Investigating Frontal Precipitation Enhancement Upstream of the Olympic Mountains

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ABSTRACT

Orographic precipitation enhancement is the tendency of mountains to cause clouds to produce more precipitation than they would otherwise, which greatly affects the total rainfall in mountainous regions and plays a major role in flooding and mudslides. Most past studies have examined this enhancement close to the mountains themselves. The present study examined the orographic enhancement of frontal precipitation upstream of the Olympic Mountains of Washington State, using data from a Weather Research and Forecasting (WRF) regional climate simulation. Using this simulation, we strived to determine how thermodynamic and dynamic conditions affect the enhancement of frontal precipitation upstream of the Olympic Mountains. To do so, the characteristics of frontal passages were analyzed, including frontal type, orientation, velocity, warm-air moisture content, and accumulated precipitation. Of the five fronts analyzed to date, there were two cold fronts, two warm fronts, and one occluded front. We then analyzed each characteristic by comparing each event to each other and as a function of distance from the mountains. We found that all fronts slowed down as they approached the mountains, four of which to almost half of their original speeds, and some even beginning to decelerate upwards of 700 km upstream. Areas of enhanced precipitation were observed along the two cold fronts, as far upstream as 560 km. These results document upstream impacts on frontal passages, but further analysis is needed to examine additional frontal passages and determine if the observed precipitation enhancement and frontal deceleration were caused by orographic effects from the Olympic Mountains.

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1. Introduction

The west coast of the United States is home to hundreds of kilometers of mountain ranges. As extratropical cyclones propagate eastward over the Pacific Ocean, the fronts associated with these systems cause ascent, which can lead to precipitation and cloud formation if coupled with the moist ocean air. As these fronts get closer to the mountainous west coast, the presence of these mountains can alter and sometimes enhance the fronts and their associated precipitation. There can be many dire consequences from the additional precipitation that falls as a result of this enhancement. Flooding and mudslides are not unheard of as a result of this phenomenon and can cause significant property damage and even injury or death. Additionally, precipitation is often one of the hardest quantities to accurately forecast (Fritsch et al., 1998). To remedy this, gaining a better understanding of precipitation enhancement and terrain-weather interactions is the first of many steps that will allow for more accurate and precise forecasts and warnings to the public.

Mountains have been observed to affect precipitation in many ways. Upslope lifting occurs when air flows over a mountain barrier, allowing water vapor to condense into clouds and precipitation. It is also possible, however, that air is diverted around a mountain and does not ascend, also referred to as flow blocking. The Froude number can be used to determine whether or not the wind normal to the barrier will rise over a mountain (Smith, 1980; Smolarkiewicz & Rot, 1989). The Froude number is defined as $Fr = U/(Nh_m)$, where $U$ is the wind speed normal to a barrier, $N$ is the Brunt–Väisälä frequency, and $h_m$ is the maximum barrier height. If Fr > 1, air is likely to rise over the mountain. This occurs when the mountain height is lower, when the air is less stable, or when winds are strong enough to overcome the stability and height of the mountain. If Fr < 0.5, air is more likely to be diverted around the mountain. A Froude number between 0.5 - 1, may result in partially blocked flow, but specific flow behavior will depend on the topography of the given mountain (Smolarkiewicz & Rotnun, 1989).

Different effects can occur depending on how the airflow interacts with a mountain. For example, when air is diverted around a mountain, frontal stretching deformation can occur (Spensberger & Spengler, 2014). Frontal stretching deformation occurs as airflow normal to a mountain compresses the front, but flow closer to the mountain is diverted around it. Oftentimes, the diverted flow can stretch the already-compressed front and temperature gradient with help from barrier jets which are parallel-blowing jets on the windward side of mountains caused by low-level flow being blocked (Braun et al., 1999; Lundquist et al., 2010). Thus, stretching deformation can strengthen fronts by increasing the frontal temperature gradient. The opposite has also been observed through previous simulations that have shown that shorter mountains, and thus weaker diverted flow, often results in weaker fronts (Colle et al., 1999).

