1A.4 UTILIZING STANDARDIZED ANOMALIES TO ASSESS SYNOPTIC SCALE WEATHER EVENTS IN THE WESTERN UNITED STATES

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1. INTRODUCTION

Numerous methods have been developed to rank the severity, societal, or economic impact of meteorological events. The Fujita scale (Fujita 1971), Saffir-Simpson scale (Simpson 1974), Palmer drought index (Palmer 1965) are a few scales developed to account for the severity of a weather event. Hart and Grumm (2001; hereafter HG01) presented a method for objectively ranking synoptic-scale events. They noted that frequently the storms that are subjectively deemed the most significant are often those that impact population centers and, therefore, receive the greatest media attention. The methodology presented in HG01 attempts to utilize the standardized anomalies for a variety of elements and a series of levels to rank synoptic events. However, the original work presented in HG01 only examined historical standardized anomalies for the eastern portion of North America. The work presented here applies the same methodology as that presented in HG01, but the area of focus is instead centered on the western United States and adjacent coastal waters (Fig 1).

2. METHODOLOGY

2.1 *Datasets*

Following the work of HG01, a comprehensive climatology was developed for the western U.S. in order to derive departures from normal for each six hour period from January 1948 through December 2006. The National Centers for Environmental Prediction (NCEP) reanalysis dataset (Kalnay et al. 1996) was utilized to generate this analysis. The NCEP reanalysis dataset has a horizontal resolution of 2.5° X 2.5° and is available for 17 pressure levels. The climatology was developed for four basic variables over the range of 1000 hPa through 300 hPa (for Specific Humidity) or 200 hPa (for Height, Temperature, and Wind) at 6-h intervals. The wind components were used and u- and v-wind anomalies were computed. Climatological data for other variables, such as mean-sea level pressure and precipitable water were also developed.

Anomaly values were generated for over 85,000 six hour time steps. The anomalies are relative to a climatology that is a subset of the entire period of investigation. The climatology was developed utilizing the 30-year period extending from 1971-2000. With this climatology as a foundation the ranking of the climatological departures was performed for the period from January 1, 1948 through December 31, 2006. It should be noted that HG01 used only 0000 and 1200 UTC data when developing rankings for eastern United States weather systems.

2.2 *Definitions*

The pressure weighted standardized anomalies were computed for each variable at each level (i.e., 1000 hPa through 300 hPa or 200 hPa) at all time periods. For each variable the value of $M_{variable}$ was computed, where $M_{variable}$ is the average departure (of all levels) from the climatological 21-day running mean in standard deviations. Variables used included temperature, heights, specific humidity, u-winds, and v-winds. The overall score M_{Total} was computed as the arithmetic average of the pressure weighted variables for each time and day. The overall ranking was

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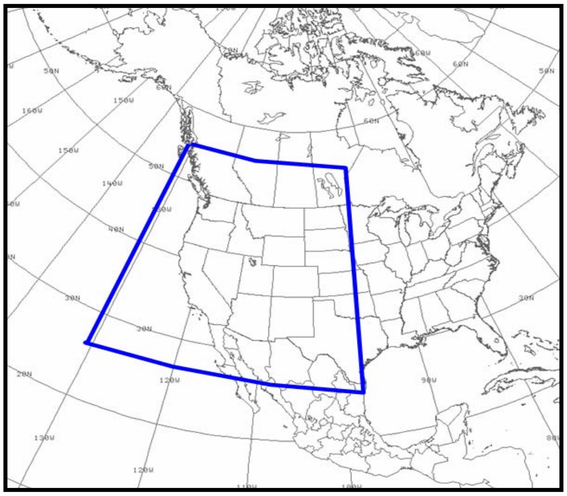

Figure 1. The approximate domain utilized for the calculation of standardized anomalies is

determined by the value of M_{TOTAL}. However, the pressure weighted variables were also used to find unique anomalies associated with each variable.

3. RESULTS

The rankings for the standardized anomalies are broken down into several sections, first examining the M_{TOTAL} departures and then examining the departures for each individual element (M_{HEIGHT}, M_{TEMP}, M_{WIND}, and M_{MOIST}). The results are valid for the western half of the United States and the adjacent areas in the eastern Pacific (Fig. 1).

3.1 *Rankings*

The top 20 total anomalies (M_{TOTAL}) of the 59-yr period are summarized in this paper and brief descriptions are provided for several of the events. In addition, the top 10 anomalies for each of the four component elements (M_{HEIGHT}, M_{TEMP}, M_{WIND}, and M_{MOIST}) will be listed.

