COMET – Partners Outreach Project SO6-58387

Final Report

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Project Title: Quantitative Precipitation Forecasting of Extreme Winter Rainfall in the Sierra Nevada

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1. Summary of Project Objectives

The objective of this project is to provide research findings on the cause of heavy winter "spillover" rainfall events to the NWS forecasters so that they can improve their ability to predict potential major rainfalls that cause flooding in the Truckee River basin. This is a highly relevant problem for the NWS Reno, Nevada forecasters because floods can occur relatively frequently and it is so very difficult with existing observations and numerical model products to reliably differentiate in advance between the likelihood of a major rainfall event and minor rainfall event in the populace "spillover" region just downstream from the Sierra Nevada Mountains. Forecasting precipitation in this lee side region represents a major challenge given the lack of upstream observations and limited operational model horizontal resolution of the deep air flow to the lee of the Sierra Nevada. Additionally, accurate forecasts of temperature in higher elevations are equally challenging and critical to the local flash flooding problem as snowmelt and the elevation of rainfall have major influences on the runoff rates in the Truckee River Basin.

2. Project Accomplishments and Findings

The project's accomplishments are primarily its findings concerning the processes that cause heavy "spillover" precipitation in the Washoe Valley. These findings can be grouped into two main categories: 1) an improved understanding of the short period mesoscale dynamics leading to "spillover" precipitation to the lee of the Sierra Nevada and 2) the long period synoptic and mesoscale scale transport dynamics responsible for the advection of substantial midtropospheric moisture to the lee of the Sierra Nevada. "Spillover" refers to a category of precipitation, which occurs to the lee of very tall mountain barriers. In reality, much of spillover precipitation is the result of blowover precipitation as hydrometeors are advected by a strong mid-level jet into a moist unstable environment established by larger scale processes. Two case studies were closely analyzed employing observations and mesoscale numerical simulations. Both were major flooding case studies, i.e., 1-2 January 1997 and 30-31 December 2005. Observations and numerical simulations down to 1 km horizontal resolution indicate a sequence of events, which starts several days before over Eastern Asia and the western Pacific resulting in ideal conditions for extreme spillover precipitation to the lee of the Sierra Nevada. We will describe these findings first from the multi-day transport scenario and second from the lee side mesoscale dynamics perspective. It needs to be emphasized that upstream over the Pacific as well as downstream over northern Nevada the atmospheric flow can be described in terms of 3 jets, an upper-level polar air stream, a mid-level jet sandwiched in between the upper-level polar air stream and a low-level jet.

Finding #1: The transport of moisture from the Pacific to northern Nevada is the result of a sequence of baroclinic cyclone scale waves that build upscale to produce a massive jet streak spanning most of the Pacific just prior to the heavy rainfall event. Each wave transports moisture downstream at low-levels by its low-level return branch as part of a transverse ageostrophic circulation as well as at mid-levels by convectively-induced outflow. The mid-level moisture, so important to cross mountain flow, results from convective forcing in which air parcels are lifted due to the upstream diabatic heating from mesoscale convective systems. Moisture is being pumped vertically in sequences of mesoscale convective systems. This mid-level moisture then can be lifted and advected over the Sierra Nevada by the mid-level jet ascending the mountain resulting in orographic uplift and heavy precipitation.

Finding #2: The lee side spillover precipitation is favored when both a transverse ageostrophic and along-stream ageostrophic circulation occur in the exit region of the jet streak. These circulations are associated with a jet streak undergoing a progressively more curved flow and they cause the surface pressure to drop under the upper-level jet exit region. These ageostrophic circulations create a lee side mesoscale trough, which turns the near surface flow from the west to the south to be mountain parallel producing mass flux convergence, upward vertical motion and increased relative humidity over the lee side.