When air can freely flow over a mountain, precipitation enhancement can occur through the seeder-feeder effect (Houze, 2012; Viale et al., 2013; Yu & Cheng, 2013). This can occur when an upper-level “seeder” cloud precipitates into a lower-level “feeder” cloud. The feeder cloud is generally an orographically-produced cloud on the windward side of a mountain caused by upslope lifting. The hydrometeors from the seeder cloud then aggregate with cloud water in the feeder cloud, which can result in more precipitation falling on the windward side of a mountain (Bergeron, 1965).

The seeder-feeder effect has also been observed to have a bigger impact on areas with shorter and narrower mountain barriers (Yu & Cheng, 2013). In the cases with the strongest seeder-feeder effect, enhancement can be proportional to the intensity of background precipitation multiplied by the oncoming wind speed (Yu & Cheng, 2013).

In addition to how mountain height can affect the Froude number, mountain size and shape can affect upstream air in several other ways. Winds both aloft and near the surface can change in speed and direction due to upstream effects of flow blocking or due to barrier jets (Viale et al., 2013). As a result, frontal orientation along with propagation speed and direction can be altered (Colle et al., 1999). Additionally, barrier jets and upstream blocking can contribute to increases in low-level frontogenesis, convergence, and ascent (Houze, 2012; Viale et al., 2013).

When it comes to narrower barriers, faster wind speeds can limit the growth of hydrometeors and thus reduce the amount of precipitation that falls on the windward side (Eidhammer et al., 2018). In contrast, higher wind speeds have less of an effect on wider mountains in this regard (Eidhammer et al., 2018; Yu & Cheng, 2013). Additionally, precipitation efficiency has been observed...
to increase with mountain width and height, although the relationship is not as strong for the latter. Typically, height has more of an impact on the precipitation efficiency around wider mountains, where for the same width, taller mountains are steeper and thus precipitate more efficiently (Eidhammer et al., 2018).

The impacts of mountains on weather are common in many regions around the world, and many studies have observed features of such orographic impacts (Chiao et al., 2004; Houze et al., 2017; Stoelinga et al., 2003; Yu & Cheng 2013). However, most studies focus on precipitation enhancement around the base or the top of barriers (e.g. Eidhammer et al., 2018; Hobbs et al., 1973; Wicraft et al., 2005). As a result, there is a distinct lack of studies observing the orographic effects on precipitation further upstream of mountains. Additionally, few studies have looked at this phenomenon in the Pacific Northwest (e.g. Liu & Bond, 2002). As a result, this study looks at frontal precipitation enhancement upstream of the Olympic Mountains of Washington State.

The Olympic Mountains Experiment (OLYMPEX) field campaign gathered data in the Olympic Mountains region of the Pacific Northwest to validate satellite measurements of precipitation from November 2015 - mid-January 2016 (Houze et al., 2017; McMurdie et al., 2018). This data has been utilized by the primary author in a separate analysis of this phenomenon. This separate analysis will later be used in conjunction with the present research, which shares the same region of study. The Olympic Mountains of Washington State, U.S.A. stretch around 80 km in diameter with peaks approaching 2,000 m (Fig. 1). As a quasi-circular mountain range, the Olympic Mountains present a unique case to study orographic precipitation enhancement compared to the quasi-linear ranges that have often been studied (e.g. Viale et al., 2013; Yu & Bond, 2002; Yu & Cheng, 2013). The purpose of this study is to determine how far upstream of the Olympic Mountains orographic enhancement of frontal precipitation occurs and to understand how thermodynamic and dynamic conditions, such as wind speed, direction, and atmospheric moisture affect this enhancement.

Fig. 1. Map of terrain height showing the domain analyzed from the CONUS simulation

2. Data and Methods

To perform the analysis, model simulation data was utilized. Model simulation data has the advantage of having more readily-available variables to work with while also bypassing common complications of observational data (e.g. radar noise). Furthermore, model simulation data has more information over bodies of water compared to observational data and has larger spatial coverage overall. This will be advantageous when looking at the regions upstream of the Olympic Mountains, which are primarily over the Northern Pacific Ocean. A separate analysis of the OLYMPEX observational data, however, will complement the present study by allowing us to compare the results of a real-life event to a simulated event.

