Analysis of the Western U.S. Winter Storm 3-7 January 2008: Part 1 - Correlating Normalized Anomalies with High Impact Weather and Event Rarity

RANDALL A. GRAHAM
National Weather Service, Salt Lake City UT

CHRIS SMALLCOMB
National Weather Service, Reno NV

RICHARD H. GRUMM
National Weather Service, State College PA

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ABSTRACT

An intense winter storm impacted much of the western United States during the first week of January 2008. Utilizing NCEP reanalysis data for the first week of January 2008, anomalies are derived for a variety of atmospheric variables and levels. These analyzed anomalies are correlated with the significant weather (extreme winds, heavy rain, and record snowfall) that impacted the western U.S. during this time. In addition, the analyzed anomalies are put in historical perspective relative to atmospheric departures observed across the western U.S. between 1948 and 2006.

1. Introduction

During the first week of January 2008 a significant winter storm impacted the western United States. The impacts from this storm were felt from the West Coast through the Great Basin with extreme winds, heavy rain, and record snowfall observed across portions of the West. The storm was unusual not only for its intensity, but also for the areal extent of the severe winter weather. In all, more than a dozen fatalities across the western United States were attributed to this event. In recent years, tropospheric anomalies have been increasingly utilized to understand and better anticipate high impact weather events (Grumm and Hart 2001; Junker et al. 2008; Junker et al. 2009). The use of normalized anomalies to objectively rank synoptic scale systems was introduced by Hart and Grumm (2001, hereafter HG01). While HG01 only looked at eastern

Corresponding author address: Randall A. Graham, National Weather Service, 2242 West North Temple Street, Salt Lake City, UT 84116
E-mail: randall.graham@noaa.gov

Northern America, Graham and Grumm (2007; hereafter GG07) applied the same methodology for the western United States. The use of normalized anomalies provides a method by which forecasters can objectively analyze the departures from normal for specific variables and levels. This information gives forecasters a sense as to the relative intensity or rarity of a particular storm. Stuart and Grumm (2007) demonstrated the use of normalized anomalies with respect to the prediction of significant East Coast Winter storms. Root et al. (2007) showed the value of the patterns in anomalies in predicting a range of significant weather events over the eastern United States. By investigating tropospheric anomalies associated with an event, forecasters may be able to better anticipate significant events in the future, resulting in improved communication regarding the potential impacts associated with an event.

This paper will examine the impacts associated with the western U.S. winter storm of 3-7 January 2008, as well as the analyzed anomalies from the NCEP reanalysis data set. In particular, the presence of significant atmospheric anomalies will be correlated with observed weather that occurred across the western U.S. Section 2 will briefly discuss the methodology and data sets utilized for this review. Section 3 will provide an overview of the event and the associated impacts and also discuss the NCEP reanalysis data and the analyzed anomalies. Finally, this section will provide insight with respect to the return periods associated with some of the more significant anomalies, as well as associate the analyzed anomalies with observed weather. Section 4 will provide a brief summary of the event and the conclusions of the analysis presented in Section 3. A companion manuscript will examine the anomalies forecast by the NCEP Global Ensemble Forecast System (GEFS), as well as how this information was utilized to increase forecaster confidence that an anomalous winter weather event would impact the western U.S.

2. Data and methodology

HG01 utilized the National Centers for Environmental Prediction (NCEP) reanalysis dataset (Kalnay et al. 1996) to develop a comprehensive climatology for a variety of atmospheric variables (e.g., heights, temperatures, winds and specific humidity) and levels (surface to 200 hPa) for eastern North America. GG07 followed this same methodology to create a climatology for the western United States, covering the period from 1971-2000. The NCEP reanalysis dataset has a horizontal resolution of 2.5° X 2.5° and is available for 17 pressure levels (extending from 1000 hPa to 10 hPa), many of which were examined for this review.

This coarse resolution dataset was utilized as opposed to the higher resolution North American Regional Reanalysis (NARR) because the analyzed anomalies will be correlated with output from the NCEP GEFS in a companion manuscript (Part 2). The GEFS dataset has a resolution of 1.0° X 1.0° out to 384 hours. This more closely corresponds to the 2.5° X 2.5° dataset from the NCEP reanalysis than the .3° X .3° (32 km) output from the NARR. As a result, the analyzed anomalies from the NCEP reanalysis data set are more readily correlated to the forecast output in the form of the ensemble mean.

The NCEP reanalysis data for the period 3 January 2008 through 7 January 2008 was compared to the climatology developed by GG07 to determine tropospheric anomalies associated with this event. Normalized anomalies were examined for four primary elements including heights, temperatures, specific humidity, and u- and v-wind. In addition, return periods of the analyzed anomalies are discussed. The return periods were calculated utilizing the analysis created by GG07, which included analyzed anomalies from over 85,000 six-hour time steps covering the period from January 1948 through December 2006. Information on western U.S.

anomaly return periods as well as forecast graphics are available at: http://www.wrh.noaa.gov/slc/projects/anomalies/index.htm.

Other sources for forecast anomalies include:

http://www.hpc.ncep.noaa.gov/training/SDs/ and http://nws.met.psu.edu/ensembles/index.html

3. Results

a. Event overview

The initial impact from the system was felt along the West Coast beginning on 3 January 2008 as high winds and heavy rain moved onto the coast from California north to Washington. As a strong cold front moved into the Western U.S. on 4 January, the high winds continued (Fig. 1). There were numerous gusts of 60 to 80 mph from the southern Washington coast south into California on the 4th (Fig. 2) and more than 2 million people from near the Oregon border south to Los Angeles lost power during the event as the high winds toppled nearly 500 miles of power lines. High winds were also reported across Nevada and Utah on the 4th (Fig. 2).

In addition to the winds, other impacts of this storm included heavy precipitation and snowfall. Rainfall totals of 2 to 5 inches were reported along the Oregon and California coasts (Fig. 3) while significant inland totals were also observed. Storm total snowfall amounts were also very impressive, particularly in the Sierra Nevada Mountains where up to 11 feet of snow was reported. The Kirkwood Ski Resort in Kirkwood, California (Fig. 4) reported 132 inches of snow, with 10 feet reported in a two day span. At the height of the storm, snowfall rates upwards of 6 inches per hour were reported near Lake Tahoe. According to the California Data Exchange Center, the water equivalent Sierra Nevada snowpack increased from 6 to 13 inches in the four day period from January 3rd through January 7th (USDA 2008). This increase took the water equivalent of the Sierra snowpack from 56 to 111 percent of normal. Further east, many sites in the Wasatch Mountains of northern Utah received 2-4 inches of snow water equivalent (Fig. 3) from this storm.

According to data from the National Climatic Data Center (NCDC), thirty-six daily precipitation records were set across the western United States, on 4 January 2008 (Fig. 5 and Table 1). On the 5th, fifty-one daily records (Fig. 6 and Table 2) were exceeded, with forty-one new daily records across the west on the 6th (Fig. 7 and Table 3).

b. Anomalies associated with observed weather

1) 4 January 2008

An intense closed low approached the Pacific Northwest coast on 4 January 2008 with the central pressure of the surface low analyzed below 960 hPa at 1200 UTC (Fig. 8). Based on the NCEP reanalysis data the sea level pressure (SLP) and 850 hPa height anomalies bottomed out around 5.5 standard deviations (SD) below normal off of the Oregon and Washington coasts at 1800 UTC (Fig. 8). The return period on negative SLP and 850 hPa height anomalies of this magnitude, or greater, is about once every seven months across the entire western United States. The negative height anomaly at 700 hPa bottomed out at near -5 SD at 1800 UTC on the 4th. Negative 700 hPa height anomalies of this magnitude or greater are historically observed about three 6 hour time steps a year (or once every four months on average) in all of the western U.S. (Fig. 9).

Also on the 4th, a plume of enhanced moisture, with precipitable water values in excess of 1.25 inches, was moving onto the central California coast. The precipitable water anomaly associated with this moisture plume was around +2.5 SD at 1200 UTC, with the greatest anomaly of nearly +3.5 SD recorded at 0000 UTC on the 5th (Fig. 10). More impressively, the

850 hPa moisture flux anomalies, which tend to have a higher correlation with significant liquid equivalent than precipitable water, were in excess of 6 SD (not shown) just off the coast of California near San Francisco (W. Junker 2009, personal communication). The return period for anomalies of this magnitude is around once every 5 years (Junker et al. 2009). Moisture plumes such as this are frequently observed with cool season west coast heavy rain events (Neiman 2002; 2004, Junker et al 2008). As is frequently the case, heavy precipitation was observed in the vicinity of this land falling moisture plume (Fig. 11). The heaviest precipitation across most of California, southern Oregon, and western Nevada, including the high Sierra Mountains, occurred as this anomalous plume of moisture traversed the area between 1200 UTC 4 January and 1200 UTC 5 January 2008 (Fig. 12). Bishop, California received 4.0 inches of rain on the 4th which is the highest daily total on record (1948-2008). By comparison, the annual average precipitation in Bishop is only 5.02 inches. Also on the 4th, Williams, California had its wettest January day on record when 3.44 inches was recorded and Reno, Nevada had its third wettest day in the last century when 1.91 inches was recorded.