Finding #3: The increased lee side relative humidity accompanying the convergence forced by the mesolow makes it possible for hydrometeors formed in the moist mid-level air lifted up the windward side to blow over the crest as snow and then melt as they fall into warmer air and are transported downstream. This transport of hydrometeors downslope would normally not result in surface precipitation because cross-mountain flow would cause drying and little precipitation in lee side descending air, however the lee side mesolow induces strong low-level ascending motion, which counters the effect of mid-level sinking and sustains a wet enough environment for the downstream advection of hydrometeors to extend well beyond the mountain crest as well as sustaining the development of newly forming convective cells as cold air in the upper-level jet exit region overruns the low-level flow.

Finding #4: In comparison simulations from the AVN analysis first guess initial conditions and the NCEP-NCAR reanalysis first guess initial conditions subtle differences in mid-level moisture and deep jet streak structure upstream over the California coast made a huge difference in the magnitude of spillover precipitation as they had a profound effect on lee side mesolow formation, low-level wind flow, relative humidity and windward side hydrometeor formation.

Finding #5: Numerical models with resolutions significantly coarser than 1 km are likely to truncate away much of the lee side spillover precipitation due to the downstream advection of hydrometeors. This is likely due to the fact that the strong terrain gradients that create the windward side hydrometeors are smoothed out resulting in an upstream shift in precipitation maxima. This is very dependent on model initial conditions and microphysics.

3. Benefits and Lessons Learned: Operational Partner Perspective

Lesson Learned and Benefit #1 – The mid-level moisture transport necessary for heavy spillover precipitation in the lee of the Sierra Nevada originates over the southwest Pacific. The moisture is lifted to mid-levels by mesoscale convective systems triggered by baroclinic waves and then advection downstream by the systems' outflow. Tracking the series of baroclinic waves and the associated moisture transport across the western Pacific and their downstream development will help forecasters anticipate potential significant spillover events many days in advance. Using this information, forecasters at WFO Reno can better communicate potential flood events to affected emergency managers several days in advance. This is especially important due to the rapid response times of rivers and streams to heavy rainfall in the lee of the Sierra Nevada.

Lesson Learned and Benefit #2 – The divergent area of the upper-level jet streak exit region plays an important role in turning the low-level flow more mountain parallel from the ageostrophic low-level return circulations and by changing the low-level pressure gradient force. This in turn also permits more low-level convergence in the lee side of the Sierra Nevada and a more moist low-level environment favoring spillover precipitation. Understanding the interactions between the upper level jet streak, its associated ageostrophic circulations, and a cold front aloft will aid forecasters at WFO Reno in anticipating and forecasting significant spillover events, as well as the formation of the mesolow.

Lesson Learned and Benefit #3 – The increased humidity on the lee-side due to the low-level convergence forced by the mesolow allows for more hydrometeors generated on the windward side of the Sierra Nevada to fall as spillover precipitation on the lee side. The colder the air aloft behind the cold front aloft and the stronger the winds aloft are more likely to produce snow on the windward side. The snow is more easily advected downstream into the lee side where it can fall as rain as it descends into a warmer environment. Forecasters at WFO Reno can use the underlying microphysics to better estimate the amount of hydrometeors that will fall as spillover precipitation due to advection downstream. However, forecasters must be aware of model microphysics and initialization as the microphysics and initialization can have a profound effect on the amounts of spillover produced by the model. This knowledge can aid forecasters in making necessary adjustments to model forecasts.

Lesson Learned and Benefit #4 – There is great sensitivity to model forecasts of spillover precipitation to the initial conditions. Forecasters at the WFO should pay close attention to the model initialization of both the upper level and low level jet structures and understand how any model initialization errors may impact the forecast. Forecasters can then make the necessary adjustments and/or utilize ensemble forecasts to better gauge the uncertainty of the amount of spillover precipitation.

Lesson Learned and Benefit #5 – Model resolution plays a major role in the ability of the model to forecast lee side precipitation. Model resolution much coarser than 1 km are likely to produce too weak a mesolow with precipitation too light in the lee-side. Currently, the highest resolution model available to forecasters at WFO Reno is the Weather Research and Forecast Environmental Modeling System (WRF-EMS) run locally at 4 km. Forecasters will be aware that even this model may under do the strength of the mesolow and therefore under forecast spillover precipitation. Forecasters must make adjustments and downscale accordingly to the best of their knowledge using the conceptual model described above.

