boundary conditions were set equal to the initial conditions at the boundaries for the entire integration.
Since the initial state was in hydrostatic and geostrophic balance, frictional effects were not included. Thus, during the spin-up period during model integration, minor adjustments took place, predominantly near the surface, since drag and planetary boundary layer processes were in the full physics model. Modifications of the flow due to the interaction with terrain also occurred. These corrections took only a few hours of integration before reaching a quasi-steady state with only small variations in state variables thereafter (not shown). Considering the spin-up period, the initial twenty-four hours of integration were not used in the analysis.

Although this initialization method creates a balanced state, it does not incorporate large-scale forcing, particularly synoptic-scale vertical motions. While the precipitation patterns
produced are thus different from real AR events, which are also driven by large-scale synoptic motions, this modeling set-up is able to describe precipitation forced solely by orographic processes, which is generally dominant in this region. As observed by Browning et al. (1975), even the much lower terrain of southern Wales caused an increase in accumulated precipitation by a factor of six for an AR-like event over the British Isles. Similarly, James and Houze (2005) showed a significant increase in radar-derived precipitation intensity over terrain as opposed to over water for heavy rain events near Eureka, California (cf. their Fig. 6a). Thus, it is expected that orographic precipitation represents the majority of the anticipated totals, although as noted by Houze (1993), the feeder-seeder mechanism can produce significant additional rainfall. Roe (2004) noted that there are two mechanisms typically referred to as “feeder-seeder,” namely an internal variety whereby a seeder region of an orographic cloud produces hydrometeors that fall through a lower-level feeder cloud, and an external variety whereby a high cloud, unaffected by the orography below, produces hydrometeors that fall through an orographically-forced feeder cloud. While the model set-up used here is able to capture this first type of feeder-seeder cloud, the lack of synoptic-scale forcing precludes the existence of the second variety. It should be noted that all previous idealized studies of orographic precipitation share this lack of synoptic scale forcing and coincident reduction of anticipated precipitation.

2.3 Quillayute Climatology

Neiman et al. (2008) used Special Sensor Microwave Imager (SSM/I) observations of column-integrated water vapor to identify AR landfall events on the North American west coast following the technique of Ralph et al. (2004; 2005) and then created composites of NCEP-NCAR Reanalysis data to compare summer versus winter AR events at different latitudes. They showed that while AR events defined by integrated water vapor alone occur year-round in the northeastern Pacific, the intense rainfall and societal impacts are limited mostly to winter events, since the cross-terrain flow, low-level moisture, and associated midlatitude disturbances tend to be stronger during the cold season. To determine the frequency of moist flow from various wind directions, a climatology (1971-2015) of winter (NDJF) conditions was constructed from
soundings launched from Quillayute Airport (KUIL) on the western side of the Olympic Peninsula.

Figure 2.3. A climatology of winter (NDJF) 1971-2015 wind and water vapor flux at 850 hPa for soundings launched from KUIL. The count of wind observations in each 10-degree wind bin is shown in the grey columns and five different percentile values of vapor flux (kg m\(^{-2}\) s\(^{-1}\)) in each bin are shown by the blue lines.

Wintertime conditions at 850 hPa are summarized (Figure 2.3) through a histogram of wind direction frequency, binned every ten degrees. There is a single peak centered on southerly to west-southwesterly winds (180-240°), with very low frequencies for northerly to easterly directions. The colored lines show five different percentiles of water vapor flux (\(= \rho_{\text{air}} w |\vec{V}|\)) over the same wind direction bins, where \(\rho_{\text{air}}\) is the air density, \(w\) is the water vapor mixing ratio, and \(|\vec{V}|\) is the wind speed. All percentiles show peaks around 190-200°, with the distribution becoming more peaked for higher water vapor fluxes. AR events are generally among the top 10% of moisture
transport cases, and the moisture flux for this subset is largest for southerly to south-southwesterly flow. Since large low-level moisture flux is associated with heavy rain on Pacific Northwest terrain (Warner et al. 2012), it would be expected that major precipitation events occur under southerly and southwesterly 850-hPa flow.

Neiman et al. (2008) showed that while ARs may approach the Pacific Coast from westerly or even north of westerly directions, these events primarily occur in the summer season and do not produce flooding due to lesser wind speeds, attenuated moisture flux, and lack of synoptic support. The focus of this study will thus be constrained to flow with wind directions from southerly to westerly.
Chapter 3. RESULTS

3.1 BAROTROPIC (UNSHEARED) WIND CASE

The initial sounding for barotropic cases is shown in Figure 2.2 and discussed in Section 2.2. In this set of experiments, winds were a uniform 20 knots (10 ms\(^{-1}\)) from a specific wind direction throughout the depth of the atmosphere. Model runs were initialized every 10° from 180° to 300°, with additional runs every 5° from 220° to 260°. As mentioned previously, a steady state is reached after a few hours of integration, with friction and terrain producing steady wind directions slightly rotated from their initialized values. The initial sounding location of 47.5°N, 123.75°W is well into the steep slopes and high terrain of the southwestern Olympic Mountains, and thus experiences more deviation of the winds from the initial values than model grid points over the ocean. Therefore, in each experiment, the 925-hPa wind direction at 47.5°N, 125.0°W, a point due west and offshore of the location of the initial sounding, was used to quantify the actual wind direction of the flow impinging on terrain.