The mid-level wind anomalies also increased substantially by 1200 UTC on the 4th as a 90 knot westerly 500 hPa jet streak, and its associated +3.4 SD (westerly) anomalies, approached the west coast (Fig. 13). The low level winds also increased on the morning of the 4th with significant positive v-wind anomalies analyzed from northern California through western Oregon. The v-wind anomalies increased to around +3.5 SD (southerly) at 700 hPa and 850 hPa as wind cores of 80 knots and 45 knots, respectively, shifted over the coast (Fig. 14). These anomalously strong winds, in combination with the negative SLP anomalies (and the associated pressure gradient), were associated with a significant windstorm that extended from the Washington Coast to central California. Wind gusts to near 70 mph were reported in the San

Francisco Bay area with several sites along the Oregon coast reporting gusts in excess of 80 mph including Cape Blanco with 87 mph and Newport with a gust to 93 mph (Fig. 2). As the 700 hPa wind core crossed the Sierras the highest recorded wind gust with the storm was observed west of Lake Tahoe, California when a 165 mph gust was measured on Ward Mountain (Fig. 4) around 2100 UTC. The 700 hPa v-wind anomaly was approaching 4 SD above normal at this time.

The strong low level wind maxima shifted east on the evening 4^{th}, with southwesterly 700 hPa winds ranging from 60 to 70 knots from the interior Great Basin to the West Coast. By 0000 UTC 5 January 2008 the extent of the +3 SD or greater v-wind anomalies at 700 hPa was quite extensive stretching from southern Utah and central Nevada north into southern British Columbia. Within this larger area of impressive positive v-wind anomalies was a core of +4.5 SD (southerly) values which covered northern Utah and southeast Idaho (Fig. 15). The return period for a v-wind anomaly of at least +4.5 SD at 700 hPa, occurring anywhere in the western U.S., is about 6 months (Fig. 16). In other words, a 700 hPa v-wind anomaly of this magnitude, or greater, was observed just over 100 times in the ~85,000 six hour time steps included in the GG07 dataset. It is important to note that GG07 found that extreme anomalies often occurred in successive time steps, which indicates that the number of storm systems associated with anomalies of this magnitude is less than the return interval would suggest. The presence of anomalies this large in the same geographic area, over successive time steps, would increase the likelihood of a significant weather event. Given this perspective on the occurrence of significant anomalies, it is easy to see why this is considered an unusual event. The winds were increasing dramatically across the interior Great Basin as the significant mid and low level southerly wind anomalies spread east. Winds near 100 mph were observed near Las Vegas, NV and in Baker, NV an elementary school lost part of its roof near the time that winds were measured at 82 mph.

2) 5 January 2008

Significant anomalies continued through 5 January 2008 as the mid-level trough axis shifted slowly to the east. The core of enhanced precipitable water stretched from southern California through northern Arizona, much of Utah and into eastern Montana. The precipitable water anomalies in this moisture axis were between +2 and +3.5 SD (not shown). Heavy precipitation was associated with this moisture plume in the Sierra-Nevada Mountains as well as across northern Arizona and the mountains of Utah between 0000 UTC 5 January to 0000 UTC 6 January. Numerous mountain sites across Utah received 3 to 4 inches of snow water equivalent (SWE) in this 24 hour window, including Alta Ski Resort which reported 4.01 inches SWE and Snowbird Ski Resort with 4.0 inches of SWE. Both of these totals come from the Wasatch Mountain Range in northern Utah. Several southern Utah mountain sites also received significant totals, including the Kolob SNOTEL (Fig. 4) with 3.60 inches of SWE and the Midway Valley Junction SNOTEL with 3.30 inches of SWE.

By 1200 UTC on the 5th, the v-wind anomalies in excess of +3 SD were confined to northeast Utah and the coverage of the v-wind anomalies greater than +2 SD had diminished greatly (Fig. 17). High winds were reported across Nevada and Utah (Fig. 2) as the core of anomalous v-winds aloft continued to sweep across the area. Some mountain reports include 105 mph both on Ogden Peak and a sensor at Straw Top in northern Utah. Valley reports included 85 mph at the Stockton Bar mesonet site (Fig. 2), 75 mph in the town of Tooele, and 73 mph in the Olympus Cove section of Salt Lake City, all in northern Utah. These winds were associated with downed power poles and trees in the Tooele and Salt Lake Valleys of northern Utah.

3) 6 January 2008

By 1200 UTC 6 January 2008, 850 hPa and 700 hPa heights were 1 to 3 SD below normal across much of the United States west of the Rocky Mountains (Fig. 18). However, extreme height departures were no longer noted across the western United States. Also, at 1200 UTC on 6 January 2008, the core of the positive precipitable water values stretched from extreme southern California across much of Arizona and into Colorado. The precipitable water anomalies in the moisture plume had diminished a bit and were generally 1 to 3 SDs above normal, by this time. Still, NCDC records indicate that forty-one daily precipitation records were set across the west on the 6th, primarily across Arizona, Utah, and Colorado (Fig. 7).

By the evening of the 5th the significant wind anomalies were diminishing and this was reflected in the cessation of the high wind event across the west. At 1200 UTC on the 6th the maximum 700 hPa u- and v-wind anomalies had decreased to about +2.5 SD with the maximum u-wind anomalies centered over southern Nevada and the maximum v-wind anomalies covering a small area in northeast Utah. 700 hPa u- and v-wind anomalies of this magnitude are observed approximately once per week across the western U.S. domain.

4. Summary

Over the course of this significant event, synoptic scale anomalies were well correlated with severe winds, heavy rain, and significant snowfall across the western United States. The correlation of these anomalies to extreme sensible weather offers promise that rare and historical events, such as that which occurred during the first week of January 2008, can be better anticipated utilizing anomalous departures from normal and climatological anomaly return periods as forecast from numerical models, including Ensemble Prediction Systems. It should be noted that the height, v-wind, and specific humidity anomalies had a strong tendency to be maximized at or below 700 hPa throughout this event. It is believed that correlating specific anomalies (e.g., positive 700 hPa v-wind departures) to specific hazards (e.g., strong southerly surface winds) may provide forecasters insight on key parameters to further interrogate when assessing the potential significance of a pending winter storm.

During this event, the large anomalies were associated with an event that was both meteorologically and climatologically significant. The fact that large anomalies occurred in the cool season, when large scale significant weather events are more frequent in the Western U.S., is an indication that they are more likely to be correlated with an unusual event. Several of the analyzed anomalies associated with this event had return periods of six months, or more. Information such as this can be utilized by forecasters to better place forecast values in historical perspective. Ultimately, this may result in better service to the public by giving forecasters sufficient confidence that an unusual event is unfolding, resulting in improved communication of the threat to the public.

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TABLES AND FIGURES

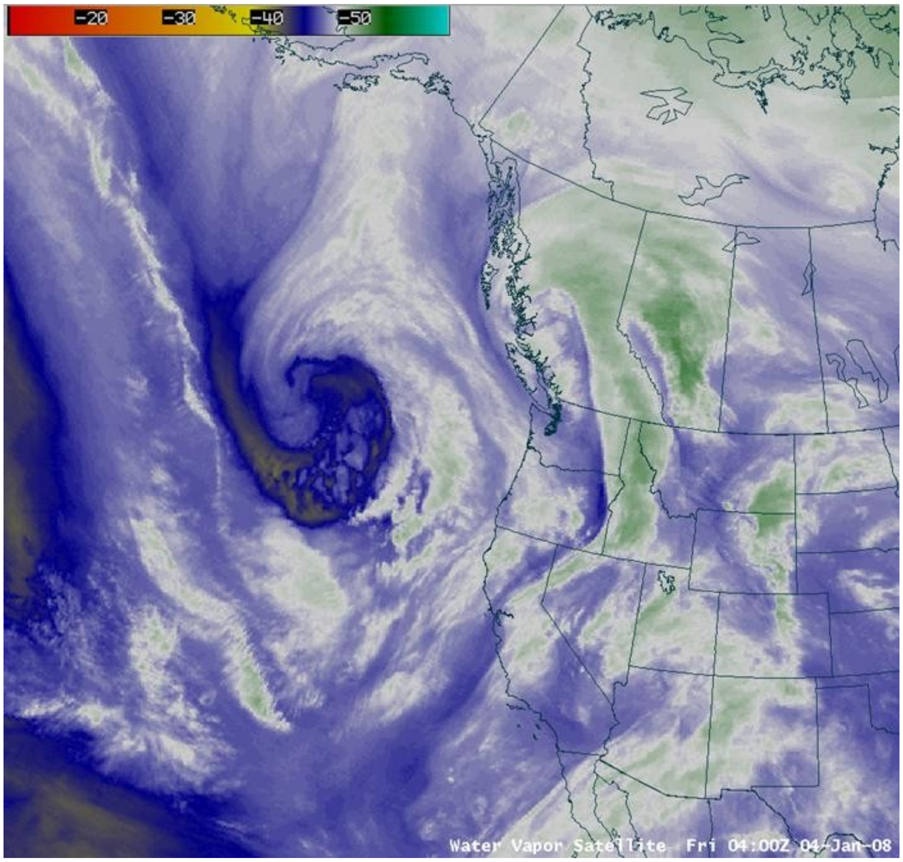

Figure 1. Water vapor loop valid from 0000 UTC 4 January 2008 through 2300 UTC 4 January 2008. **NOTE: This figure is an animation. A representative image is shown above.**