3.1a *Top 20 Normalized Anomalies across the Western U.S. from January 1st, 1948 through December 31st, 2006*

The top 20 climatological anomalies (Table 1) represent the most significant synoptic scale departures across the western U.S. for a period of nearly 60 years. Several of these events are associated with memorable systems that had major societal impacts while others had little economic or societal impact. A variety of event types were represented in the top 20 M_{TOTAL} events for the study region (Table 1), including coastal heavy rain, southwest U.S. heavy snow, and Pacific Northwest windstorms, amongst others.

Since the M_{TOTAL} calculation equally weights the impact of the M_{HEIGHT}, M_{TEMP}, M_{WIND}, and M_{MOIST} values a system generally needs to be anomalous in at least several of these categories to rank in the top 20 events overall. As a result, deep anomalous lows which exhibit significant departures in height, temperature, wind, and moisture are most favored for inclusion in the top 20. Despite this tendency there are several events in the top 20 that appear to have had minimal impact on the western US. Around 25 percent of the events in the top 20 were associated with cut-off lows off of southern California or the Baja Coast. Frequently, these events were in the southwest corner of the domain and despite their minimal impact on the western U.S. they were certainly meteorologically anomalous.

The magnitude of the top 20 events range from M_{TOTAL} = 4.529 to M_{TOTAL} = 3.962. These top 20 values over the western US are comprised of relatively lower M_{TOTAL} values when compared the values from the top 20 events across eastern North America as discussed in HG01. In fact, the top event for the western U.S. would rank only fifth in the eastern North America dataset. To provide additional perspective on the difference in the M_{TOTAL} values between the domain in HG01 and the western domain presented here, the 20th ranked event in HG01 (22 Jan 1959 with an M_{TOTAL} of 4.176) would have ranked 5th in the top 20 events for the western domain. The reasons for this discrepancy are beyond the scope of this paper, but are an interesting artifact of the climatology none-the-less.

Still, impressive events comprise much of the top 20 list for the western U.S. Of note are events such as the Columbus Day Storm of 1962, Arizona Winter Storm of December 1967, and a July 1987 event which included record heavy rain across Montana and an F4 tornado in Yellowstone National Park. Despite these impressive events nearly a third of the systems which comprise the top

20 are not known to have a major societal or economic impact across the western United States. Several of these anomalous, yet low impact, events were associated with cut-off lows off the coast of the southwest U.S.

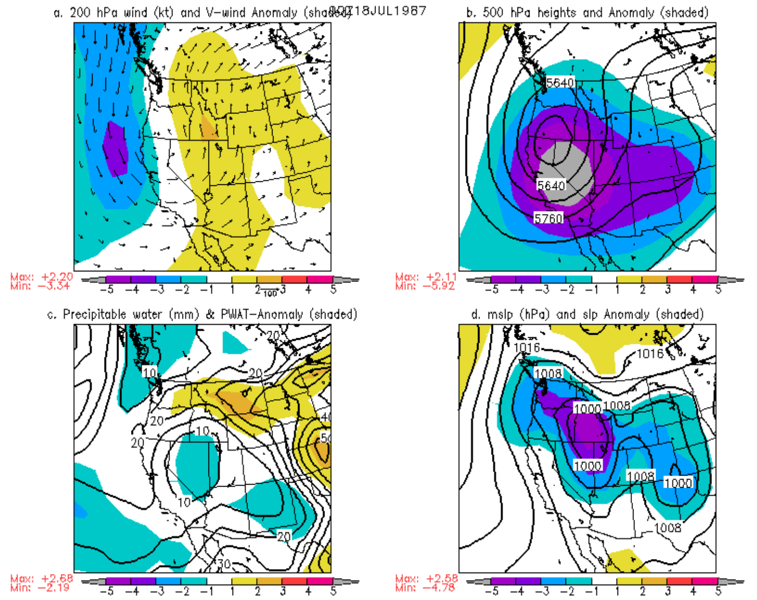

Fig 2 – Selected anomaly images associated with the 18 July 1987 event. Clockwise from the upper left: 200 hPa wind (kts) and 200 hPa V-wind anomaly; 500 hPa heights (m) and anomaly; MSLP hPa and SLP anomaly; Precipitable water (mm) and precipitable water anomaly.

