Western U.S. Heavy Precipitation Event – December 18-23, 2010
By: Sean Ryan, HPC Meteorologist

<u>Overview:</u> From December 18-23, 2010, a series of strong Pacific storm systems impacted the west coast of the U.S., resulting in an extended period of heavy rain and snow across the region. Rainfall totals in excess of two feet fell in portions of southern California, with some snowfall totals in the Sierra Nevada estimated in excess of 200 inches. Figure 1 shows the 24-hour Stage IV quantitative estimated precipitation (QPE) across the western U.S. for the duration of the event. One can see that rainfall amounts of 3 to 6 inches in 24 hours were common, especially in areas where the precipitation orographically enhanced. Daily rainfall records were set in Los Angeles and Santa Barbara, 2.80 inches and 2.79 inches, respectively, on December 19. Mud and debris flows occurred across southern California as a result of the duration and intensity of the rainfall. As a result of this storm, Los Angeles Airport reported the wettest December on record, as did Long Beach, Burbank, and Santa Barbara among others. A funnel cloud was even reported in San Pedro on December 22. Overall however, severe convective weather was minimal with this event.

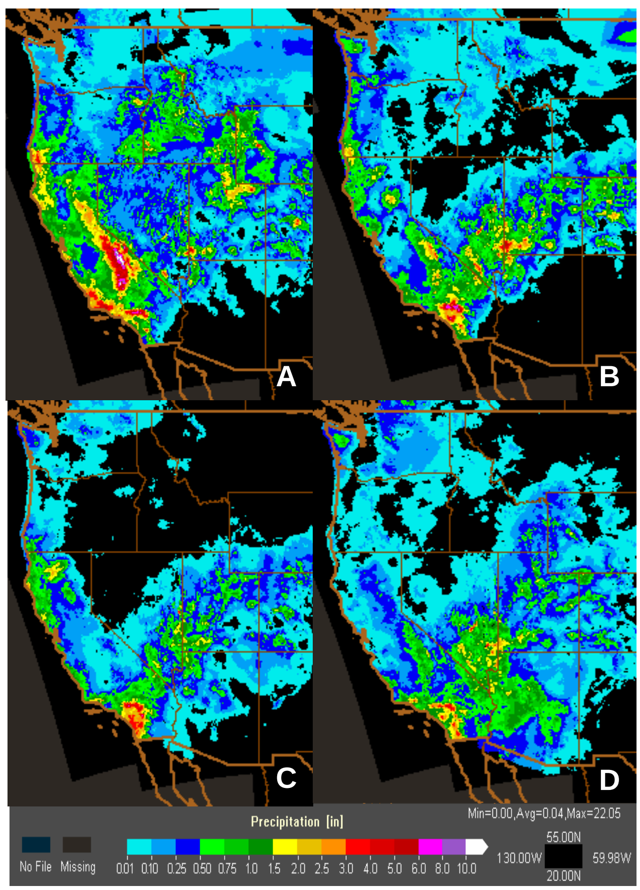

Figure 1: 24-hour Stage IV ending at 12 UTC on 20 December (a), 21 December (b), 22 December (c), and 23 December (d).

Snowfall amounts with this event, as described above, were very impressive, with many mountainous locations measuring snowfall in feet. Table 1 shows some of the more impressive snowfall totals for the region from 18-23 December.

California	
Pascoes Snotel	204
West Woodchuck Meadow	192
Mammoth Lakes 3 WSW	108
Northstar	98
Colorado	
Gothic	82
Crested Butte 6.2 N	78
Coal Bank Pass	48
Red Mountain Pass	45
Nevada	
Heavenly Valley	77
Mount Rose	65
Wheeler Peak	31
Reno 9 W	17
Utah	
Brighton Crest	84
Alta - Collins	69
Provo Canyon	68
Snowbird	50

Table 1: Selected snowfall amounts (inches) from 18-23 December, 2010.