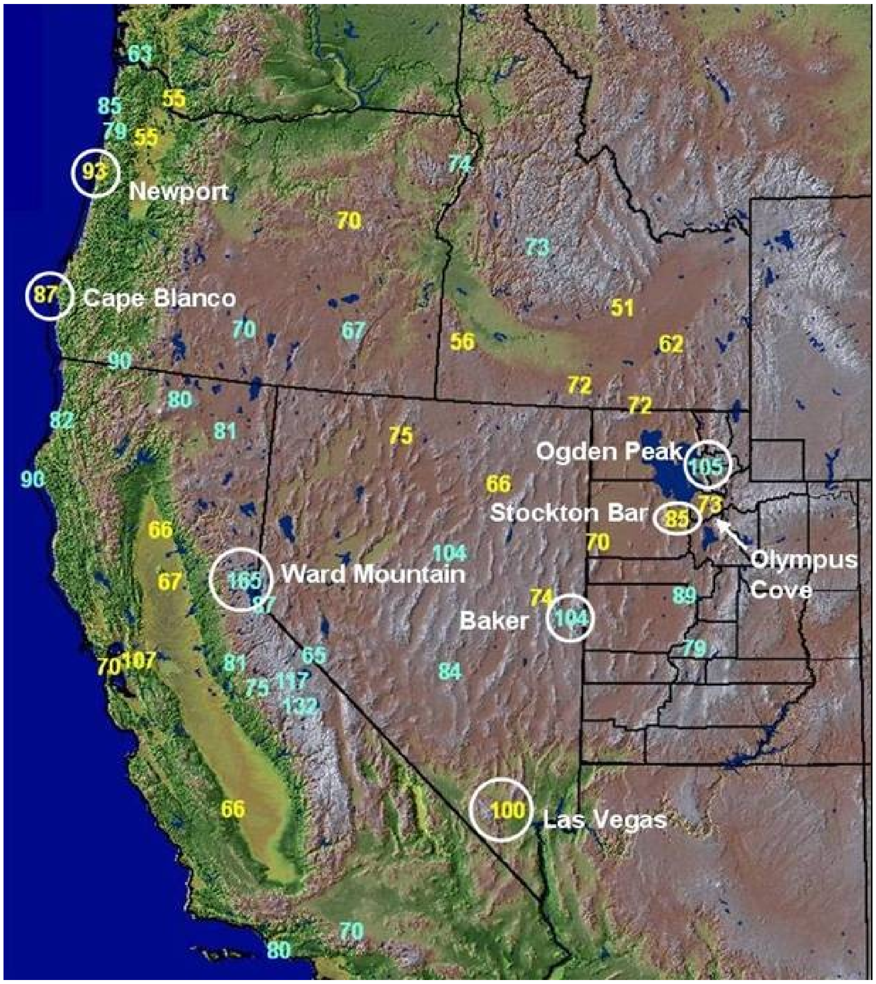

Figure 2. Selected wind reports (mph) across the western United States from 4-5 January 2008. Yellow numbers mark valley locations while blue numbers denote mountain sites. Stations in white circles are specifically mentioned in the text.

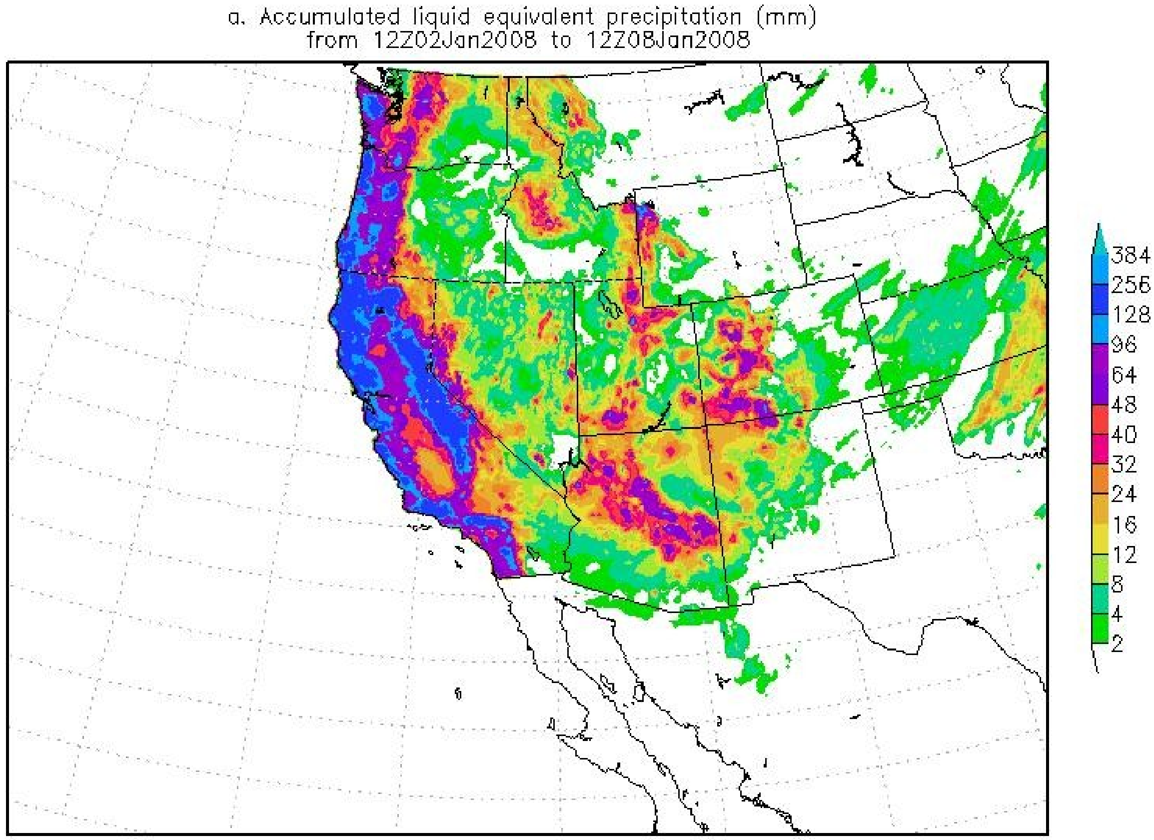

Figure 3. NCEP Stage IV (4 km) estimated accumulated liquid equivalent precipitation (mm) valid from 1200 UTC 2 January 2008 through 1200 UTC 8 January 2008.