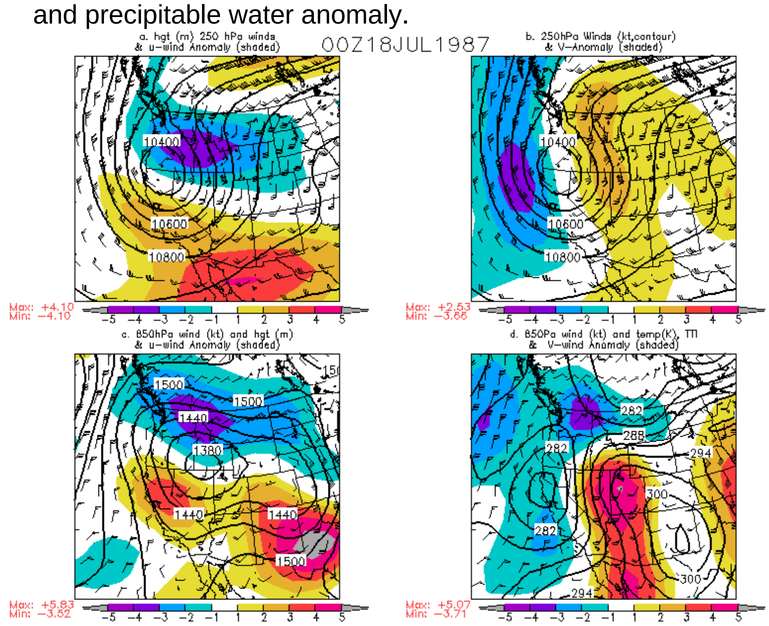

Fig 3 – Selected anomaly images associated with the 18 July 1987 event. Clockwise from the upper left: 250 hPa height (m) and winds (kts) and 250 hPA U-wind anomaly, 250 hPa height and winds and 250 hPa V-wind anomaly; 850 hPa wind and temperatures (K) and 850 hPa V-wind anomaly; 850 hPa wind and heights and 850 hPa U-wind anomaly.

The most anomalous synoptic-scale event across the western U.S. for the period from 1948 through 2006 was associated with a system for which the impact was most pronounced from the northern Great Basin to the northern Intermountain Region and into the plains of central and eastern Montana. The storm moved through the region in the middle of July 1987 and is best known for being associated with an F4 tornado which struck Yellowstone National Park on July 21st (Fujita 1989, Evans 1995). While being noted for the severe weather outbreak which stretched from northern Utah into northwest Wyoming, and in particular the F4 tornado in Yellowstone National Park, this system had far-reaching impacts to the north. Widespread rainfall totals in excess of 2 inches (50 mm), with some locations receiving over 4 inches (100 mm) were reported across Idaho and Montana on the 16-17th of July with some sites receiving warm season (April-September) record 24-hr precipitation amounts. While heavy precipitation in the warm season in this region is not in itself particularly unusual, the widespread coverage of the heavy precipitation was indeed impressive.

This storm stood out in that it supported anomaly departures that ranked in the top 10 with respect to height, temperature, and wind when compared to the standardized climatology. On the day of the greatest M_{TOTAL} for this event (18 July 1987), or on the day prior, anomalies for height, temperature, and wind ranked in the top 5 for all events back to 1948. Massive height anomalies in excess of 5 standard deviations (Fig 2) from normal were associated with the unseasonably deep trough as it moved into the Great Basin and, in particular, across southern California and Nevada. Anomaly values in excess of 4 Standard Deviations from normal were associated with both the u- and v- wind at various levels (Fig 3) resulting in a highly anomalous M_{WIND} totals. Even the though the M_{MOIST} total for this event was not in the top 10 for all moisture anomalies it still supported moisture anomalies; with respect to precipitable water values; two to three Standard Deviations above normal. The degree of departure in all four elements investigated is what makes this event truly stand out from all other events in the 59-year dataset.

In contrast, the second most anomalous event of the study period occurred on 10 November 1969 and did not have a significant impact on the western United States. Despite being meteorologically anomalous this event appears to have had relatively limited tangible impact across the region affected by the system. This event was associated with a trough that dug down the west coast and resulted in a cut-off low off the Baja Coast that drifted slowly inland into the desert southwest. Locally heavy rain was associated with the system with numerous sites in southern California and southern Arizona receiving one to two inches of rain. The cooperative observer station at near Tacna, Arizona had their fourth highest single day precipitation total on record (1969-2006) with 2.18" (55.37 mm) recorded on 10 November 1969. This total represented over half of the average annual precipitation at this site. Several other sites in southern California and southern Arizona received 25% to 35% of their annual precipitation in a single day as this system moved toward the coast.