4. Benefits and Lessons Learned: University Partner Perspective

Lesson Learned and Benefit #1 – The transport of mid-level moisture for heavy precipitation over and downstream from the Sierra Nevada likely originates in the southwestern Pacific and is lifted to mid-levels by mesoscale convective systems and their downstream outflow. Thus an understanding of certain flow regimes across the Pacific can help a weather forecaster anticipate a potential major rainfall event over and downstream from the Sierra Nevada many days in advance.

Lesson Learned and Benefit #2 – The divergent flow accompanying upper-level jet streak exit regions plays an important role in turning the low-level wind flow to be mountain parallel by modifying the low-level pressure gradient force. This results in much wetter air in the lee side environment and a better chance of spillover precipitation, which can be recognized in advance by forecasters. When combined with a strong cold front aloft embedded within the jet exit region the effect on column moistening and destabilization due to adiabatic expansion and cold air advection can be substantial. Forecasters must learn to anticipate this type of feature prior to major flooding events.

Lesson Learned and Benefit #3 – The preponderance of precipitation on the lee side in these heavy precipitation events is likely due to precipitation that forms on the windward side of the mountains near the crest of the mountain range and is blown over by a strong mid-level jet. The colder the air aloft and the stronger this airflow the more likely snow will form on the windward side, which can be available for rainfall downstream on the lee side. This is also very important for forecasters to know in estimating the potential for heavy lee side precipitation. However, this very dependent on model initial conditions and microphysics.

Lesson Learned and Benefit #4 – The initial conditions in numerical models upstream over coastal California are critical in determining the magnitude and distribution of lee side precipitation in Northern Nevada. Forecasters need to recognize that upstream mid-level jet structure and water vapor as well as low-level jet structure are important to recognize as potential precursor signals to downstream spillover precipitation. Additionally, forecasters need to be cognizant of the fact that huge differences in numerical model simulations downstream can be in large part due to numerical model initial conditions as opposed to intrinsic differences in model formulation.

Lesson Learned and Benefit #5 – Forecasters must also be aware of the fact that numerical models with resolutions significantly coarser than 1 km are likely to truncate away much of the lee side spillover precipitation due to the downstream advection of hydrometeors. This is because the mesolow will be truncated out of numerical models resulting in much drier leeside air.

5. Publications and Presentations:

Conference Preprints and Presentations:

12th AMS Conference on Mesoscale Processes Presentation:

Marzette, P. J., M. L. Kaplan, C. Adaniya, J. Wallmann and R. Milne, 2007: Model simulations of extreme orographic precipitation in the Sierra Nevada during the New Year's holiday flood of 2005-2006. Preprints, *12th AMS Conf. on Mesoscale Processes*, Waterville Valley, NH. 9-12 August 2007, 12 pp.

NWA Conference Presentation:

Wallmann, J., R. Milne, P.J. Marzette, M. L. Kaplan, and C. Adaniya, 2007: Model simulations of extreme orographic precipitation in the Sierra Nevada during the New Year's holiday flood of 2005-2006. *2007 National Weather Association Annual Meeting,* Reno, NV. 13-18 October 2007.

Journal Articles in Preparation:

Marzette, P. J., M. L. Kaplan, C. Adaniya, J. Wallmann and R. Milne: Factors influencing major lee side Sierra Nevada rainfall events: Part I: Local mesoscale dynamical processes. In preparation, Mon. Wea. Rev.

Adaniya, C., M. L. Kaplan, P. J. Marzette, J. Wallmann and R. Milne: Factors influencing major lee side Sierra Nevada rainfall events: Part II: Long range transport of moisture from the western Pacific. In preparation, Mon. Wea. Rev.

6. Summary of University/Operational Partner Interactions and Roles:

The university partner and the operational partner have collaborated closely and regularly on this problem. Meetings were held monthly or every other month in which results of the research where presented by the university partners and these results subsequently informally evaluated by the operational partner. Constructive suggestions were made by the operational partner concerning analyses results as well as their potential forecast utility. Results from analyses of observations and simulations have been communicated to the operational partner and feedback presented to the University partner by the NWSFO. A preliminary forecaster's checklist on conditions likely to lead to Sierra Nevada lee side flooding rainfalls has been prepared by both groups collaboratively for eventual use operationally and is included below. Additionally, conference papers and journal articles are being jointly prepared.