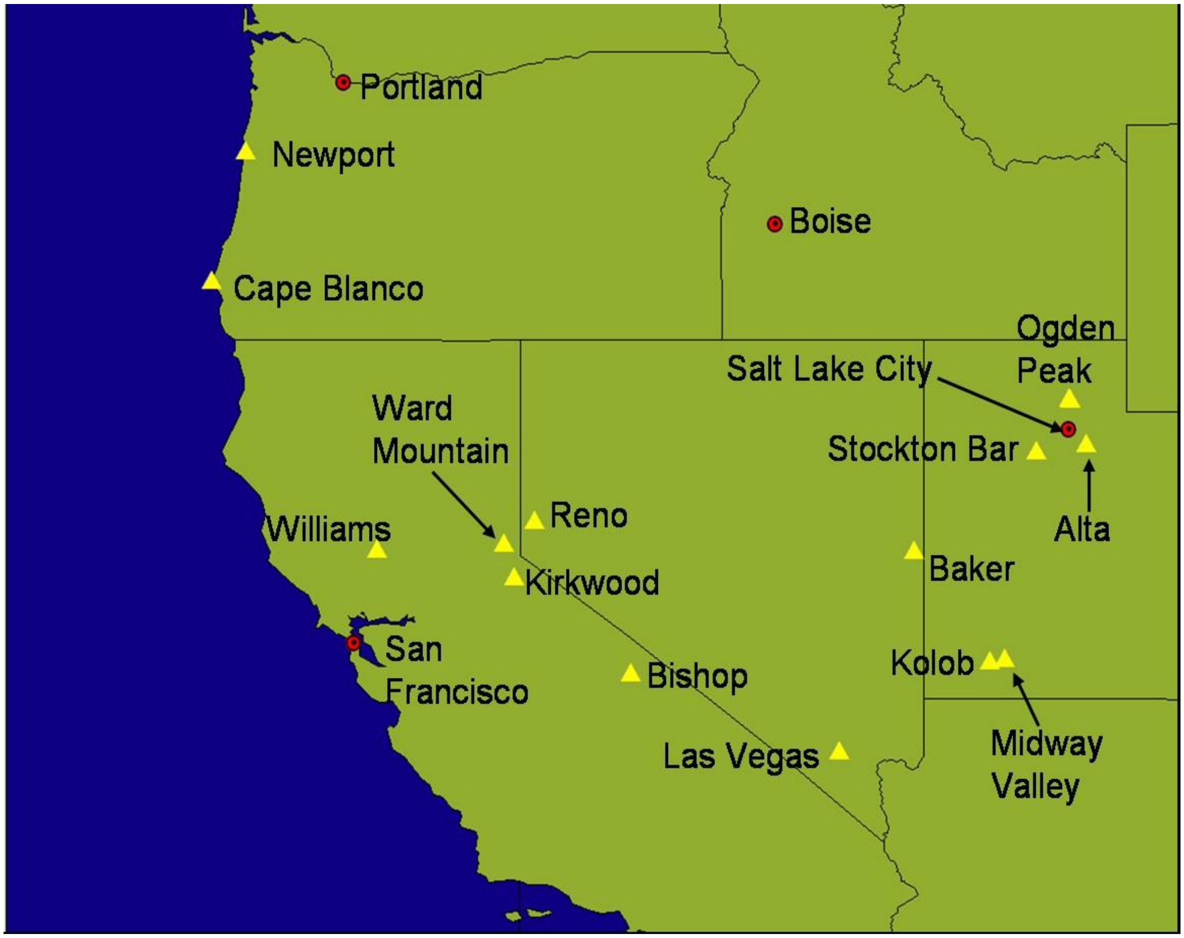

Figure 4. Yellow triangles denote sites mentioned in the text of the article. Red circles mark location of some major western cities for reference.

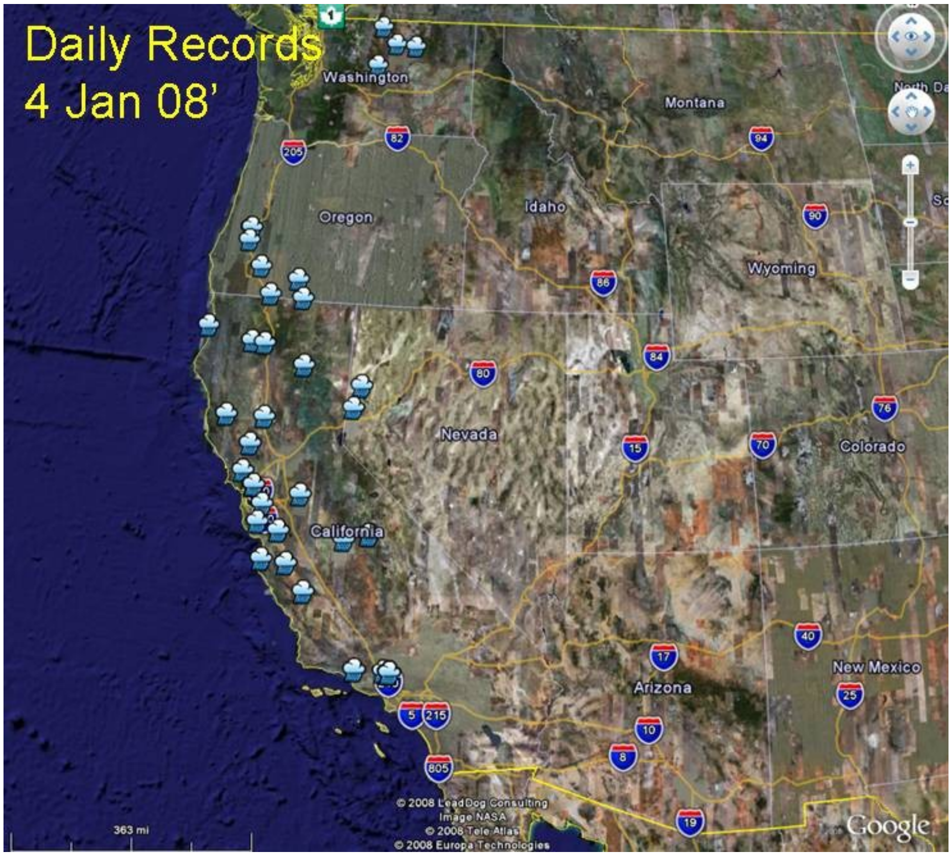

Figure 5. Cloud icons mark the location of daily precipitation records set on 4 January 2008. Data from NCDC.

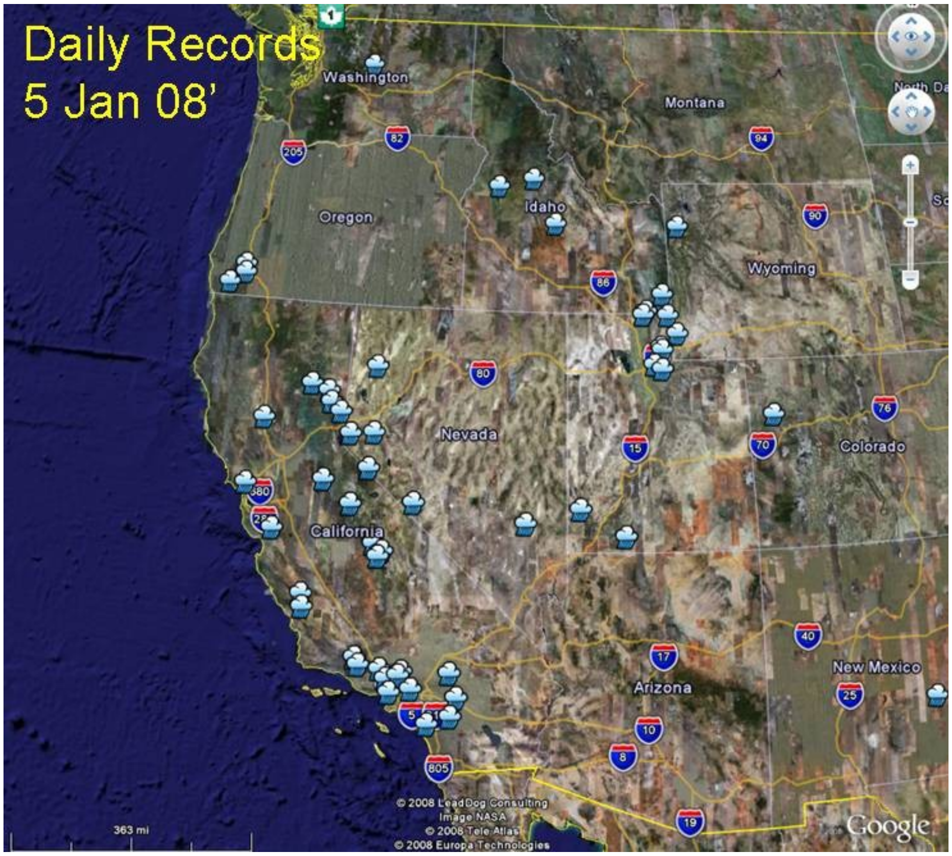

Figure 6. Same as Figure 5, except for 5 January 2008.

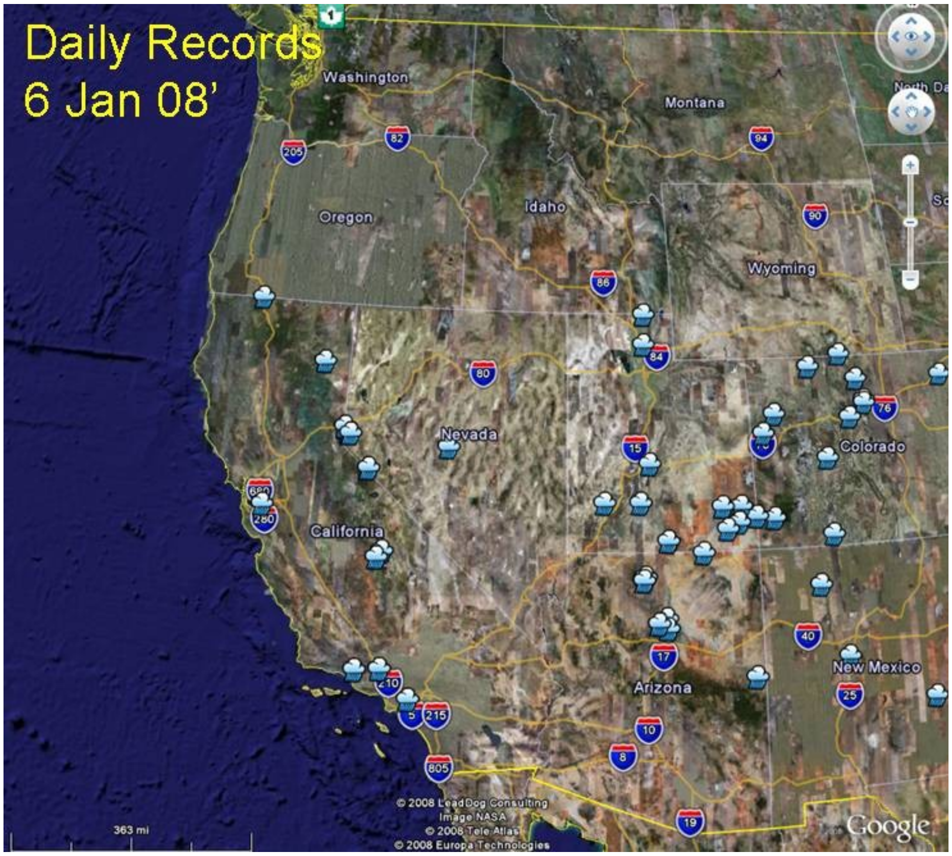

Figure 7. Same as Figure 5, except for 6 January 2008.