Specifically, this study used NCAR’s 13-year Contiguous United States (CONUS) Weather Research and Forecast (WRF) model current-climate simulation (Liu et al., 2017). The CONUS simulation consists of simulated weather data from 1 October 2000 - 30 September 2013. Unlike most reanalysis datasets and regional climate simulations, this WRF simulation is high-resolution with 4-km grid spacing. At this grid spacing, no convective parameterization was utilized given the model can directly resolve most meteorological phenomena larger than shallow convection.

For this simulation, Liu et al. (2017) made numerous changes to the Noah-MP land surface model (LSM) which resulted in significant improvements to WRF skill. Such improvements included implementing a superior precipitation type diagnosis, reducing low-temperature biases caused by over-assuming snow coverage, allowing patchy snow in the calculation for surface energy balance to prevent snow from melting too early, and allowing heat transfer from precipitation
particles to the ground (Liu et al., 2017). However, during the cold season, precipitation intensity was found to be suppressed by the model. This resulted in a precipitation reduction by about 10% over the mountains of the western United States when compared to SNOTEL gauge data. Regardless, this simulation is noted to simulate coastal and topographic modification of precipitation proficiently in the western United States (C. Liu, personal communication; Liu et al., 2017). As described in Liu et al. (2017), the simulation was compared to seven observational datasets, including the Parameter-elevation Regressions on Independent Slopes Model (PRISM), to evaluate WRF’s precipitation accuracy. PRISM data provides 4-km resolution temperature and precipitation data both daily and monthly. By comparing the CONUS simulation to PRISM data, Liu et al. (2017, their Fig. 7) shows that the model precipitation spatial pattern bias stays within the range of observational uncertainty (among the seven datasets) around the Olympic Mountains. Since the model simulation data is within the range of observational uncertainty in the Olympic Mountains region, we believe that this data is sufficiently accurate for the present analysis. Further information on the simulation, including the methods and parameters used and evaluation of the model’s accuracy, is discussed in (Liu et al., 2017).

The present study focuses on the cooler months for the Pacific Northwest since the vast majority of precipitation commonly falls between the months of October-March (Warner et al., 2012). This is due in part to storm tracks moving further northward during the summer months, resulting in less precipitation. As of the publication date of this study, we have focused on the months of January, February, and March of 2001.

We used a domain that encompasses the area from the far western border of the model simulation over the Northern Pacific Ocean to the eastern edge of the Cascade Mountains. It also roughly extends from central Oregon, U.S.A. to southern British Columbia, Canada (Fig. 1). This large domain ensures that the vast majority of precipitation enhancement is captured including any effects by the Cascade Mountains. The large western extent of the domain is included since the predominant wind direction is westerly and thus most upstream precipitation enhancement will be contained in that area.

The present analysis looked at the model output times with frontal passages. These times were manually identified by using six-hourly plots of 925-mb potential temperature and wind to identify potential temperature gradients and wind shifts which are commonly associated with fronts. To identify patterns, we analyzed five characteristics for each front: frontal type, orientation, velocity, warm-air moisture content, and accumulated precipitation. The following five methods were employed to analyze each characteristic:

1. To determine whether a front was a warm or cold front, we looked at the direction that the wind in the cold air was blowing relative to the front (e.g. wind in the cold air blowing towards the front is a cold front). For occluded fronts, we looked for potential temperature ridges.

2. Fronts were manually drawn onto the plots to illustrate their locations and orientations. By looking at these fronts throughout time, we identified how frontal orientation changed with distance from the Olympic Mountains and we identified which side of the mountains primarily impacted the fronts. We looked at the latter because wind direction can change the effective mountain width that the flow will experience, which also affects how precipitation will be enhanced (Eidhammer et al., 2018).

3. Frontal velocity was analyzed by manually plotting a point on any given front every six hours until the front reached the Olympic Mountains. We then calculated frontal speed by dividing the distance that the front traveled between two points by the amount of time that elapsed (six hrs). This allowed us to see how frontal propagation velocities changed with distance from the Olympic Mountains.