The regional 24-hour precipitation totals over western Washington and Oregon for various incoming wind directions at 925 hPa are shown in Figure 3.1. For 187°, precipitation is mostly limited to the exposed ridges along the southern and southwestern flanks of the Olympic Mountains and along the windward side of the high terrain of Vancouver Island, with only light showers on the coastal mountains. Virtually no precipitation is found over the Cascades. The amount of rainfall on the Olympic slopes and in southern Vancouver Island increases as the wind turns more southwesterly, with significant accumulations developing over the northern Cascades for south-southwesterly winds (204°). Enhancement of the precipitation over the Washington and Oregon coasts increases as the winds turn to southwesterly (223°) and beyond. Over the Cascade Range, precipitation becomes increasingly more widespread for southwesterly and west-southwesterly (247°) directions, while rainfall begins to slowly decrease over the high terrain of the Olympic Mountains. As the winds near westerly (261°), Cascade precipitation is largest while Olympic precipitation has diminished significantly, with the majority of accumulation on the Olympic Peninsula occurring close to the coastline.
Figure 3.1. Precipitation totals (mm) for the final 24 h of integration over western Washington and Oregon and the northeast Pacific Ocean for various 925-hPa wind directions.
Figure 3.2. Wind speeds (shaded, in kt) and directions (arrows) at the second model level averaged over the final 24 h of model integration over western Washington and Oregon.
Figure 3.2 shows the winds on the second model level (approximately 60 to 70 m above ground level) during the 24-hr period for the same 925-hPa wind directions. At 187°, despite the winds above the surface being slightly onshore, the winds at lower levels are still predominantly offshore in Washington and Oregon. There is some upslope flow on the southern Olympic Mountains and on the southwestern side of Vancouver Island, accounting for the precipitation accumulating in those locations. The surface winds turn onshore with south-southwesterly flow at 925 hPa, coincident with the onset of coastal enhancement of precipitation on the Washington coast. As the winds shift from coast-parallel to coast-perpendicular, two important differences in the flow develop. First, the speed of the flow at the coast decreases from 20 kt to 15 kt. This deceleration is potentially caused by increasing pressure over land due to interaction of the incoming flow with major terrain barriers. As the winds continue to turn more westerly, the flow decelerates even more with the onshore speed falling below 10 kt for 261° winds. Second, while southerly flow leads to very low wind speeds in the Puget Sound lowlands, the speed increases to over 30 kt for flow from 223° and 231° before weakening for westerly flow. As this northward flow in the Puget Sound increases or decreases, so do precipitation totals in the north Cascades because of increased upslope flow on that terrain.

While the regional precipitation distribution displays a qualitative sensitivity to wind direction, a quantitative analysis is needed to evaluate the drainage-scale sensitivity. In particular, are there large changes in basin-scale precipitation for small changes in direction? As in Neiman et al. (2011), four river basins were considered: the Queets and Satsop Rivers draining the western and southern Olympic Mountains respectively, and the Duwamish/Green and Sauk Rivers draining the western slopes of the Cascade Range (Figure 3.3). The Queets River, much like the neighboring Hoh and Quinault Rivers, drains the relatively high terrain of the central Olympics, with the river valley bounded on both sides by parallel high ridges. Despite the elevation, most precipitation in warm AR events falls as rain (Neiman et al. 2011). The Satsop River, in contrast, primarily drains the lower terrain on the southern flank of the Olympics before joining the main stem of the Chehalis River. The Green River rises in the Central Cascades between Snoqualmie Pass and Mt Rainier, the highest peak in Washington State. After passing through the Army Corps of Engineers’ Howard A Hanson Dam, the Green flows through the densely populated Kent Valley in the southern suburbs of Seattle before entering the city itself as the industrial Duwamish Waterway. The Sauk River is the highest of the basins considered, but
remains primarily below the melting level of AR events (Neiman et al. 2011). The Sauk is the largest tributary of the Skagit River, draining the high terrain of the North Cascades, nearly due east of the Strait of Juan de Fuca. While the Olympic Peninsula rivers are often exposed to moist flow directly off the Pacific Ocean, rivers in the Cascade Range are shadowed by the Olympic Mountains under specific wind regimes. For a more complete discussion of these river basins, the reader is directed to Section 3 of the aforementioned paper by Neiman and coauthors.

