EFFECTS OF OROGRAPHY ON MESOSCALE ENSO PRECIPITATION ANOMALIES IN THE WESTERN U.S.

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1. INTRODUCTION

Located to the east of the Pacific Ocean, hydroclimate conditions of the western U.S. are strongly affected by large scale atmospheric circulation bringing abundant moisture during the cold season into the continent. Because of strong interannual variability of atmospheric circulation mainly associated with the El Nino-Southern Oscillation (ENSO), hydroclimate of the western U.S. also displays strong interannual variability. Precipitation and temperature anomalies during ENSO often show opposite and spatially coherent warm-dry and cool-wet patterns in the PNW and California or vice versa. They exert major influence on the interannual variability of surface hydrologic budgets and water resources of the region (e.g., Dracup and Kahya (1994), Cayan (1996)).

While the foundation of predictability of large-scale seasonal climate is based mainly upon the interactions of the atmosphere with the slow-varying surface boundary conditions such as sea surface temperature, soil moisture, and snow, predictability of regional scale seasonal climate may also depend upon the interactions between the anomalies of atmospheric circulation and geographic features such terrain, land cover, and oceans or lakes. The role of orography in establishing mesoscale ENSO anomalies has not been fully explored in previous studies owing to the lack of high spatial resolution observational data and modeling results. This paper will examine the ENSO anomalies in the western U.S. based on observed precipitation and temperature data at $1/8^{o}$ spatial resolution and regional climate simulations at 40 km spatial resolution. Diagnostics will be performed to elucidate the role of orography in the establishing the ENSO anomaly patterns.

2. DATA AND REGIONAL SIMULATION

Two sets of data were used in our analyses. They are the maximum and minimum surface temperature and precipitation gridded at $1/8^{o}$ for 1949-2000. This dataset covers the conterminous U.S. and the Columbia River basin north of the U.S.-Canada border (Maurer et al. 2001). The second dataset is the NCEP/NCAR reanalyses that were spatial interpolated to the regional climate model domain for our analyses.

A 20-year regional climate simulation performed using the Penn State/NCAR Mesoscale Model MM5 (Grell et al. 1993) driven by the NCEP/NCAR reanalyses was used in our analyses. The simulation was initialized on July 1980 with lower and lateral boundary conditions updated every 6 hours based on the NCEP/NCAR reanalyses large-scale conditions. Simulation was performed using a nested configuration with the larger domain covering the whole U.S. and surrounding oceans at 120 km resolution and the nested domain covering the western U.S. at 40 km resolution. Analyses were performed using simulation at the nested domain from 1 September 1980 to 30 June 2000. An evaluation of the seasonal statistics of the simulation was described by Leung et al. (2002).

3. ANALYSES

It is generally accepted that regional temperature and precipitation tends to vary as a whole within regions such as the Northwest and California, and therefore spatial variations are less important when looking at interannual variability than seasonal means, which have spatial distribution highly resembling that of the terrain. Using the Southern Oscillation Index (SOI), defined as the standardized difference in sea level pressure anomalies between Tahiti and Darwin, to classify El Nino years when SOI is -0.5 or less, we selected 1983, 1987, 1988, 1992, 1995, and 1998 as El Nino years for our analyses.

Figure 1 shows the observed and simulated composite El Nino anomalies of precipitation during 1980-2000. Anomalies are estimated based on the difference between mean El Nino year conditions and long term mean conditions. The major patterns of the anomalies are indeed dictated by the North-South patterns- warm-dry in the Northwest and cool-wet in California (temperature not shown). However, the effects of topography are not negligible. Most notably, the largest dry anomalies during El Nino in the Northwest are found on the windward side of the

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Olympic Mountain, the Cascades, and the Northern Rockies. The rest of the Northwest region typically shows very small anomalies except on the lee side of the mountains (e.g., northeast of the Olympic Mountain and the Cascades) where regions of positive anomalies are often found instead. The largest wet anomalies are located in northern California and along the Sierra and the southern coast.