Synoptic Pattern: The primary factor that caused this heavy precipitation event was a favorable synoptic pattern which was supportive of the transport of copious amounts of sub-tropical Pacific moisture into the region. The synoptic pattern remained in place for several days, leading to the long duration of the event. 500-hPa geopotential height anomalies for 19 December (Fig. 2) for the northern hemisphere reveal the large scale pattern present during the event. An anomalous low at 500 hPa was present off the Pacific Northwest coast, resulting in anomalous cyclonic (onshore) flow along the entire U.S. west coast. Also note the anomalous blocking highs at higher latitudes, over the Aleutian islands as well as over northern Canada, correlated with the negative phase of the Arctic Oscillation. The blocking highs helped to stagnate the large scale pattern, keeping the upper-level low in place off the U.S. west coast for an extended period of time. This pattern is consistent with anomaly patterns of atmospheric river events documented by Neiman et al. (2008) and Junker et al. (2008).

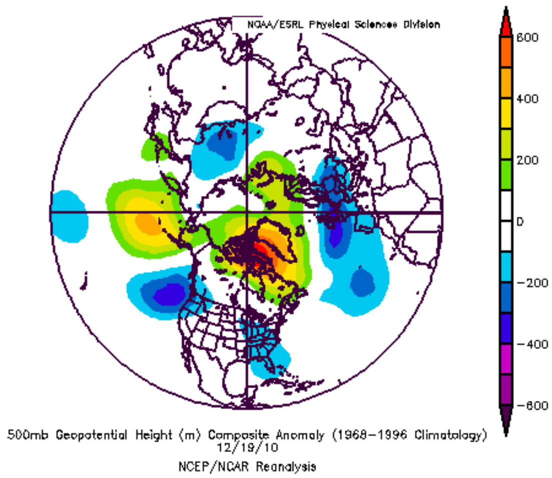

Figure 2: 500 hPa geopotential height anomalies (m) across the northern hemisphere for 19 December 2010.

Analysis of 850 hPa winds at 12 UTC on 19 December (Fig. 3) reveals strong onshore flow of 40 kt across central and southern California. These strong low-level winds served to transport large amounts of moisture northward from sub-tropical regions.

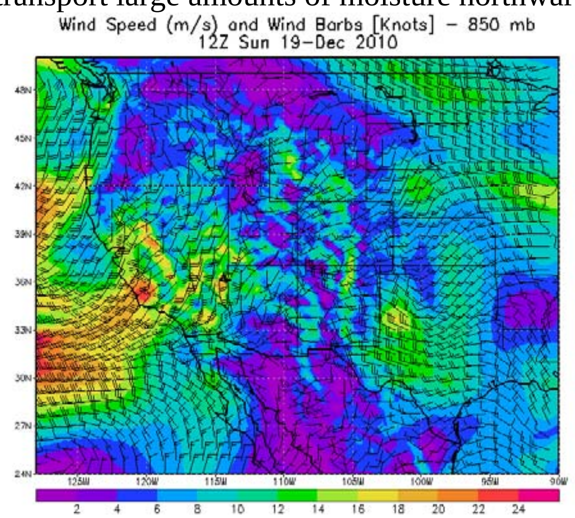

Figure 3: 850 hPa wind speed (m/s) and wind barbs (kt) for 12 UTC 19 December 2010.

Evidence of a long, narrow plume of moisture being transported from the sub-tropics by strong low-level winds is shown on a total precipitable water (TPW) image from 19 December (Fig. 4). A narrow, elongated plume of moisture extending from the central Pacific eastward to the coast of California is evident in the TPW image. Such plumes of moisture from the tropical or sub-tropical Pacific into the U.S. west coast are known as 'atmospheric rivers,' due to their ability to transport large amounts of moisture for long distances away from the tropics. Neiman et al. (2008) provide an excellent description of atmospheric rivers on the west coast, and the heavy orographic precipitation that results when strong low-level winds transport the deep tropical or sub-tropical moisture onto a coastline with elevated terrain.