![Figure 3.3. Terrain heights (shaded and contoured every 500 m) for western Washington with the four river basins analyzed outlined in red.](image)

Figures D and E show the same fields as figures A and B, respectively, but only for western Washington. Enhanced precipitation on the ridges of the southwest Olympics is apparent for all wind directions up to 231°, while the coastal enhancement through blocking contributes significantly to precipitation totals for flow from 213° to westerly. This combination of effects results in a maximum in Olympic Peninsula precipitation around 231°. An Olympic Mountain
rain shadow is also present in Figure 3.4, rotating around the leeside of the range as the wind direction turns clockwise. It is first evident over the Puget Sound lowlands with winds from 213° as a small break in precipitation over Fidalgo Island and northern Whidbey Island, at approximately 48.5°N, 122.5°W. This gap in precipitation proceeds southward as the winds shift to westerly, over southern Whidbey Island at 48°N, 122°W for 231° and down to greater Seattle at 47.5°N, 122°W in the most westerly case at 261°. Precipitation in the Cascade Range spreads from north to south as the onshore flow is able to reach the windward slopes through the Chehalis Gap. For southerly to south-southwesterly winds, the precipitation in the Cascades is restricted to the northern sector, but begins to fill in to the south for more southwesterly flow. Finally, as the high terrain of Vancouver Island shadows the northern Cascades for westerly flow, the precipitation there begins to decrease while the rest of the Washington Cascades remain very wet.

The blocking and coastal convergence impacts on wind speed are pronounced in Figure 3.5, which shows the local wind fields. The deviation of winds around the Olympics is appreciable for all wind directions. At 187°, the approximately southerly flow is strongly deflected to the west over the southern portion of the Olympics, with similar patterns apparent at 194° and 204°. For all angles some of the flow is directed through the Puget Sound lowlands to the east of the Olympics, with this flow greatly accelerated to over 30 kt for wind directions from 204° to 231°. For directions from 231° to westerly, the deceleration of flow on the windward side of the Olympics becomes substantial, with upslope winds decreasing to near zero for westerly winds. This near stagnation on the windward slopes coincides with the rapid reduction of Olympic precipitation as the flow changes from 231° to 261°. Stagnant flow in the lee of the Olympics is found for all wind directions as an area of light and variable winds shifting from the Strait of Juan de Fuca to over Whidbey Island in the Puget Sound as the winds shift from southerly to westerly.
Figure 3.4. As Figure 3.2, over western Washington, with the Queets, Satsop, Duwamish/Green, and Sauk River drainages outlined in white.
Figure 3.5. As Figure 3.3, over western Washington, with the Queets, Satsop, Duwamish/Green, and Sauk River drainages outlined in red.
Figure 3.6 summarizes the average precipitation in the four river basins under varying 925-hPa wind directions offshore. The rapid increase in precipitation for both the Satsop and Queets Rivers as winds turn onshore illustrates the impacts of the Olympic Mountains on moist Pacific flow, with the average rainfall increasing from just over 1 mm at 178° to between 12 and 16 mm at 204°. As the winds turn past 210° and terrain blocking becomes more significant, evidenced by the deceleration of the onshore winds (Figure 3.5), the precipitation spreads across coastal areas, causing a large increase in Queets River precipitation while rainfall over the inland Satsop River remains fairly steady. Both the Queets and Satsop Rivers reach a maximum precipitation at 228° of 36.0 mm and 19.3 mm respectively, although the Satsop basin also receives 19.1 mm at 198°. For directions beyond southwesterly, the total precipitation in both basins begins a slow decline as enhanced blocking weakens the speed of upslope flow and as the wind direction becomes less favorable for ridge enhancement in the southwestern Olympics.

The Cascade rivers show patterns of precipitation that are distinct from those of the Olympic Peninsula rivers, and from one another. The Sauk River experiences accumulations at more southerly directions than the Duwamish/Green River as flow through the Chehalis Gap is able to accelerate over the Puget Sound lowlands before encountering the high terrain of the North Cascades. The precipitation maximum of 25.9 mm at 239° coincides with the maximum of upslope winds in the basin (Figure 3.5). The Duwamish/Green River to the south receives little to no rainfall for southerly to south-southwesterly winds due to its shielding from moist flow by the Rainier massif. Precipitation does rise dramatically as the wind turns from 210° to 220° as stronger flow begins to impinge directly on the slopes draining into the river. From there, rainfall continues to increase as the winds turn more westerly before reaching a maximum of 32.9 mm at 261° when the basin is directly downstream of the Chehalis Gap, before declining sharply as the Olympic Mountain rain shadow sets up over the lower part of the basin at 275° (not shown), as there is more variation along the Cascade Range due to varying upstream topography.