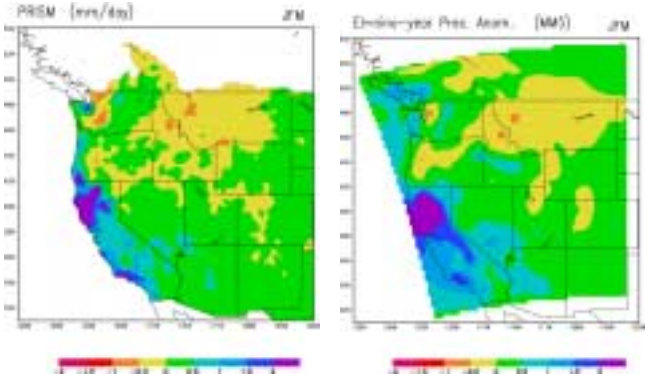

Figure 1. Observed (left) and simulated (right) El Nino precipitation anomalies (mm/day) during 1981-2000 for January-March (JFM).

The NCEP/NCAR reanalyses (not shown) only captures the very broad spatial features of the temperature and precipitation anomalies, namely the gradual increasing warming trend towards the north, and wet and dry anomalies along the coast and further inland. The regional simulation represents a clear improvement over the NCEP/NCAR reanalyses that provided the large-scale conditions for driving the simulation. It correctly captures mesoscale features associated with the complex terrain such as the positive-negative-positive anomalies on northeast Olympic Mountain and windward and lee side of the Cascades, and the large wet anomalies in northern California.

To understand the impacts of orography on the mesoscale ENSO anomalies, we analyzed the relationships between circulation and precipitation during the cold season. Our analysis is based on the regional simulation alone because it was able to reproduce the mesoscale features being studied. We restrict our analysis to the Pacific Northwest since more interesting signals of positive and negative signs are found in the mesocale anomalies. Three regions corresponding to locations with positive-negative-positive precipitation anomalies near the Olympic Mountain and the west and east sides of the Cascades are selected. The anomaly correlations between monthly mean zonal wind and the zonal component of moisture flux along the Pacific coast (near 125^{o}W and 45^{o}N) with precipitation are 0.89 and 0.86 respectively showing significant impacts of zonal flow and moisture flux on precipitation events in the Northwest.

During El Nino winters, the total moisture flux along the Pacific coast increases by about 23% compared to normal years, and the increase is mainly associated with southwesterly flows. There is also a change in the frequency distribution of wind direction as shown in Figure 2. During El Nino years, the frequency distribution is narrower and the mean wind direction shifts from about 185^{o} near westerly during normal years to about 202^{o} towards more southwesterly.

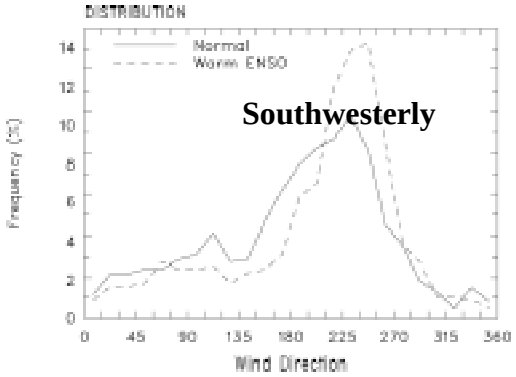

Figure 2. Frequency distribution of wind direction near Washington coast during El Nino (Warm ENSO) and Normal years.

The reduction in precipitation caused by such a change in flow frequency is largest on the west of the Cascades because orographic precipitation, which is strongest with westerly flow, is much reduced. At the Olympic Mountain (which has no preferred direction of orographic forcing) and east of the Cascades, the increase in precipitation related to the increased moisture flux and frequency of flows near 225^{o} more than compensate for the loss of precipitation associated with the reduced frequency of flows near 200^{o} to create positive precipitation anomaly during El Nino years.