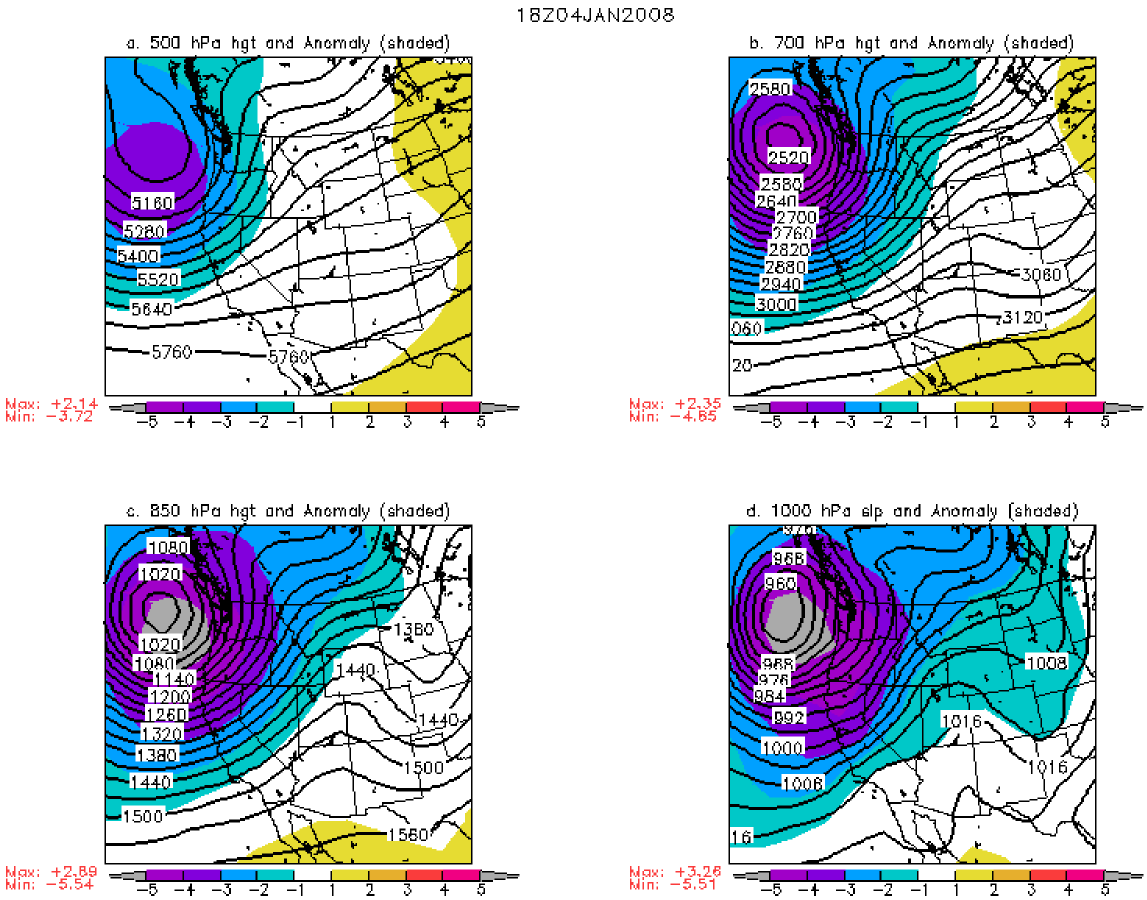

Figure 8. Contours are analyzed heights (m); images are the associated anomalies (Standard Deviations) from the NCEP reanalysis dataset valid at 1800 UTC 4 January 2008. (a) 500 hPa heights and anomalies, (b) 700 hPa heights and anomalies, (c) 850 hPa heights and anomalies, (d) SLP and anomalies.

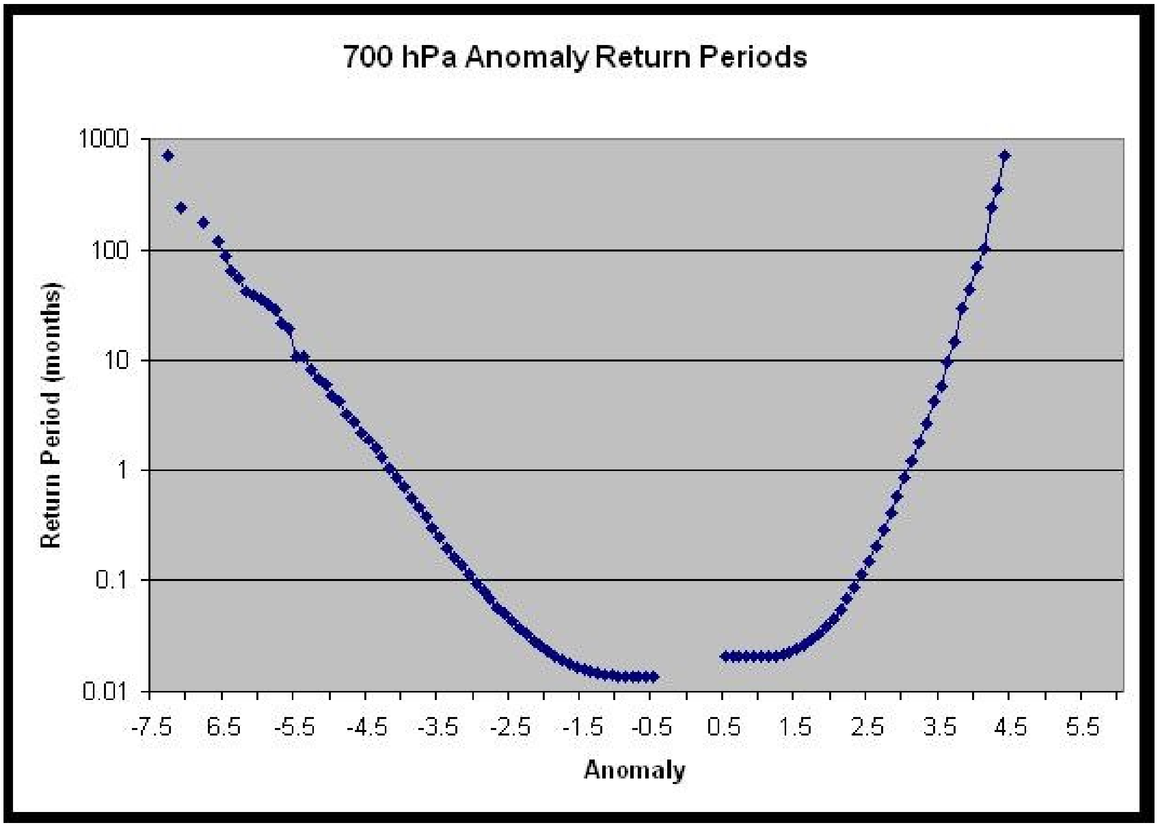

Figure 9. Chart showing the return periods associated with 700 hPa height anomalies. Y-axis is the return period in months while the x-axis displays the anomaly values (Standard Deviations). Return periods are displayed for the given anomaly *or greater*. For example, a 700 hPa height anomaly of -4.0 SD or lower (-4.1, -4.2, -4.3…) occurs about once a month (on average) across the entire western United States.

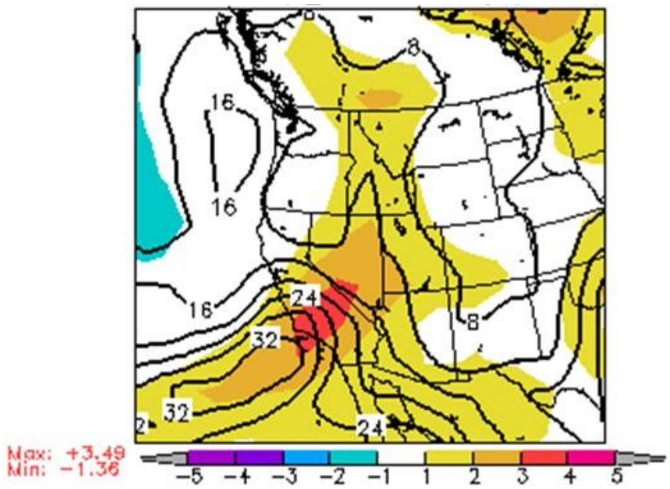

Figure 10. Contours display precipitable water values (mm); image shows the analyzed anomaly values (SD) from the NCEP reanalysis data valid at 0000 UTC 05 January 2008.