The most anomalous aspect of this system was the height anomalies (Fig 4) which were by far the most significant in the 59-year dataset. The M_{HEIGHT} anomaly with the 10 November 1969 event was 6.884 while the second largest M_{HEIGHT} value in the dataset was only 5.619 which occurred on 9 June 1976. The heavy precipitation was associated with an M_{MOIST} anomaly of two to three Standard Deviations (Fig 4) above normal and a mid level southerly wind anomaly into the extreme southwestern U.S. (not shown).

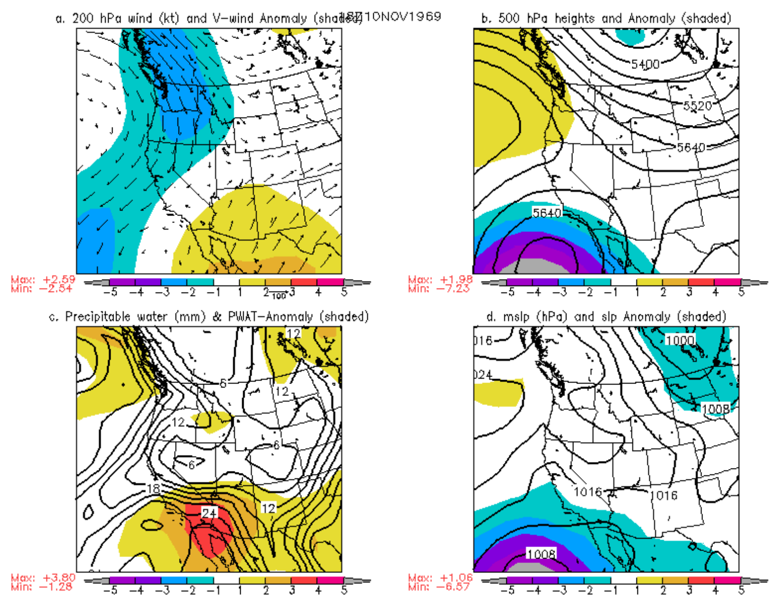

Fig 4 – As in Fig 2 except for 10 November 1969.

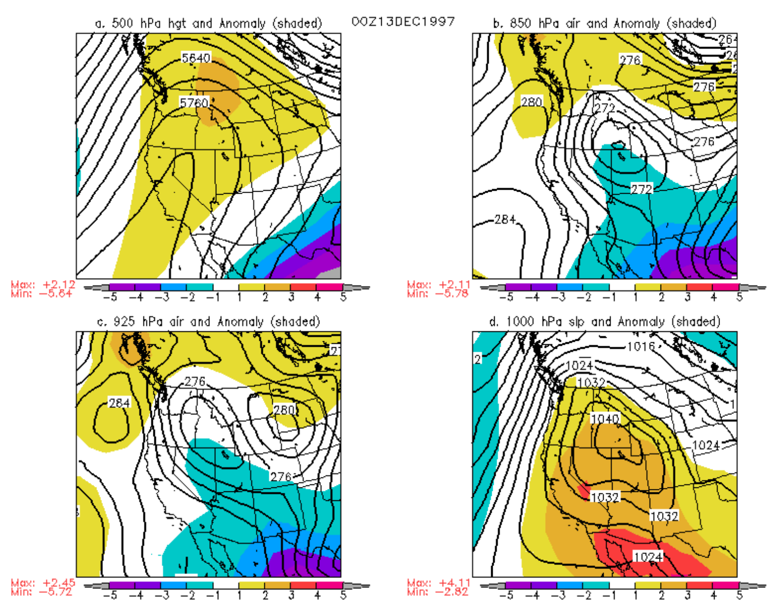

Fig 5 - Selected anomaly images associated with the 13 December 1997 event. Clockwise from the upper left: 500 mb height (m) and anomaly; 850 mb temperature (K) and anomaly; 100 hPa SLP (hPa) and anomaly; 925 hPa temperature and anomaly.

3.1b *Top 10 Anomalies by Variable*

As previously discussed, the M_{TOTAL} for each six hour period for the 59-yr period has four anomaly magnitudes associated with it. Anomaly magnitudes for height, temperature, wind, and specific humidity have been calculated. The top 10 anomalies for each of these variables are listed in Tables 2a-d.

The largest M_{HEIGHT} anomaly of 6.884 (Table 2a) was associated with a large cut-off low situated off of the Baja Coast on 10 November 1969 (Fig 4). This low was associated with rainfall amounts of 1-2" (25-50 mm) across southern California and Arizona on the 9th and 10th of November 1969. Several locations received amounts of 25% to 50% of their annual precipitation in a single day as this system approached the coast. The second largest height anomaly (5.619) over the 59-yr period occurred on 9 June 1976. On the 9th ofJune 1976 an unseasonably strong trough sat off of the southern California coast. As this system moved inland it was associated with a significant severe outbreak across North and South Dakota. The June 11th, 1976 outbreak resulted in the most tornadoes recorded in a single day in North Dakota (nearly 30 separate tornado events) and produced large hail and flash flooding in the Black Hills of South Dakota.