Neiman and coauthors (2011) concluded from their compositing analysis that the Queets River was most susceptible to heavy precipitation under west-southwesterly (247.5°) flow, the Satsop River under south-southwesterly (202.5°) flow, the Sauk River under southwesterly (225°) flow, and the Green/Duwamish River under flow between 245° and 275°. This analysis found that under barotropic flow, the maximum precipitation in the Queets River drainage occurred at 228°, the Satsop River at 228° with a slightly lower second peak at 198°, the Sauk
River at 239°, and the Duwamish/Green River at 261°. These values agree fairly well with those from Neiman et al. with the Duwamish/Green River peak determined here lying within their optimal range, and with the Queets, Satsop, and Sauk River peaks coming within 20° of their values.

![Graph](image)

Figure 3.6. 24-h precipitation (mm) averaged over the Queets (blue), Satsop (green), Duwamish/Green (red), an Sauk (orange) River basins for various 925-hPa wind directions.

Nuss and Miller (2001), on the other hand, found 20-40% accumulations differences over only 1° of wind rotation. Excepting the edge cases where the moist flow first turns onshore and precipitation begins in the Olympic Mountains, the largest sensitivity found in this set of experiments occurs in the Queets basin as the wind shifts from 204° to 209° and the resulting precipitation increases from 15.9 mm to 27.8 mm. This 15% increase in precipitation per degree of wind rotation is slightly smaller than that estimated by Nuss and Miller for coastal California.
and represents the extreme case found here. For the majority of wind directions in all four basins, the sensitivities are much more modest.

3.2 **REALISTIC (SHEARED) WIND CASE**

A second set of experiments was carried out with the same temperature and humidity sounding as the barotropic case but with a more realistic wind distribution, both vertically and horizontally. The vertical profile of wind was smoothed from the same sounding at KUIL for a real AR event from which the temperature profile was selected, 12 UTC 07 January 2009. The initial sounding for initially 270° case is shown in Figure 3.7. In this sounding, winds near the surface are set to 15 kt, increasing steadily to 115 kt at 250 hPa (the tropopause) before decreasing above. Horizontal shear was also included with the wind speed decreasing smoothly with horizontal distance to half its initial value as \( V = \frac{1}{2} V_{\text{sond}} \left( 1 + \exp \left( -\frac{d^2}{a^2} \right) \right) \) where \( V_{\text{sond}} \) is the wind specified in the sounding, \( d \) is the perpendicular distance to a line through the sounding point (47.5°N, 123.75°W) along the specified wind direction, and \( a \) is the parameter controlling the width of the Gaussian curve, here set to 1 degree of latitude, or 111 km. The resulting structure approximates the jet-like structure associated with pre-cold frontal ARs. As in the barotropic cases, model runs were initialized every 5 or 10°, from 180° to 280° and run for 48 hours with the last 24 hours used for analysis.

Figures 3.8 and 3.9, as in Figures 3.1 and 3.2, show the 24-hour accumulated precipitation and surface winds over western Washington and Oregon and the Pacific Ocean for a range of model 925-hPa wind directions. In general, precipitation totals are higher in this set of simulation as wind speeds are increased at most levels. Similar to the barotropic case, this more realistic case shows large precipitation accumulations over the windward ridges in the southwest Olympics for southerly to south-southwesterly winds. And as before, as the onshore winds shift more westerly, the heavy precipitation over the steep terrain shifts to a broader, more uniform distribution over the coastal region. Another similarity is the increase in Cascade Range precipitation as winds turn to westerly, but with less uniform totals along the full north-south extent due to the gradient in onshore wind speed (Figure 3.9).
Figure 3.7. Initial sounding for realistic wind shear cases (270° initial winds case shown).
Figure 3.8. As Figure 3.2, for the realistic (sheared) wind case.
Figure 3.9. As Figure 3.3, for the realistic (sheared) wind case.
A notable difference from the barotropic case is the extension of light precipitation well offshore. This can potentially be explained by two factors. Figure 3.10 shows vertical cross-sections of potential temperature and relative humidity along the 925-hPa wind direction through the sounding point for the 247°-barotropic and 246°-realistic (roughly west-southwesterly) wind cases. In both, the atmosphere over the ocean is at or near saturation from approximately 950 hPa to well above the crest of the Olympic Mountains. However, the realistic case shows isentropes that slope gently upward as the flow approaches the terrain and saturated air reaching all the way to the surface well offshore, while the barotropic case exhibits a slightly subsaturated layer immediately above the surface and horizontal isentropes. Because the realistic wind case incorporates vertical shear, horizontal temperature gradients are present in the domain unlike in the barotropic case. So while in both, a shallow mixed layer develops near the surface, as friction turns the winds slightly counter-clockwise, higher mixing ratio air is advected northward in the sheared case. This local increase in absolute humidity, combined with the slight isentropic lift, leads to considerably more oceanic precipitation.