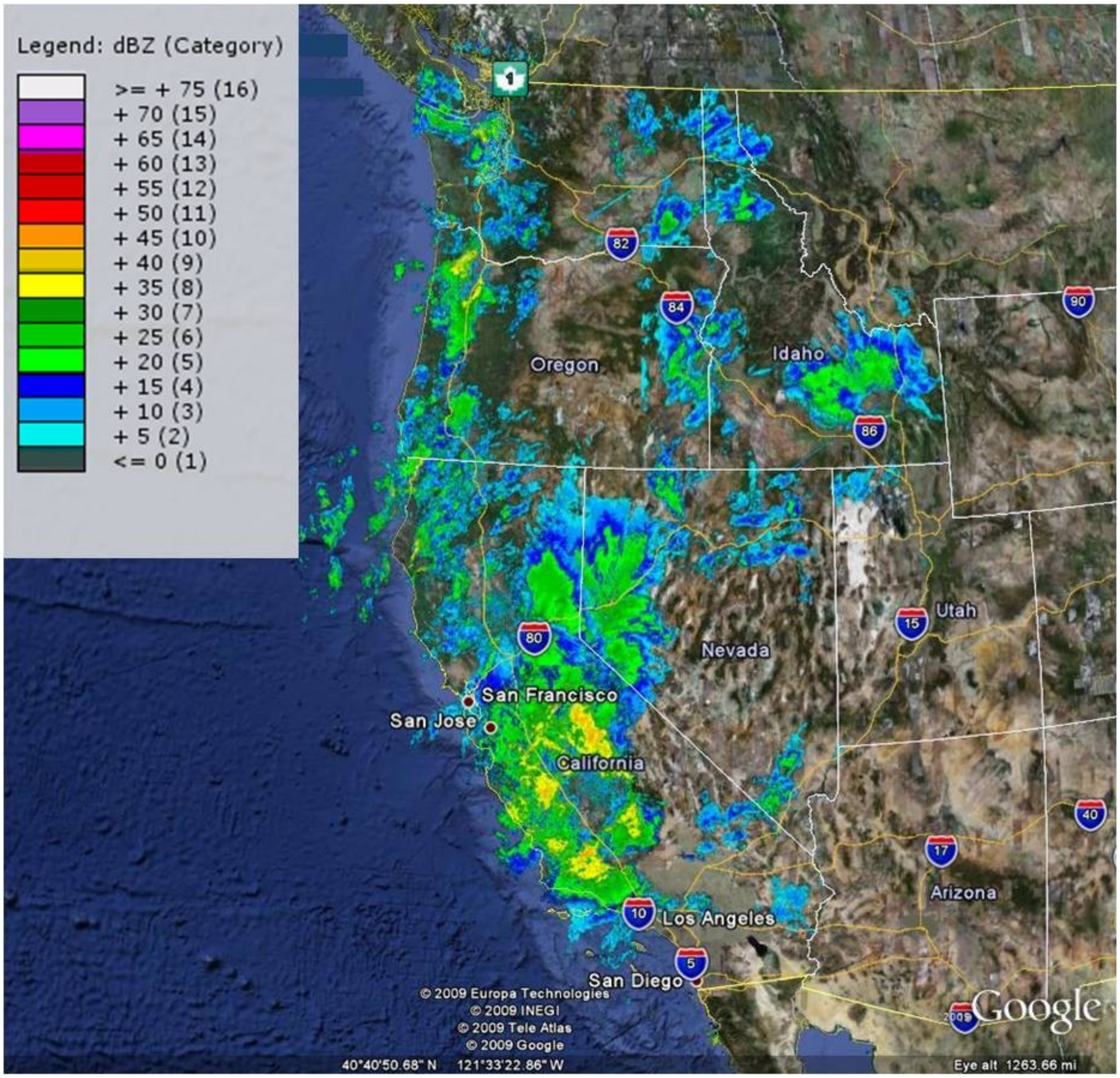

Figure 11. Western U.S. base reflectivity mosaic 0000 UTC 5 January 2008.

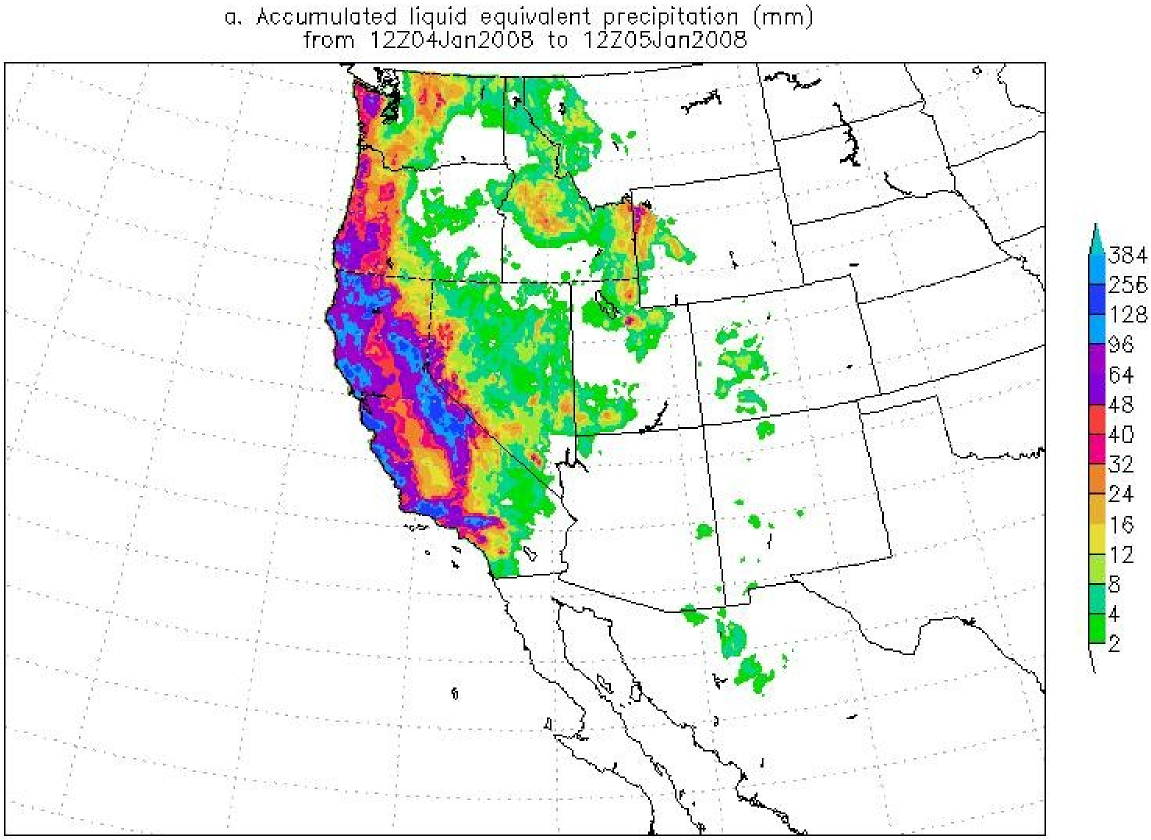

Figure 12. Same as Figure 3, except for 1200 UTC 4 January 2008 through 1200 UTC 5 January 2008.

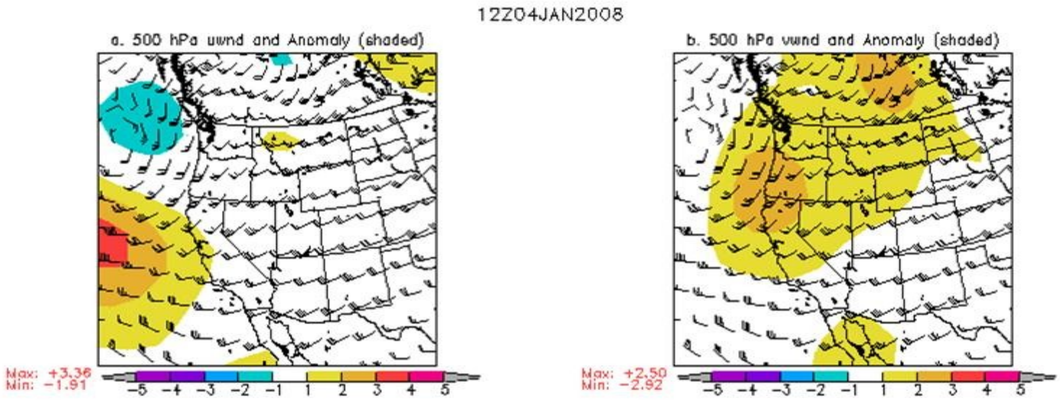

Figure 13. 500 hPa wind barbs (knots) and analyzed anomalies (SD) from the NCEP reanalysis data valid at 1200 UTC 4 Jan 2008. (a) 500 hPa u-wind analyzed speed and anomalies, (b) 500 hPa v-wind analyzed speed and anomalies.