The largest value of M_{TEMP} (5.062, Table 2b) was associated with a sprawling area of high pressure which settled over the Great Basin and extended into southern Texas on 13 December 1997 (Fig 5). Frigid air settled into much of the Great Basin and southwest U.S. and the system was associated with a widespread freeze across southern Texas with temperatures even dropping to near or below freezing in the Phoenix, AZ area. Morning lows in Yellowstone, WY dropped as low as 32° F below zero (-36 C). In addition, a rare sleet event occurred in Brownsville, TX in what was only the 12th occurrence of frozen precipitation in 50 years. Even with impressive cold air sliding into the southwestern U.S., the most significant temperature anomalies with this event actually extended into northern Mexico.

The second largest M_{TEMP} anomaly (4.958) was associated with the 18 July 1987 western U.S. trough which was also the largest M_{TOTAL} departure on record in the western U.S. (see section 3.1a). This system was associated with heavy rainfall across Idaho and Montana as well as a severe weather outbreak across northern Utah and western Wyoming which produced an F4 tornado in Yellowstone National Park.

The largest M_{WIND} value (4.962, Table 2c) occurred on 2 July 1997 in association with a vigorous trough moving onto the California coast. The system resulted in local precipitation amounts in excess of one inch (25 mm) across northern California and Oregon on 30 June and 1 July 1997.

The second largest M_{WIND} anomaly (4.701) occurred on 26 June 1996. A deep trough dug down the west coast and then moved inland with a 110 knot southerly jet at 250 hPa on 26 June 1996 increasing to 130 knots over the Great Basin on the 27th. As the system moved into the Great Basin it was associated with a significant severe weather outbreak across western and central Montana on the 26th with hail as large as softballs reported.

The top M_{MOIST} anomaly (9.459, Table 2d) was associated with a massive moisture plume which stretched into the Pacific Northwest on 10 February 1972. In fact, the top three moisture anomalies all occurred within a two week period (stretching from the 9th to the 23rd) in February 1972 across the Pacific Northwest. These anomalies coincided with a period of widespread heavy precipitation across Oregon and Washington. Stampede Pass (3958 ft MSL) recorded over 60" (150 cm) of snow and nearly 8" (200 mm) of water between the 13th and 17th of February 1972 and nearly 9" (228 mm) were reported near Randle (900 ft MSL) between the 14th and the 18th. More widespread amounts of 4 to 7 inches (101-178 mm) were reported in the lower elevations during this same period. Flooding on numerous rivers occurred as result of this heavy rain and a Federal Disaster area was declared for several counties in western Washington as a result.

4. RETURN PERIODS

In addition to objectively ranking these synoptic scale events, the ultimate goal of this work is to be able to utilize anomaly information in the forecast process across the western U.S. To place a given anomaly value in perspective for a specific element and level, or an M value, it is useful to know how frequently that anomaly is observed within the domain. To quantify this information return periods have been calculated for different elements and levels. Bins with a width of .1 standard deviations for each 6-hour period were utilized to assess the frequency of occurrence of observed M_{TOTAL}, M_{HEIGHT}, M_{TEMP}, M_{WIND}, and M_{MOIST} values. The return periods are related to the monthly frequency with which a given anomaly is observed (Figs 6-9).

The return periods for M_{TOTAL} values are displayed in Fig 6. The most common M_{TOTAL} value in the database is 2.4 which was observed more than 13 times per month on average. To expand on this, M_{TOTAL} values between 2.1 and 2.7 are observed numerous times in a given month (more than 8 times per month) and thus are quite common. Meanwhile, M_{TOTAL} values of around 1.4 and 3.7 are observed about once a month. M_{TOTAL} values lower than 1.4 and greater than 3.7 occur with rapidly decreasing frequency as you move away from those two values. The M_{TOTAL} of .8 standard deviations represents the 'least active' weather found in the database, having been observed once in the 59-year period of the study. This value is much lower the minimum value observed in HG01 which was 1.3 standard deviations. In general, M_{TOTAL} values exceeding 3.7 standard deviations would warrant closer observation from a forecast perspective as M_{TOTAL} values this high are only observed a small number of times each year. Return periods for M_{HEIGHT}, M_{TEMP}, and M_{WIND} are shown in Figs 7-9.