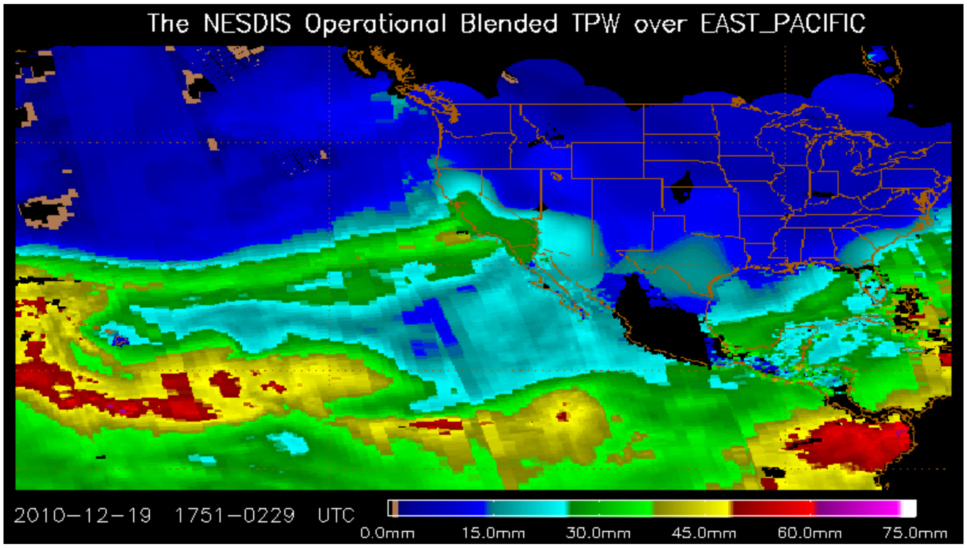

Figure 4: Blended total precipitable water image from NESDIS for 19 December 2010.

As shortwave troughs rotated around the anomalous upper-level low off the Pacific northwest coast, these waves provided the necessarily lifting mechanisms for moisture in the plume to be realized as heavy precipitation.

At the upper-levels, a strong jet stream was present across the region. At this time, California was positioned in the right-rear quadrant of the western U.S. jet streak (Fig. 5) – a favorable location for upper-level divergence and ascent. A NAM 250-hPa analysis (Fig. 6) confirms strong upper-level divergence across the region. A surface analysis from the same time (Fig. 7A) reveals a 977 hPa surface low beneath the anomalous upper-level low over the northern Pacific. Farther south, a cold front was pushing southward off the coast of central California. Strong convergence is evident in the surface winds across coastal California at this time, further aiding the vertical motion across the region. The surface analysis from three days later (Fig. 7B) reveals another storm system just offshore, with heavy rain spreading into central and southern California. The system that impacted southern California on 22 December was the final system in the series affecting the region.

Intense lifting due to warm advection did not seem to play as large of a role in this event as one expects with strong synoptic cyclones across the eastern half of the U.S. A NAM analysis of theta-e advection across the region (not shown) only depicts modest positive theta-e advection across portions of coastal California on 19 December, with negative theta-e advection present across much of coastal California for the remainder of the event. Upper-level vorticity advection was present in episodes as short-waves passed. Thus, weak to moderate synoptic scale forcing for ascent was present. However, this forcing was strongly modified by orographic lifting as the stream of moist air approached the mountain ranges across the western U.S., which served to further increase upward motion on a more localized scale. The orographic lifting present during this event will be discussed in more detail in the next section of the review.