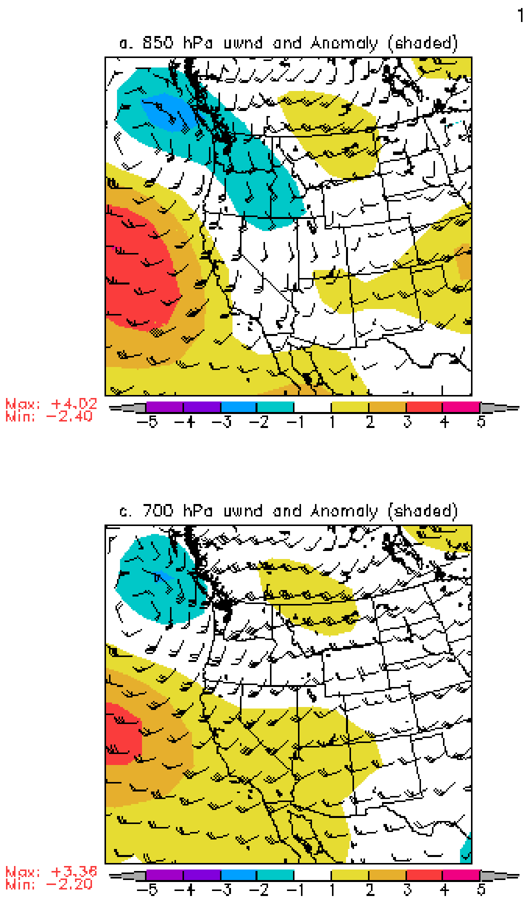

Figure 14. 850 hPa and 700 hPa wind barbs (knots) and analyzed anomalies (SD) from the NCEP reanalysis data valid at 1200 UTC 4 Jan 2008. (a) 850 hPa u-wind analyzed speed and anomalies, (b) 850 hPa v-wind analyzed speed and anomalies, (c) 700 hPa u-wind analyzed speed and anomalies, (d) 700 hPa v-wind analyzed speed and anomalies.

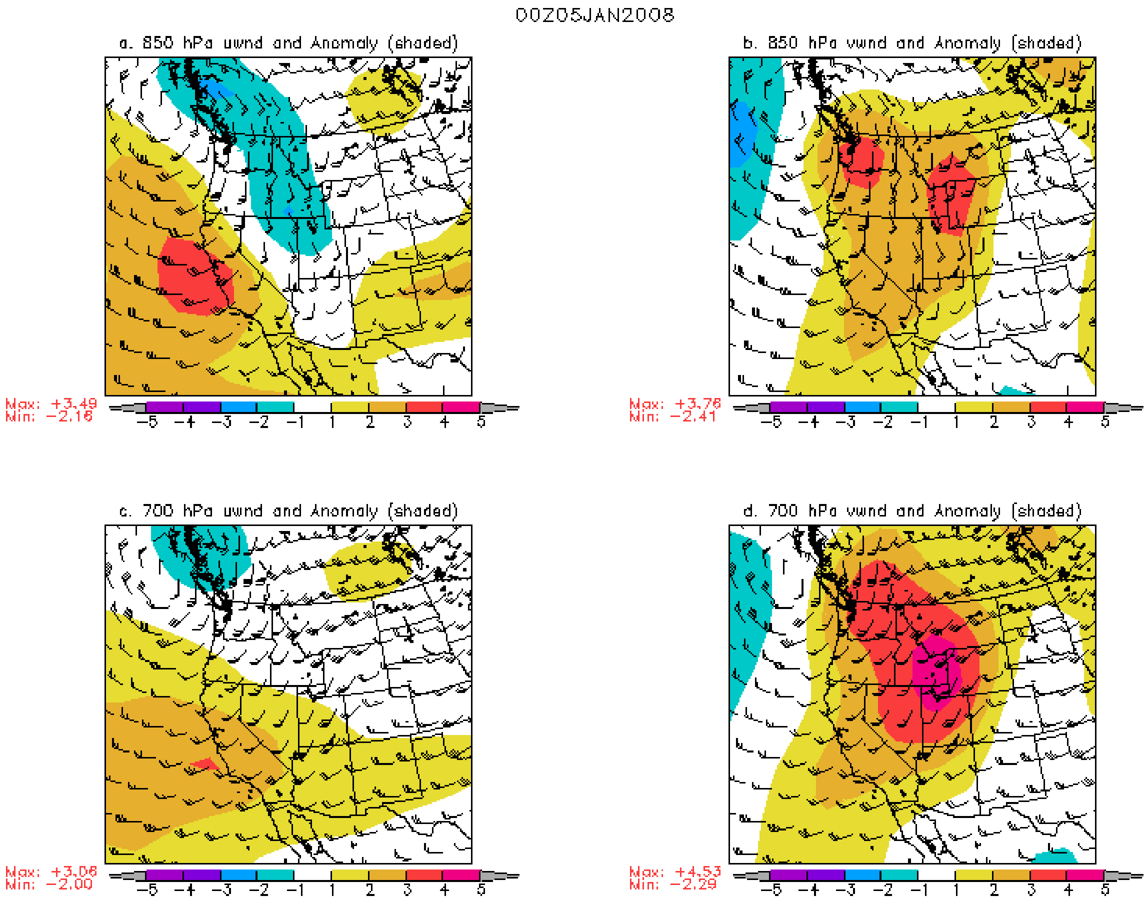

Figure 15. Same as Figure 14 except for 0000 UTC 5 January 2008.

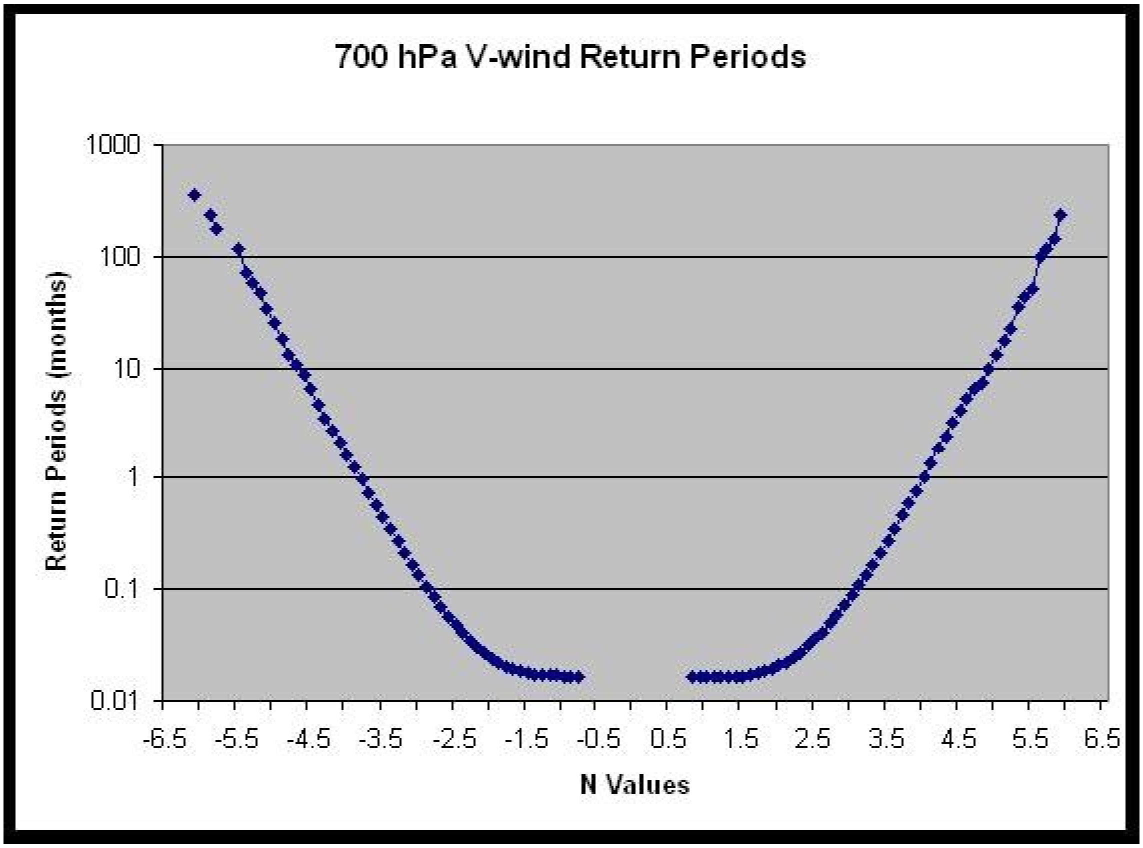

Figure 16. Same as Figure 9 except for 700 hPa v-wind anomalies.