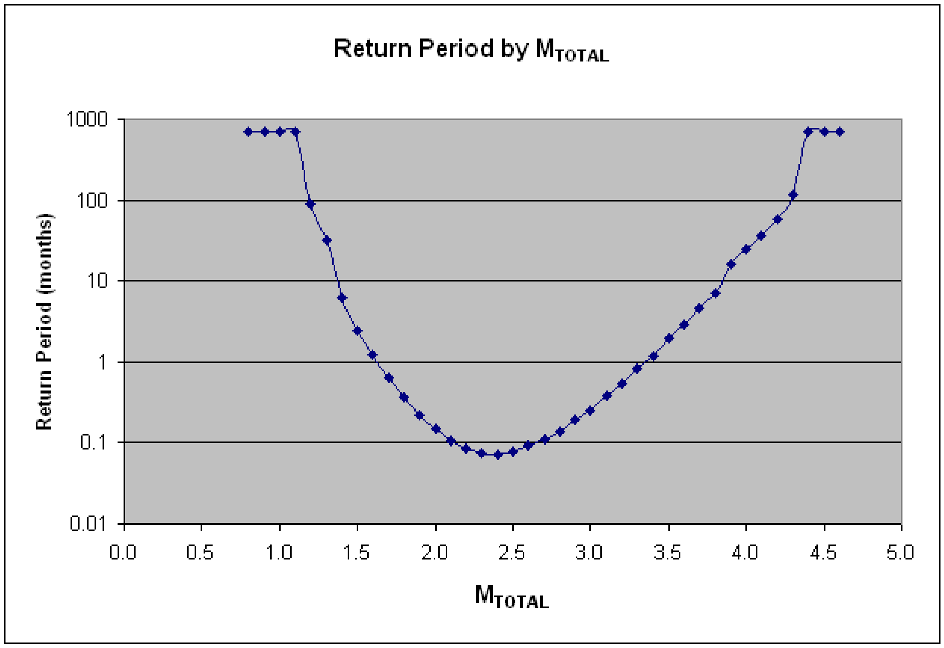

Fig 6 – Return period (in months) for M_{TOTAL} values

5. CONCLUSIONS

Utilizing the methodology presented in HG01, a climatology of standardized anomalies was developed for the western U.S for the period of 1948-2006. Six-hourly anomaly departures for a series of levels were examined for Height, Temperature, Wind, and Moisture from 1948 through 2006. In addition, the total anomaly (accounting for the M_{HEIGHT}, M_{TEMP}, M_{WIND}, and M_{MOIST}) was identified for each six-hour time step. Through this process the most meteorologically anomalous periods for the western U.S. between 1948 and 2006 were identified.

Similar to the results found for the East Coast, the larger M_{TOTAL} events in the western United States were dominated by significant weather events. Events listed in Table 1 produced a wide spectrum of significant weather ranging from a rare F4 tornado event to record snow events and extreme rainfall and flooding.

Examining the data by variable (Tables 2a-d) suggested that many of the top-10 events by type were also top-20 M_{TOTAL} events. Many of the large height anomalies were associated with heavy rain and snow events. Virtually all of the anomalous precipitable water events were associated with significant heavy rain events.

The top-10 thermal anomalies were all associated with cold outbreaks. Surprisingly, there were no record heat events associated with the largest thermal anomalies. Heat events in the western United States will likely require some unique methodology to uncover the key parameters associated with these event types.

6. REFERENCES

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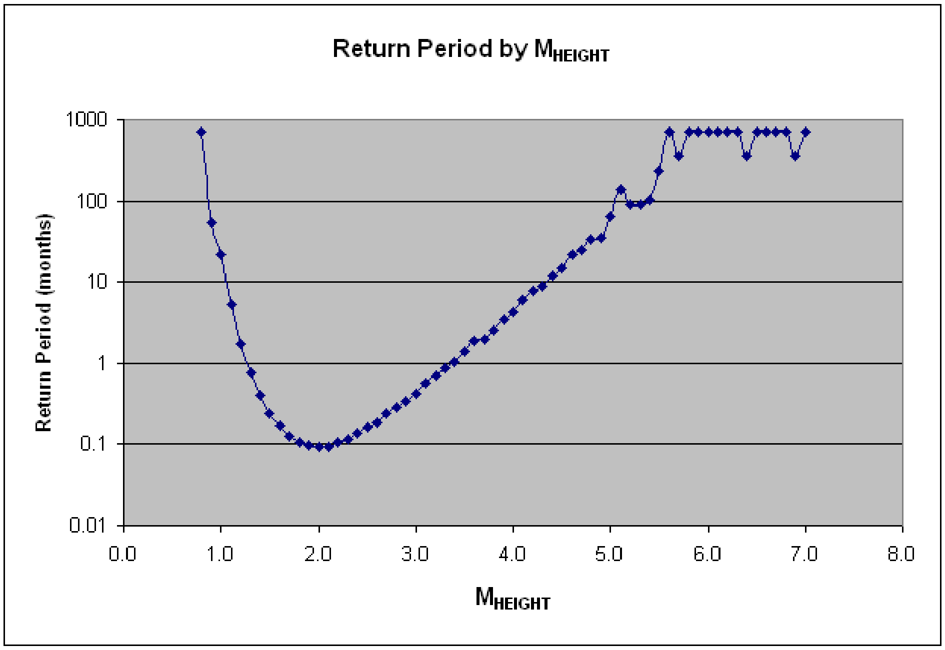