Figure 3.10. Cross-sections, along the 925-hPa wind direction through the Olympic Mountains, of potential temperature (contours, in K) and relative humidity (shading) for both cases.

Figures 3.11 and 3.12, as with Figures 3.4 and 3.5, show the 24-h precipitation and surface winds over western Washington. As in the barotropic case, preferential enhancement of precipitation in the Olympics is evident for southerly and south-southwesterly winds, with a
more uniform shield of rainfall in southwesterly to westerly cases. Also apparent is the north-to-
south shift in the location of the maximum Cascade Range precipitation as the winds turn to
westerly due to the horizontal shear and jet-like structure included in this set of experiments.
Large rainfall totals first appear in the North Cascades to the north of the Sauk basin at 205° and
generally move southward to the Duwamish/Green River basin for winds of 253°. An Olympic
rain shadow is more distinct in this set of runs than in the barotropic case, with a gap in the
inland precipitation apparent over the San Juan Islands (48.5°N, 123°W) at 215° and slowly
migrating to the southwest as the wind turns more westerly, over Whidbey and Camano Islands
(48.25°N, 122.5°W) at 253°.

Blocking and coastal convergence again appear to be important phenomena, with
pronounced slowing of winds as they approach the coast and Olympic terrain (Figure 3.12).
Upslope winds at 205° on the southern flank of the Olympics are less than 5 kt and coincide with
high precipitation totals in the Satsop River basin. As the wind turn to 215° and beyond, coastal
convergence is apparent as winds slow to less than 10 kt, and even less than 5 kt at 253°. The
near-stagnation of flow over the western Olympics corresponds to the peak of precipitation in the
Queets River basin as the rainfall distribution becomes more uniform as ridge enhancement is
reduced. While the acceleration of winds in the Puget Sound lowlands is reduced in this more
realistic case, increasingly west-southwesterly flow allows for stronger upslope flow in both
Cascade basins. Leeside stagnation over the Strait of Juan de Fuca and the islands of the Puget
Sound is apparent and coincides with the precipitation minimum in the Olympic Mountain rain
shadow.

These model simulations are quantified and summarized in Figure 3.13. As before, the
Queets and Satsop Rivers show large increases in precipitation as low-level winds turn onshore,
although the rise is more dramatic in this case, potentially due to the presence of increased
surface moisture. The Satsop reaches its maximum of 44.0 mm at 195° before slowly declining
through to west-southwesterly winds (247°) and then dropping quickly as the wind direction
approaches westerly. The Queets River, in contrast, remains fairly steady for south-southwesterly
and southwesterly directions, reaching its maximum of 45.4 mm at 247° before falling back
below 5 mm as winds move beyond westerly. The Cascade rivers require more south-
southwesterly winds before rainfall begins to accumulate, though there is less separation between
the two in this case as both rivers begin to experience accumulations between 190° and 200°.
The Sauk River reaches its maximum of 45.4 mm at 233° and the Duwamish/Green rises to its maximum of 41.2 mm at 253° before both basins show steep declines toward westerly winds.

Figure 3.11. As Figure 3.4, for the realistic (sheared) wind case.
Figure 3.12. As Figure 3.5, for the realistic (sheared) wind case.
Figures 3.6 and 3.13, summarizing the precipitation in the four river basins for each set of experiments, show important commonalities and differences between the barotropic and sheared cases. In both cases, Olympic Mountain rivers show higher precipitation totals for more southerly wind directions than Cascade Range rivers due to their exposure to moist Pacific flow. They both also show that the highest accumulations in the Queets basins occur not when the precipitation is enhanced on the surrounding ridges in south-southwesterly flow, but instead when coastal blocking allows for a more uniform region of precipitation to develop. This increase in coastal rainfall in both cases does not result in an increase of precipitation in the Satsop basin farther inland. Similar patterns are also present for rivers draining the Cascades with precipitation in both the Duwamish/Green and Sauk Rivers increasing rapidly as the winds shift from south-southwesterly to southwesterly. Due to the upstream location of terrain, both experiments show a maximum in Sauk precipitation between 230° and 240° while Duwamish/Green rainfall is maximized at more westerly directions around 250° to 260°.