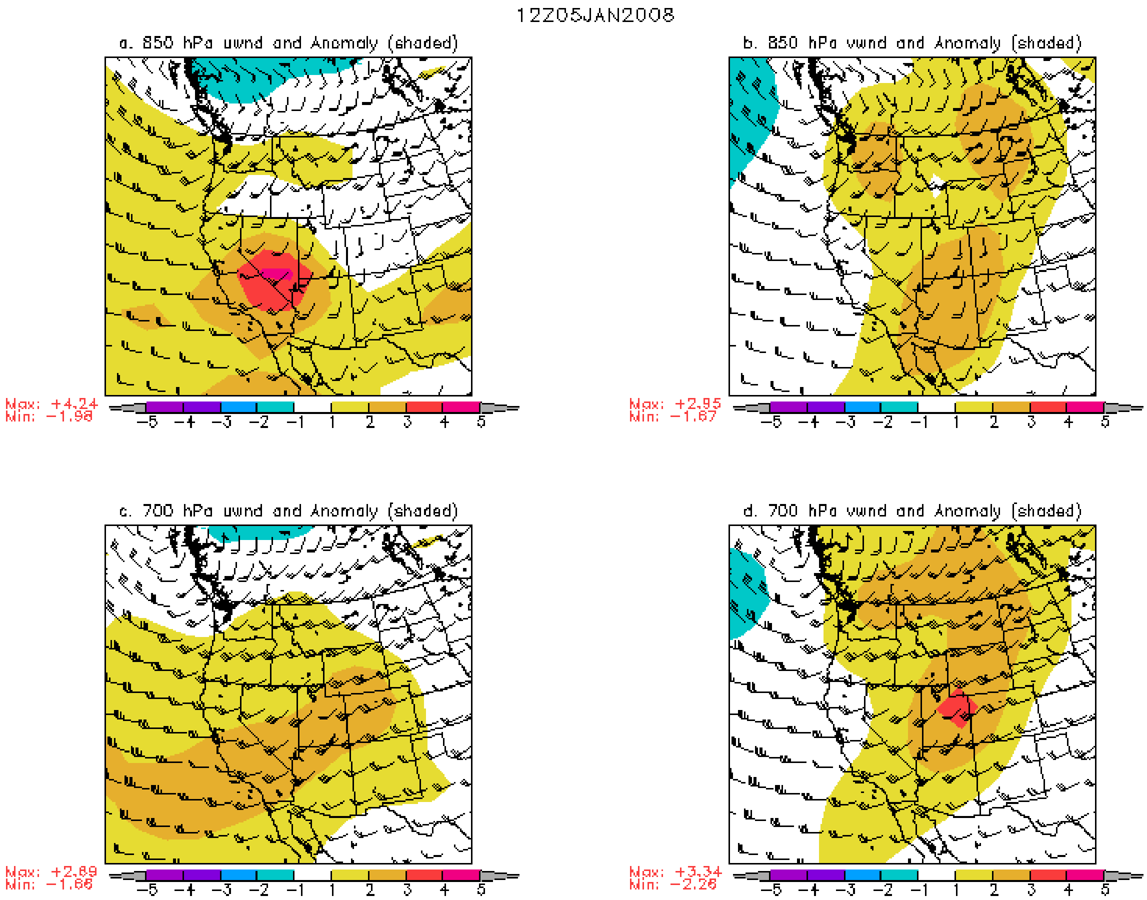

Figure 17. Same as Figure 14 except for 1200 UTC 05 January 2008.

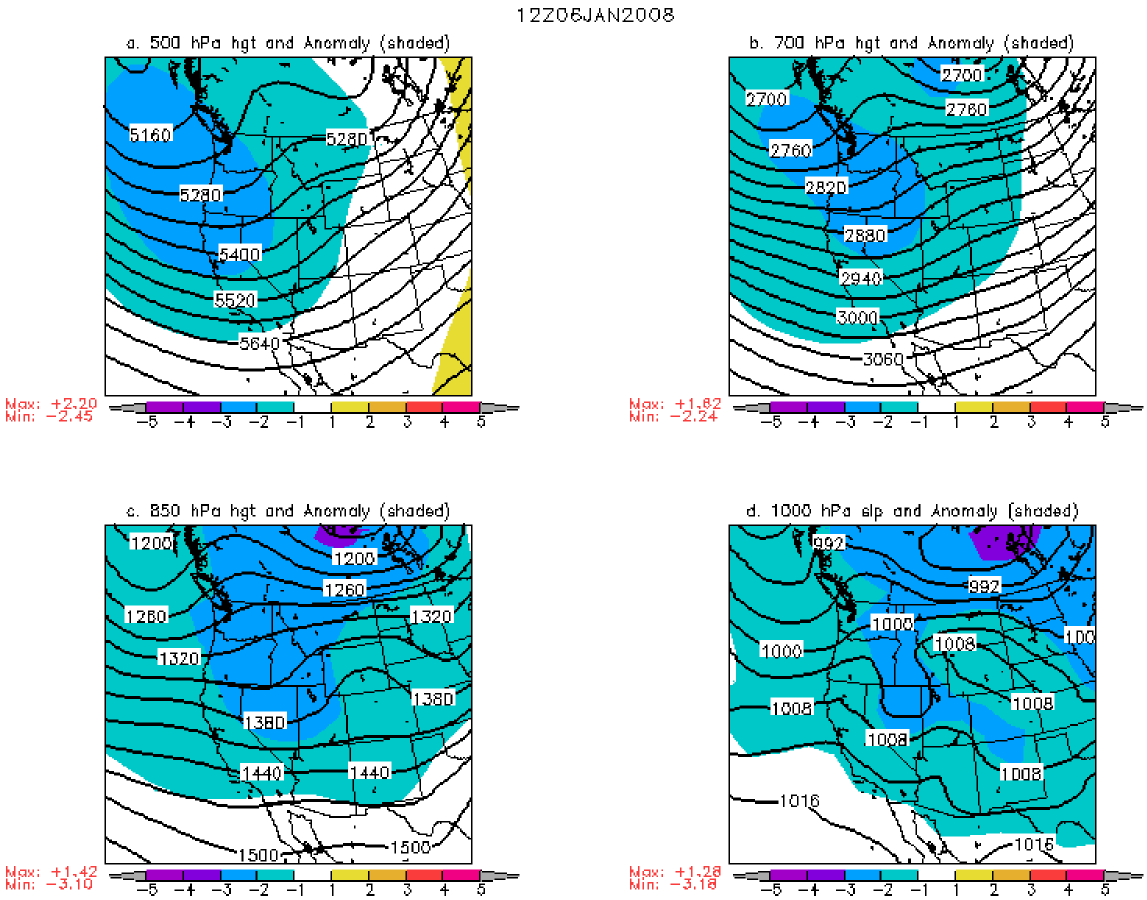

Figure 18. Same as Figure 8 except for 1200 UTC 6 January 2008.

Table 1. Select daily precipitation records set on 4 January 2008 across the western U.S.

Location	Elevation (ft)	Precipitation (in)	Previous Record (year)
Big Sur Station CA	220	6.10	2.63 (1974)
Shasta Dam CA	1070	4.76	4.16 (1966)
Santa Cruz CA	130	3.81	2.53 (1982)
San Rafael CA	120	3.67	2.24 (1965)
Williams CA	80	3.44	1.28 (2007)
Reno NV	4440	1.91	.69 (1939)
Riddle OR	680	1.75	1.01 (1966)
Lava Beds National Monument CA	4770	1.03	.11 (1988)

Table 2. Select daily precipitation records set on 5 January 2008 across the western U.S.

Location	Elevation (ft)	Precipitation (in)	Previous Record (year)
Lodgepole CA	6730	7.96	4.73 (1982)
Yosemite National Park	5120	6.95	5.0 (1982)
Santa Margarita CA	1200	5.60	2.58 (1995)
Pasadena CA	860	5.20	2.00 (1939)
Big Bear Lake CA	6790	5.00	2.55 (1995)
San Francisco CA	200	1.72	1.59 (1931)
Ketchum ID	5890	1.50	.37 (1978)
Dyer NV	4900	1.98	.22 (1997)
Heber UT	5630	1.40	.70 (1895)

Table 3. Select daily precipitation records set on 6 January 2008 across the western U.S.

Location	Elevation (ft)	Precipitation (in)	Previous Record (year)
Lodepole CA	6730	2.46	1.63 (1978)
Bright Angel CA	8400	2.10	.83 (1992)
Gunnison CO	5150	1.10	.43 (1993)
Cortez CO	6210	1.07	.33 (1979)
Glenbrook NV	6360	1.80	.56 (1959)
Minden NV	4710	1.40	.65 (1909)
Hovenweep National Monument UT	5240	1.27	.40 (1909)