Fig 7 – As in Fig 6 except for M_{HEIGHT}

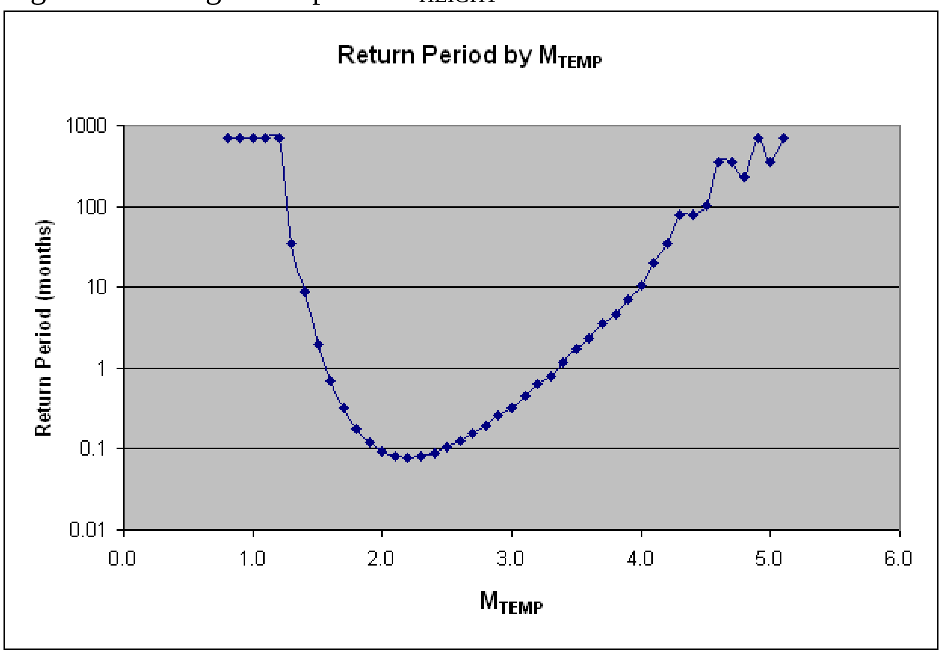

Fig 8 – As in Fig 6 except for M_{TEMP}.

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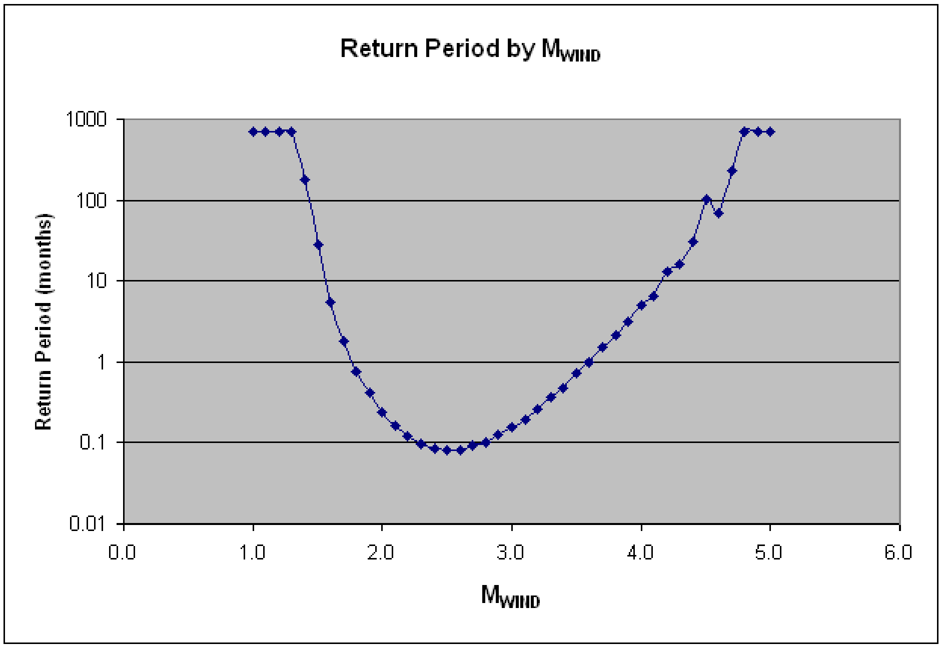