4. The warm-air moisture content was analyzed using precipitable water, the measure of total water vapor content in a vertical column of unit cross-sectional area. We identified the precipitable water values within the warmer air mass, the air mass that typically ascends and produces the most clouds and precipitation. This metric is important because more precipitable water means more water vapor in the atmosphere. As a result, orographic precipitation enhancement can then potentially yield more precipitation due to the atmosphere being closer to saturation.

5. An analysis of precipitation was done using plots of accumulated precipitation over the previous three hours (Fig. 3). We identified local maxima in the three-hour accumulated precipitation field along the
fronts that could not be explained by larger precipitable water values.

Each of these characteristics can affect how precipitation is enhanced. By looking at each characteristic as a function of distance from the mountains, we identified patterns that occurred as these fronts approached the mountains. Furthermore, we compared the changes that occurred during each event to each other to draw further conclusions regarding the influence that each characteristic may have on fronts and their associated precipitation.

3. Results and Discussion

Five fronts were identified and analyzed, namely: two cold fronts, two warm fronts, and an occluded front. Although small, this sample size was sufficient for identifying possible patterns in these events. Yet, more analysis is required in the future not only of additional fronts but of the details of the perceived patterns.

Analysis of frontal orientation revealed there was no dominant frontal orientation throughout this sample. Fronts ranged from being oriented north-to-south to being oriented east-to-west and did not seem to change in any predictable manner. Additionally, more analysis is required to determine if the small changes in the effective mountain width that flow experiences have a significant impact on upstream precipitation enhancement. Regardless, the orientation analysis will likely be useful in the future when identifying which fronts may have additional local effects based on their locations (e.g. strong winds from the Strait of Juan de Fuca; Overland & Walter, 1981).

Through the frontal propagation velocity analysis, all five fronts were observed to slow down as they approached the Olympic Mountains. Four out of five fronts slowed down to almost half of their original propagation speeds even though fronts typically move at a near-constant speed as they propagate over the ocean. “Warm Front (03/30-31)” on Fig. 2 was even observed to become near-stationary before proceeding near its original speed of around 35 km hr⁻¹.

This oftentimes substantial frontal propagation slowing can lead to a unique type of precipitation enhancement. Due to this frontal deceleration, the locations at the surface received more precipitation than they would have otherwise had the front propagated at a constant or increasing speed. This occurred because the fronts and their associated precipitation spent more time precipitating over the upstream regions due to slower propagation speeds. In the future, this analysis should be done on more fronts to identify more accurate patterns when it comes to the upstream extent of and rate of this deceleration.

Additionally, “Cold Front (01/03)” and “Occluded Front (01/12-14)” were observed to begin slowing down at around 700 km upstream of the Olympic Mountains. These fronts may have begun slowing even further upstream, but that puts the front outside of the western extent of the CONUS simulation’s domain and thus cannot be analyzed. However, the significant slowing of the occluded front may be due in part to the associated low-pressure system losing its upper-level support as evidenced by the decreasing wind speeds and the eventual disappearance of the front before intersecting the Olympic Mountains. Regardless, this upstream slowing may be evidence that the Olympic Mountains have a large range of influence in the upstream region. However, this upstream slowing may instead have been caused by the land in general, coastal mountains, the Cascade Mountains, or other effects and terrain features.

More analysis, possibly using a WRF simulation that removes the Olympic Mountains, is needed to confirm that the slowing is indeed induced by the Olympic Mountains.

This study notes that it may be possible that the “Warm Front (02/03-04)” in Fig. 2 may appear to be slowing down due to the subjective nature of frontal identification. Regardless, this warm front appears to slow down less rapidly compared to the other fronts, and thus further analysis is needed to determine why this occurred. It is speculated that the unique northwest-southeast orientation of this front may have played a role in this anomaly.