Despite these similarities between the two cases, there are also notable differences. Most significantly, each of the four river basins receives more rainfall on average in the realistic sheared case than in the barotropic case, which may be due to the increased onshore wind speed at all levels above 925 hPa and the elevated surface moisture mentioned before. The Satsop River in particular slows the largest increase in maximum rainfall between the two sets of runs, and its relatively low elevation watershed suggests that the increase of moisture in the surface layer is responsible. The Queets River shows a large shift in the location of maximum rainfall from 228° to 247°, which could be due to higher surface moisture interacting with coastal convergence and blocking. Both Cascade rivers show a slight increase in precipitation for more southwesterly directions, and the Duwamish/Green River is able to extract much more precipitation for directions between south-southwesterly and southwesterly. This seems to be related surface winds being more consistently upslope across the river drainage in the realistic case (see 215° in Figure 3.12) than in the barotropic case (see 213° in Figure 3.5).
Figure 3.13. As Figure 3.6, for the realistic (sheared) wind case.

Precipitation maxima are at 247° for the Queets River, 195° for the Satsop River, 233° for the Sauk River, and 253° for the Duwamish/Green River, which are similar to or within 10° of the values from Neiman et al. (2011), namely 247.5° for the Queets River, 202.5° for the Satsop River, 225° for the Sauk River, and 245° to 275° for the Duwamish/Green River. This better agreement with the values from the literature than the barotropic case is likely a result of the more realistic temperature and wind profile. Comparing the model runs with the results of Nuss and Miller (2001), the largest gradient in precipitation by direction was determined. This occurs in the Queets River basin where the average rainfall increases from 21.1 mm to 45.5 mm as the wind shifts from 253° to 246°, corresponding to a 18% increase per degree of wind rotation, again below the 20-40% range found by Nuss and Miller.
3.3 TERRAIN MODIFICATION EXPERIMENTS

To gain more insight into the sensitivity of the precipitation distribution in the Olympic Mountains, further barotropic model runs were carried out utilizing various modified terrain geometries. Specifically, the Olympic Mountains were smoothed or replaced entirely with a symmetric dome (Figure 3.14). To smooth the range, the mountains were isolated and a two-dimensional Gaussian filter was applied. Subsequently, the heights were scaled up so that the maximum elevation of the range remained the same as the true terrain. To replace the terrain with an ideal dome, the range was isolated and a new height field was calculated as:

\[ h = h_m \left( 1 - \frac{1}{1 + \exp \left( \frac{c_1 - d}{c_2} \right)} \right), \]

where \( h_m \) is the maximum height of the Olympics and \( d \) is the distance from the center of the ideal dome at 47.5°N, 123.55°W in km. The values of constants \( c_1 \) and \( c_2 \) were chosen to be 70 km and 14 km, respectively, in order to create a shape which had both a similar areal coverage of high terrain and similarly steep slopes at its edges. Model runs were initialized every 10° from 200° to 300°, with additional runs at 235°, 245°, and 255°. As before, only the final 24 h of integration were used for analysis and the 925-hPa winds at 47.5°N, 125°W were used to quantify the actual direction of onshore flow in each experiment.

The average precipitation for the three Olympic terrain geometries for various steady wind directions are shown in Figure 3.15. In general, the specific shape of the Olympic Mountains has only a minor impact the sensitivity of accumulated precipitation to wind direction. The true terrain and the symmetric terrain especially produce extremely similar precipitation, with the accumulations in the smoothed case being slightly more (1 mm or less) than those for the true terrain for wind directions between about 180° and 235°. The symmetric case, while still resembling the shape of the other two cases, shows a shift to greater precipitation for more southerly flow. This is likely due to the steeper slopes on the south and southwest faces of the ideal Olympic dome than those in the true and smoothed Olympics.
Figure 3.14. Real and simplified Olympic Mountain terrain elevations (m, shaded and contoured every 300 m) with the box (in red) over which precipitation was averaged.
Figure 3.15. 24-h precipitation (mm) averaged over the boxes shown in Figure 3.14 for the true terrain (blue), smoothed terrain (red), and ideal symmetric terrain (green) of the Olympics.

A feature of interest is the large increase in precipitation between 200° and 210° in all three cases, reminiscent of the pattern observed for the Queets River basin under barotropic flow (see Figure 3.6). In that case, the increase in precipitation seemed to be caused by an increase in low elevation rainfall associated with coastal convergence and blocking (see Figure 3.5). To explore this directional enhancement further, additional model experiments were carried out using the ideal symmetric terrain while eliminating surrounding features, namely the coastal mountains of Oregon and Washington, Vancouver Island, and the Washington Cascades. Two other cases were run as well, specifically the ideal symmetric dome with all other terrain in the domain removed, and this “symmetric only” terrain with friction disabled. The modified terrain used in these runs is shown in Figure 3.16 and the results are summarized in Figure 3.17.
Figure 3.16. Terrain heights (shaded, in m) for the four modified terrain cases with symmetric Olympic Mountains. Precipitation was averaged over the boxes shown in red.
Figure 3.17. As Figure 3.15, for all model runs using the ideal, symmetric dome terrain.