PRELIMINARY FORECASTER'S CHECKLIST FOR EXTREME LEESIDE SPILLOVER PRECIPITATION IN THE WASHOE VALLEY

Medium Range (5-10 days before)

- Deep huge very cold air pool spills southward over the coast of Asia from the polar region and northeastern Siberia with the 0C isotherm moving southward across Japan.
- A sequence of cyclone scale waves propagate across the Pacific initiated by this pool of cold air.
- Active waves and cyclones exist within the tropical ITCZ separating the active southern hemispheric circulations from the active northern hemispheric circulations.
- Well-organized 1000 – 3000 km or greater southwest – northeast moisture plume coupling between the tropics and extratropics with >=50 mm column precipitable water over the southwest Pacific south of Japan. Lengthening plume of moisture located in between the ITCZ moisture plume(s) and the equatorward side of the cold front and polar jet with each wave.
- Moisture plume diminishing in magnitude but increasing in depth and length to >=5000 km as it encounters more waves in its northeastwards trip across the Pacific.

Synoptic Range (1-5 days before)

- Polar jet core strengthening over the central Pacific >=75m/s within the 200 – 300 mb layer.
- A uniform polar jet streak encompassing most of the Pacific in the 200 – 300 mb layer >= 5000-10,000 km in length.
- A massive high pressure region, which forms to the southeast of the ageostrophic circulation in the polar jet's equatorward exit region over the eastern Pacific with 250 mb isoheights >=10920 m near Hawaii.

- Pooling of cold air in the midtroposphere on the left side of the polar jet exit region and the strengthening of the 500 mb cross-stream temperature gradient.
- Rightward-directed ageostrophic flow within the 200 – 300 mb layer within the polar jet exit region over a large part of the eastern Pacific.
- Increasing low-level jet development from the south-southwest in time under the exit region.
- A relatively unbroken plume of moisture and precipitation on the equatorward side of the cold front and polar jet with column precipitable water >=30 mm and <=50 mm and coherent convective signals.

Meso-α scale Range (1 day – 6 hours before)

- Polar jet exit region arrives over northern California, Oregon and Washington.
- Rightward-directed ageostrophic flow within the 200 – 300 mb layer within the increasingly diffluent polar jet exit region over northern California and Nevada.
- Increasing radar echoes on the windward side of the northern Sierra spreading southeastwards accompanying a relatively unbroken plume of moisture.
- Pooling of cold air in the midtroposphere on the left side of the jet exit region.
- >=30 mm of precipitable water in the Oakland, California sounding.
- Warm plume of air maximizing at or just below 700 mb in the Oakland sounding close to 0C and 850 mb temperatures approaching 10C with a moist neutral lapse rate in between.
- Strongly veering flow with a secondary midtropospheric west-southwesterly – southwesterly wind maximum in the Oakland sounding in between the low-level jet and polar jet.
- A north-northwest-south-southeast meso-α scale mean sea level pressure trough propagating southeastwards over the Sierras of northern California and Nevada.

Meso-β/γ scale Range (6 hours – 1 hour before)

- Increasing indication of polar jet streak curvature and a meso-β scale wind maximum over the windward side of the Sierras over northern California upstream from Lake Tahoe. The scale contraction of the ageostrophic flow into oppositely-oriented cross stream maxima with the rightward-directed maxima downstream from the leftward-directed maxima.
- Distinct height ridge in the precipitation maximum on the windward side and trough on the eastern side from 500 mb – 300 mb.
- South-southeastward cold air advection in the midtroposphere over the Sierras.
- Bifurcation of the meso-α scale pressure trough into a meso-β scale meso low just north-northwest of the Washoe Valley.
- Increasing south-southwesterly surface wind flow over the Washoe Valley.
- Decreasing static stability and increasing upward vertical motion over the Washoe Valley.