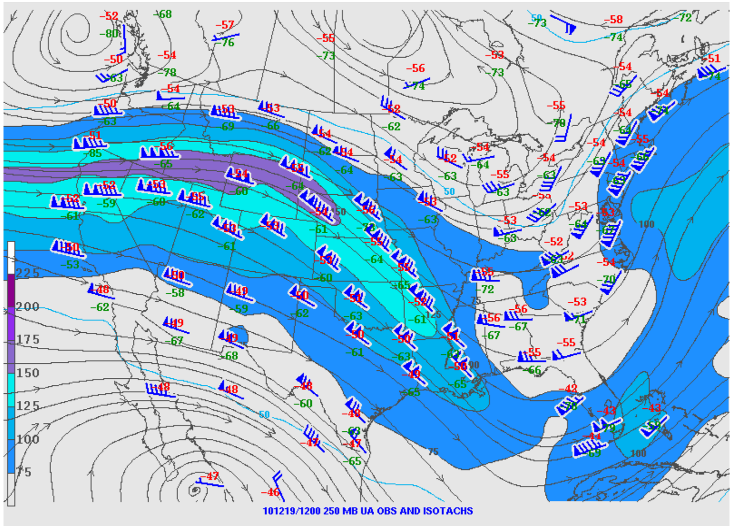

Figure 5: 250 hPa analysis from 12 UTC on 19 December 2010. Analysis shows streamlines, wind barbs, and wind speed. (SPC)

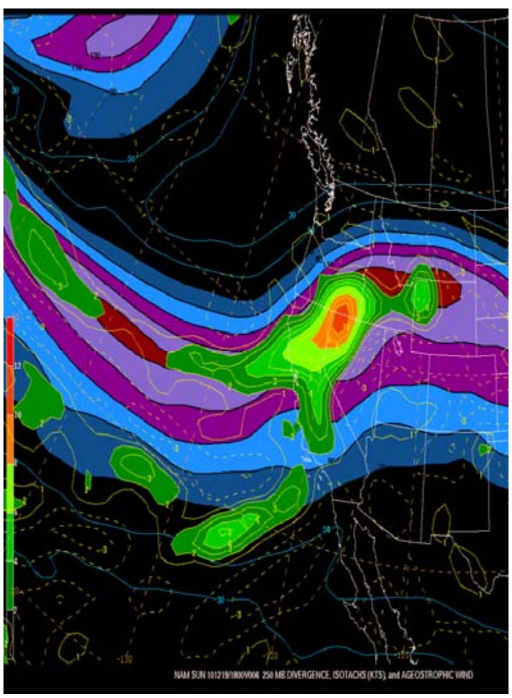

Figure 6: 250 hPa wind speed isotachs (cool color shades; kt) and divergence (warm color shades (x 10^{-5} s^{-1}) from the NAM initialization at 12 UTC on 19 December 2010.