Figure 3.17 shows how the nearby terrain features impact the average rainfall over the ideal symmetric Olympic Mountain dome under varying wind directions. For directions to the south of 210°, the coastal mountains (purple) have no significant effect on the precipitation compared to the experiment with the full terrain (green, same curve as in Figure 3.15), however flow from 210° and more westerly directions shows a systematic reduction of about 1 mm due to the removal of the coastal mountains. Vancouver Island (grey) also shows very little impact on Olympic precipitation until the wind approaches westerly, when its removal is responsible for about a 1 mm increase in rainfall likely due to a decrease in coastally blocked flow. The Washington Cascades, in contrast, exert a strong control over Olympic precipitation. For southerly to southwesterly flow, removing the Cascades causes a reduction of 3 to 8 mm averaged over the range, while for west-southwesterly and westerly flow, Olympic precipitation is increased up to 3 mm without the Cascades. Removing all terrain in the domain except the
ideal Olympic dome results in the orange curve, showing variation of only about 3 mm across the entire span of wind directions and a distinct lack of sensitivity between 200° and 210°. Removing friction from this terrain geometry (brown) also further reduces sensitivity to wind direction. The remaining sensitivity to wind direction may be due to differences in surface characteristics and their impact on the surface layer.

The origin of these terrain/friction related precipitation differences is explored in Figures R and S, showing the 24-h precipitation and surface winds, as before, for a wind direction of about 210°. For this direction, the removal of the Cascades causes a large decrease in precipitation and the removal of the coastal mountains causes a small decrease. As expected from Figure 3.15, the rainfall totals and wind distributions for the full terrain and smoothed Olympic Mountains cases are extremely similar, with only minor. Aside from the obvious changes in precipitation distribution due to different geometries, the main difference between the symmetric cases appears to be the onshore wind speed. The removal of Vancouver Island changes the upstream wind speed very little, while the flow impacting the coast in the case with real terrain except for a symmetric Olympics is slightly stronger than in the no-coastal-mountains case and much stronger than in the no-Cascades case, manifesting as decreases in both coastal and upslope precipitation. The frictionless case, while showing some of the highest wind speeds, also shows the most flow splitting, leading to lower precipitation totals.

A second set of figures (Figures 3.20 and 3.21) show the same fields for steady wind directions between 235° and 240°, where the removal of the Washington Cascades results in higher Olympic precipitation while the removal of the coastal mountains results in a 1 mm decrease in rainfall. Again, the full terrain and smoothed Olympic Mountains experiments produce extremely similar patterns, while Vancouver Island does little to change the precipitation or wind fields in the Olympics. In contrast with the 210° direction cases, however, the onshore wind speeds show little difference between the six cases with the symmetric Olympic Mountains. There are slight differences in the blocking pattern upstream of the Olympics, which appear to be modulating the distribution of rainfall across the ideal dome.
Figure 3.18. Precipitation totals (mm) for the final 24 h of integration over western Washington for various terrain geometries for steady 925-hPa wind directions of about 210°.
Figure 3.19. As Figure 3.18, showing wind speeds (shaded, in kt) and directions (arrows) at the second model level averaged over the final 24 h of integration over western Washington.
Figure 3.20. As Figure 3.18, for steady wind directions near 235°.
As Figure 3.19, for steady wind directions near 235°.
Recent modeling studies have investigated the impacts of varying terrain geometries and upstream flow characteristics on orographically-enhanced precipitation in idealized terrain, but have largely neglected the impacts of real, complex terrain. As shown by Nuss and Miller (2001), the sensitivity of the precipitation distribution in complex terrain to wind direction can be much higher than in an idealized case and thus the impacts of real orography cannot be disregarded. Atmospheric rivers in particular represent an extreme case of precipitation sensitivity to wind direction, and wind direction has been shown to determine which river basins in a region experience flooding for a given event (Neiman et al. 2011; Hughes et al. 2014). In the Pacific Northwest, the severe impacts of AR events are restricted to the winter season (Neiman et al. 2008), and, according to a climatology of wintertime 850-hPa condition as Quillayute Airport (KUIL) on the Washington coast, the moisture flux associated with extreme rainfall is far more likely to occur for flows between southerly and westerly than for other wind directions. However, in order to accurately assess the impact of a wind direction on precipitation, an idealized modeling approach is required, but was previously unavailable.

In this thesis, a method for creating balanced initial state and boundary conditions for forcing model runs over real three-dimensional terrain was developed. The initial state was determined by an input sounding and assumed horizontal distributions of winds and relative humidity. Three-dimensional fields of geopotential height and temperature were calculated through the application of geostrophic and thermal wind balance equations. The initialization was used to test the sensitivity of idealized atmospheric river precipitation distributions over the Olympic Mountains and other Pacific Northwest terrain features to wind direction for both a barotropic and a sheared case. In addition, the sensitivity of the Olympic Mountain precipitation distribution to the terrain geometry of the Olympics and nearby regions of high terrain, including the coastal ranges of Washington and Oregon, the Cascade Mountains, and Vancouver Island, was investigated.