As an illustration of how wind direction affects orographic precipitation in the Northwest mountains, Figure 3 shows the precipitation associated with flows near 180^{o} and 200^{o}, which correspond to mean flow directions during Normal and El Nino years, along a east-west transect along 47.8^{o}N. The transect is 40 km wide and cuts across the Olympic Mountain, the Cascades, upper Columbia Basin, and the Northern Rockies. Note that more moisture is typically associated with flows near 200^{o} coming from the warmer side of the Pacific Ocean than westerly flows.

For westerly flow, orographic precipitation is particularly strong on the west of the Cascades. As a

result of changes in flow direction and moisture content, the difference between the precipitation associated with the two flow regimes exhibit a positive-negative-positive pattern that is similar to the El Nino anomalies. The change in sign between the difference in precipitation associated with the two flow regimes from the Olympic Mountain to the west and east of the Cascades is clear and physically consistent with the interactions of wind with the underlying topography. Therefore the spatial distribution of the El Nino precipitation anomaly near the coast, along the Cascades, in the Columbia Basin, and the Northern Rockies can be generally explained by the interactions between changes in wind direction and moisture flux with the underlying topographic features of the Northwest.

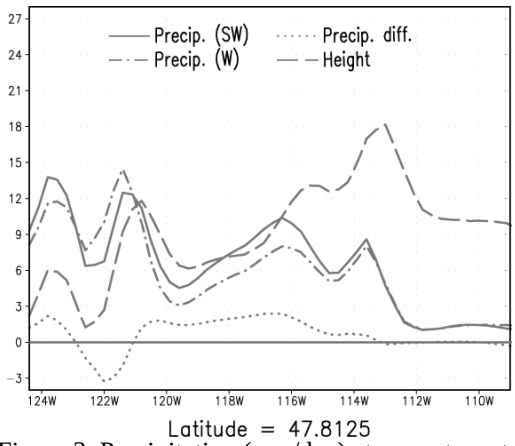

Figure 3. Precipitation (mm/day) at an east-west transect across the PNW averaged over January-March for near westerly flows (W) between 170-180^o and towards southwesterly flows (SW) between 190-200^o based on regional simulation. Also shown are the difference in precipitation associated with the two flow regimes and surface elevation (100m).

The large positive El Nino precipitation anomaly in California can be more easily explained by changes in large-scale circulation. We analyzed the wind and moisture flux off shore northern California, near 123^{o}W and 38^{o}N, and precipitation at two locations on the southern Cascades and Sierra. The shift in wind direction during El Nino years near California (Figure 4) is even more profound than that in the Northwest. During El Nino years, there are clearly reduced frequency of northerly to northwesterly flows and increased frequency of westerly to southwesterly flows with 22% increase in total moisture flux similar to that in the Northwest.

In the Sierra, changes in moisture flux and wind direction both favor stronger precipitation for the terrain features. As a result, El Nino precipitation anomaly is positive and reflects the effects of circulation changes and orographic enhancement. On the Sierra, particularly the southern area, more increase in precipitation is associated with wind directions between 225^o and 250^o which are the preferred flow direction for orographic forcing in the northwest-southeast oriented mountain range.

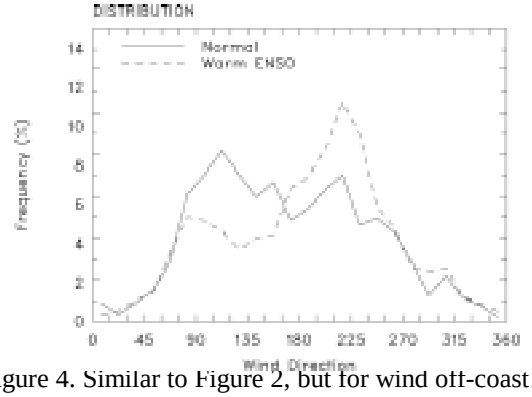

Figure 4. Similar to Figure 2, but for wind off-coast of northern California.

Summarizing the analyses for the whole western U.S., unless a model correctly captures both changes in large-scale circulation during ENSO events and orographic effects of mountains on precipitation, mesoscale ENSO precipitation anomaly features cannot be precisely predicted. This will have important implications to seasonal climate predictions and their applications to water resources in regions of complex terrain.

4. REFERENCES

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