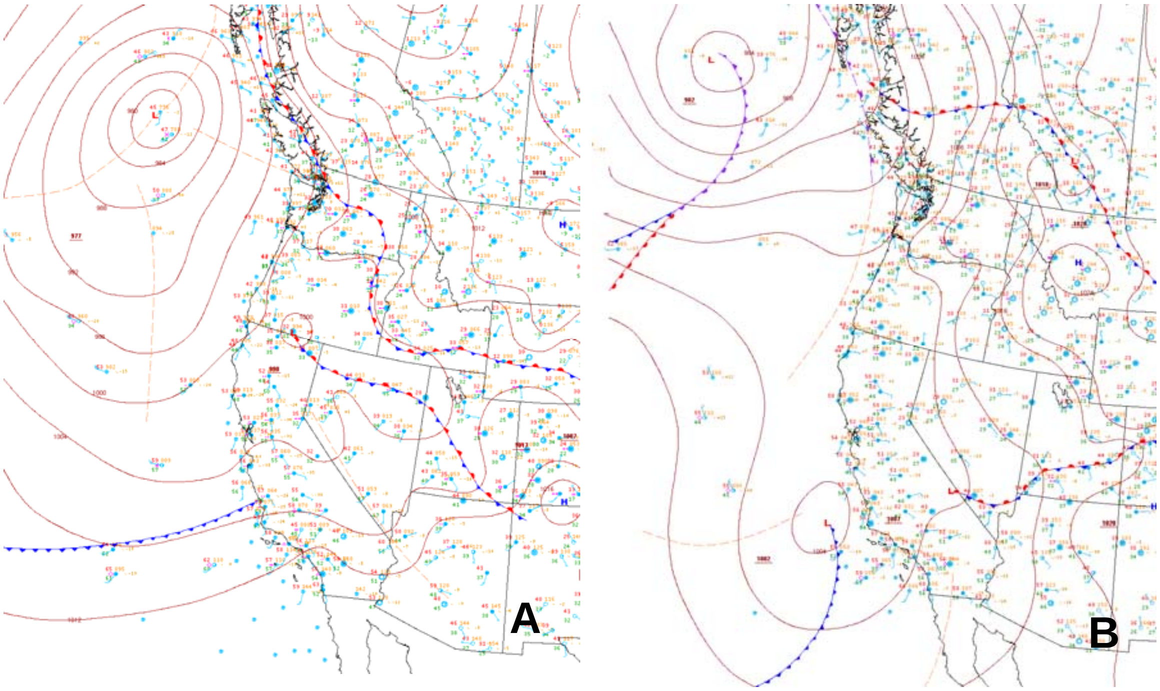

Figure 7: HPC surface analysis from 12 UTC on 19 December 2010 (a) and 12 UTC on 22 December (b).

<u>Mesoscale Features</u>: The most important mesoscale feature that played a role in this event was orographic lifting due to the steep topographical gradients that are characteristic of much of the coastal regions in the western U.S. Rises in elevation of greater than 4000 feet over the span of a couple miles are common in areas such as the San Gabriel mountains north of Los Angeles. The highest peaks of the Sierra Nevada range rise to over ten thousand feet. The topographical map of the region (Fig. 8) shows the various mountain ranges and sharp terrain gradients that are characteristic of the region.

Figure 8: Map of central and southern California showing the terrain of the region (image courtesy of Google Maps).

As strong onshore flow encounters significant rises in terrain after moving onshore, the air is forced upward, causing precipitation to develop. If the flow is strong enough and is oriented at a favorable angle (parallel to topographic gradient), heavy precipitation can develop. A sounding from the Vandenburg Air Force base, approximately 100 miles northwest of Los Angeles on the coast of California, at 12 UTC on 19 December (Fig. 9) shows strong winds in the lower levels of the atmosphere. Southwesterly winds of 30-40 kt at or just above the top of the boundary layer were oriented nearly perpendicular to the coastline, which is nearly east/west oriented at this point along the coast. A plot of 850 hPa winds from the same time (Fig. 3) shows an intense low-level jet extending from the eastern Pacific into California, with 40 kt winds oriented nearly perpendicular to the coast of central California. This amount of onshore flow would have resulted in sufficient vertical velocities to produce heavy precipitation in the mountains north of the coast. Comparison with the surface analysis from the same time (Fig. 7A) shows that the low-level jet was oriented parallel to and ahead of the surface cold front as it pushed southward along the coast of California.