Results from a barotropic, horizontally uniform case showed that both regional and river basin-scale precipitation were strongly modulated by wind direction, with both the character and amount of precipitation changing for varying wind directions. Precipitation in the Olympic Mountains for southerly to southwesterly flow was dominated by large accumulations on the
ridges of the southwest Olympics, while for southwesterly to westerly flow, the precipitation distribution was increasingly affected by a coastal enhancement due to blocking and coastal convergence. Queets River precipitation was maximized for southwesterly flow, when both terrain and coastal enhancement acted to increase rainfall in the basin while precipitation over the inland Satsop River remained fairly constant until coastal enhancement began to dominate the distribution under southwesterly flow. Precipitation in the Cascade Range of western Washington generally increased for increasingly perpendicular (westerly) flow, except when upstream terrain attenuated the moisture flux available farther inland. These patterns were apparent in the distributions of precipitation in the Sauk and Green/Duwamish River basins as the Sauk basin began to accumulate rainfall under south-southwesterly flow with totals increasing through west-southwesterly flow, after which the drainage was sheltered from moist flow by the Olympic Mountains. In contrast, the Duwamish/Green River, shielded by Mt. Rainier, received significant accumulations for flow between 210° and 220°, with totals increasing through westerly flow before also becoming sheltered by the Olympics.

A set of experiments utilizing a more realistic wind field derived from the same 1200 UTC 07 January 2009 sounding at KUIL and characterized by both vertical and horizontal shear produced similar results, with Olympic precipitation shifting from enhancement over high terrain to enhancement along the coast for southwesterly to west-southwesterly flow. Precipitation in the Washington Cascades generally increased as the flow became more westerly except when upstream terrain limited the inland penetration of moist flow. As before, the Queets and Satsop Rivers received large rainfall accumulations when the moist flow was directed onshore, with the Queets River recording its precipitation maximum for west-southwesterly flow when both inland and coastal enhancement were acting over the basin. The Satsop received its largest rainfall totals for flow from 195° to 200°, consistent with its inland location and predominantly south-facing drainage. The Sauk and Duwamish/Green Rivers also showed similar results, with precipitation first occurring for south-southwesterly flow, reaching a maximum in the Sauk basin at 230° to 240° and in the Duwamish/Green basin at 245° to 255°. Large differences between the two sets of experiments were present in the amount of offshore precipitation, potentially due to non-horizontal isentropes and veering in the frictional boundary layer allowing for positive moisture advection near the surface in the sheared case.
These results agree well with the compositing analysis of synoptic conditions leading to high streamflow on the same four rivers examined by Neiman et al. (2011). The optimal wind directions for heavy precipitation found by the modelling were very close to those determined by Neiman and coauthors, with the more realistic sheared case showing better agreement than the barotropic case. These results show less sensitivity than the 20% to 40% change over two degrees of rotation determined by Nuss and Miller (2001), with the maximum sensitivity to wind direction being 15% and 18% per degree of rotation respectively, excepting the cases when the flow initially turns onshore, and much lower on average.

Further sets of barotropic experiments were considered using varied terrain geometries in lieu of the real terrain, including a smoothed Olympic Mountains, idealized dome-shaped Olympic Mountains, and the removal of the coastal mountains of Washington and Oregon, the Washington Cascades, or Vancouver Island. The impacts of removing surface friction were also investigated. Simulations showed that the specific shape of the Olympic Mountains is not a dominant factor in determining the sensitivity of precipitation over the whole range to wind direction, although it does modestly shift the flow direction at which the maximum precipitation occurs. It was also shown that the removal of Vancouver Island or the coastal mountains only marginally impacted Olympic precipitation for southerly to westerly flow, while the removal of the Cascade Range resulted in large differences in precipitation for southerly to southwesterly flow. The removal of all terrain other than the ideal symmetric Olympics resulted in both significantly less precipitation and less sensitivity, with the lowest sensitivity occurring when the effects of friction were removed.

All simulations in this work were initialized using a temperature profile smoothed from the 1200 UTC 07 January 2009 sounding at Quillayute Airport on the Washington coast. While this sounding exhibited many of the qualities typical to an AR event, future studies should consider the impacts of differing vertical temperature profiles that alter both the freezing level and the moist stability of the column, and terrain barriers outside the Pacific Northwest should also be investigated. The initialization method, while used here exclusively to approximate AR events, can theoretically be applied to any initial sounding and could prove useful in studying the dynamics of various ideal flows over real terrain in other locations.
BIBLIOGRAPHY