Only the two cold fronts exhibited obvious local accumulated precipitation maxima (Fig. 3). Whether it
Fig. 2. Line graph of the changes in propagation velocity of five fronts as they approached the Olympic Mountains. The x-axis location of each symbol is the distance from the Olympic Mountains to the average location of the front over some 6-hr period. The y-axis location is the average propagation velocity of the front over the same 6-hr period. Distance from the Olympic Mountains decreases moving right on the x-axis.

Fig. 3. Plots of three-hour accumulated precipitation (filled contours) and 925-mb wind. Local accumulated precipitation maxima are circled and cold fronts are illustrated. The star marks the Olympic Mountains. The interval between each plot is three hours.
is a coincidence that only cold fronts exhibited local accumulated precipitation maxima in our sample or if the nature of cold fronts is more conducive to precipitation enhancement is not clear at this time. A larger sample size will be required to determine this.

These areas of enhancement seemed to be concentrated directly upstream of the Olympic Mountains. For example, as “Cold Front (01/07-08)” moved towards the Olympic Mountains, the enhancement grew in surface area until it was nearly parallel with the Olympic Mountains. Additionally, this precipitation enhancement was observed even 560 km upstream of the Olympic Mountains, thus providing further indication that the Olympic Mountains might have a larger domain of influence upstream than previously expected. This idea is further supported through our analysis of precipitable water where we determined that this enhancement did not come from an increased amount of water vapor. This was confirmed because, along the entirety of the front, there were minimal changes in precipitable water (not shown). Thus, the enhancement was unlikely to have been caused by any part of the front having more water vapor to condense compared to the rest of the front. While this is an example of precipitation enhancement, more analysis of three-dimensional flow and convergence fields needs to be done to determine if this precipitation enhancement was orographically-induced.

4. Conclusion

While previous studies have concentrated on orographic precipitation enhancement close to mountain ranges themselves, very few have looked at the phenomenon farther from the ranges, and even less in the specific region of the Pacific Northwest. This study has investigated how frontal type, orientation, velocity, and warm air moisture content impact frontal precipitation upstream of the Olympic Mountains. Furthermore, this study also gave insight into how far upstream of the Olympic Mountains frontal precipitation can be enhanced. Using data from NCAR’s high-resolution CONUS current-climate simulation from the WRF model, five fronts were observed and analyzed, namely: two cold fronts, two warm fronts, and an occluded front.

Through both the analysis of local accumulated precipitation maxima and of frontal propagation velocities, the results suggest that the Olympic Mountains may have a larger upstream influence than previously expected. All five analyzed fronts were observed to slow down as they approached the mountains. Additionally, four out of five fronts slowed down to almost half of their original speeds while two fronts even began decelerating around 700 km upstream of the Olympic Mountains. Furthermore, local accumulated precipitation maxima were observed with the two cold fronts, one maximum even occurring 560 km upstream of the Olympic Mountains. We were able to rule out an increase in water vapor as the cause of these maxima, but other factors besides the Olympic Mountains may have had a substantial influence on this enhancement.

Future work will require the analysis of more fronts to better understand these patterns. Additionally, although both the frontal deceleration and the local accumulated precipitation maxima work to enhance the amount of precipitation that an area receives, further analysis is necessary to determine if this enhancement was caused by the Olympic Mountains. This can be done by analyzing three-dimensional flow and convergence fields to identify areas of ascent and effects that could slow fronts down associated with the Olympic Mountains. Furthermore, running WRF with and without the Olympic Mountains or other terrain features will allow us to determine how the Olympic Mountains affect its upstream regions.

The seemingly large upstream impact from the Olympic Mountains on the frequent frontal passages in the area makes it crucial that the conditions that cause this orographic precipitation enhancement are understood and accurately incorporated in weather models. Accurate incorporation into weather models will not only improve forecasts for the upstream region of the Olympic Mountains, but it will also yield better forecasts for more populated areas as the upstream air propagates eastward towards the downstream regions. Additionally, this large upstream impact was largely unnoticed in the existing literature focusing on areas near the mountains themself. These results suggest that more studies should focus on the upstream regions of other mountain ranges to study the effects of this rarely-explored area of orographic precipitation enhancement.
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