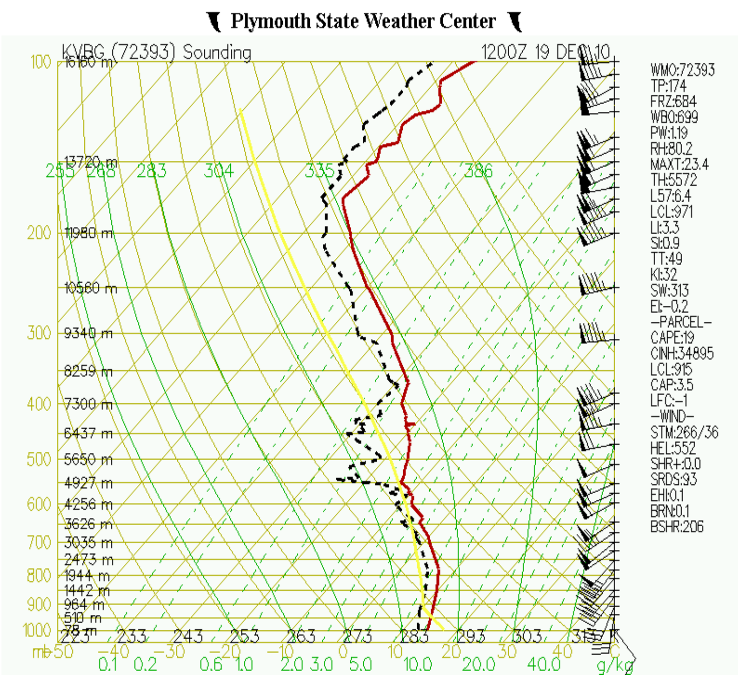

Figure 9: Sounding from Vandenburg AFB (KVBG) at 12 UTC on 19 December, 2010. (image courtesy of Plymouth State University)

The effects of terrain are illustrated most dramatically by comparing two storm total rainfall measurements from stations just a few miles apart, near San Bernadino. The northern suburbs of San Bernadino sit at just below 1500 feet in elevation. Less than 10 miles north of the city, the elevation rises quickly to over 4500 feet, where the town of Crestline sits. One observation in the northern suburbs of San Bernadino reported a storm total rainfall of 12.41 inches for the event; 26.16 inches were measured in Crestline, a difference of over 100 percent over a distance of less than ten miles. In another example, the community of Tanbark, CA, in the mountains east of Oxnard, measured a storm total of over 19 inches of rain; while nearby Oxnard (on the coast) measured just over 7 inches. These large differences in precipitation amounts at locations in close proximity demonstrate the significant role that orographic lifting played in this event. Barrier jets may also augment the precipitation distribution relative to the axis of the highest terrain (Lundquist et al. 2010; Reeves et al. 2008), although this secondary effect was not investigated.

A radar image from 18 UTC on 19 December (Fig. 10) shows widespread precipitation across most of northern and central California, with areas of heavy precipitation that are falling largely over terrain.

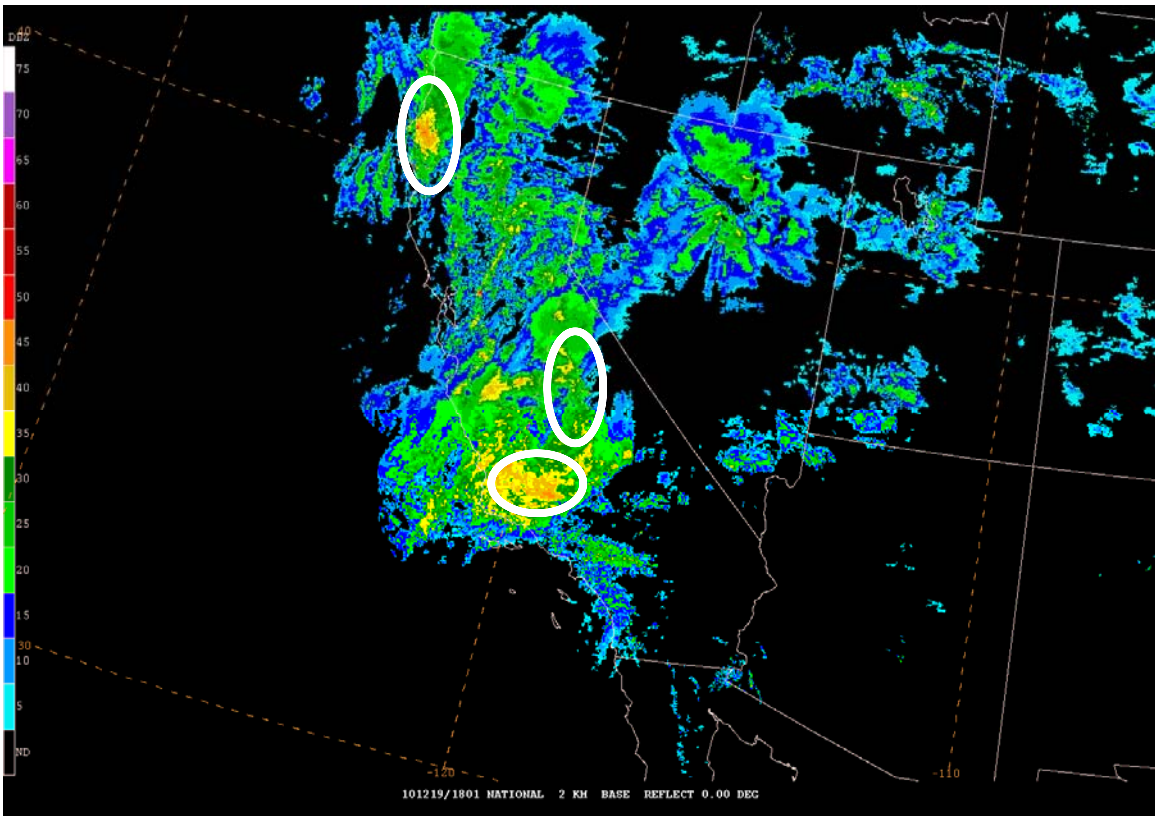

Figure 10: Radar image from 18 UTC on 19 December, 2010. Circled areas denote areas where heavier precipitation was occurring as a result of orographic lifting from terrain. The southern most area is heavy precipitation over the San Gabriel Mountains, the central area is the Sierra Nevada range, and the northern area is over the Northern California Coastal Range.

<u>Conclusion</u>: Widespread heavy precipitation occurred across much of the west coast region of the U.S. from 18-23 December, 2010. Copious amounts of rain and snow fell from the coastal areas to the highest elevations of the mountains. This event was a prime example of an atmospheric river resulting in heavy precipitation across the western U.S. The importance of topography is also demonstrated in this case by the large differences in precipitation amounts between locations at differing elevations. The factors contributing to the heavy precipitation in this case included an anomalous closed low in the north Pacific, a strong jet stream crossing the west coast of the U.S. with upward motion aided in the divergent right rear quadrant of jet streaks, and surface winds oriented favorably with respect to the topographical gradients, causing orographic lifting and enhanced precipitation over mountains. This setup persisted for several days, resulting in incredible snowfall amounts in the mountains, and flooding at lower elevations.

<u>References</u>:

Junker, N. W., R. H. Grumm, R. Hart, L. F. Bosart, K. M. Bell, and F. J. Pereira, 2008: Use of normalized anomaly fields to anticipate extreme rainfall in the mountains of northern California. *Wea Forecasting*, **23**, 336-356.

Lundquist, J. D., J. R. Minder, P. J. Neiman, and E. Sukovich, 2010: Relationships between barrier jet heights, orographic precipitation gradients, and streamflow in the northern Sierra Nevada. *J. Hydrometeor.*, **11**, 1141-1156

Nieman, P. J., F. M. Ralph, G. A. Wick, J. D. Lundquist, and M. D. Dettinger., 2008: Meteorological Characteristics and Overland Precipitation Impacts of Atmospheric Rivers Affecting the West Coast of North America Based on Eight Years of SSM/I Satellite Observations. *J. Hydromet*, **9**, 22-47.

Reeves, H. D., Y. –L. Lin, and R. Rotunno, 2008: Dynamic forcing and mesoscale variability of heavy precipitation events over Sierra Nevada mountains. *Mon. Wea. Rev.*, **136**, 62-77.