Fig 9 – As in Fig 6 except for M_{WIND}.

Date	M_{TOTAL}	Description
1. 18 July 1987	4.529	Record rain OR/ID/MT; Yellowstone F4 Tornado
2. 10 November 1969	4.288	Cut-off low…1-2” (25-50 mm) rain in southern CA and AZ
3. 25 September 1986	4.281	Significant flooding in Montana (10”/250 mm rain in 18 hrs)
4. 10 June 1955	4.235	Cut-off low…2-3” (50-75 mm) rain in AZ as it moved inland
5. 17 April 1983	4.172	Cut-off low…1-2” rain in southern CA and AZ
6. 16 February 1972	4.169	Significant Pacific Northwest Flooding
7. 01 May 1951	4.153	Heavy rain and snow event from West Coast into MT
8. 16 November 1986	4.113	Cut-off near Baja; 1-2” (25-50 mm) rain southern CA
9. 13 October 1962	4.108	Intense low – Columbus Day windstorm - northern CA to the Pacific NW
10. 13 December 1997	4.076	Strong High Pressure Great Basin…Record Lows
11. 14 December 1967	4.072	Massive winter storm in AZ…state 24 hour snowfall record
12. 23 March 1954	4.071	Heavy rain in southern CA…10-12” (250-300 mm) in CA mountains…32” (81 cm) snow in 24 hrs in Bright Angel AZ
13. 26 June 1996	4.062	Deep western U.S. trough; severe weather outbreak in MT
14. 30 March 1978	4.037	Cut-off low; 1-2” (25-50 mm) in southern CA…locally up to 5” (125 mm)
15. 23 December 1955	4.010	Record rain and flooding across northern CA and Oregon; significant Pacific Northwest windstorm
16. 26 June 1969	3.970	Heavy rain from the Pacific NW o MT and ND
17. 21 May 2006	3.966	Pacific Northwest severe weather event
18. 22 April 2005	3.962	West Coast trough
19. 02 August 1976	3.956	West Coast trough; Big Thompson Canyon flash flood
20. 27 April 1997	3.953	Texas Upper low; record spring snow in Texas

Table 1. Top 20 normalized M_{TOTAL} events for the period 1948-2006

	Date	M_{HEIGHT}	Description
1.	10 November 1969	6.884	Cut-off low…1-2” (25-50 mm) rain in southern CA and AZ
2.	09 June 1976	5.619	Record breaking Tornado outbreak in ND
3.	25 June 1969	5.551	Heavy rain from the Pacific NW o MT and ND
4.	17 July 1987	5.372	Record rain OR/ID/MT; Yellowstone F4 Tornado
5.	16 November 1986	5.356	Cut-off near Baja; 1-2” (25-50 mm) rain southern CA
6.	11 October 1962	5.347	Intense low – Columbus Day windstorm - northern CA to the Pacific NW
7.	05 December 1997	5.312	Significant heavy rain and flooding in southern CA
8.	17 April 1983	5.303	Cut-off low…1-2” (25-50 mm) rain in southern CA and AZ
9.	14 December 1967	5.095	Massive winter storm in AZ…state 24 hour snowfall record
10.	11 February 1978	5.054	California heavy rain; local 2 day totals in excess of 15” (380 mm)

Table 2a. Top 10 normalized M_{HEIGHT} events for the period 1948-2006

	Date	M_{TEMP}	Description
1.	13 December 1997	5.063	Strong High Pressure over Great Basin; Record Lows
2.	18 July 1987	4.958	Record rain OR/ID/MT; Yellowstone F4 Tornado
3.	04 September 1961	4.706	Significant early season snow in CO
4.	24 March 1955	4.615	Record breaking cold snap north central U.S.
5.	27 April 1997	4.518	Texas Upper low; record spring snow in Texas
6.	06 May 1969	4.484	Southwest U.S. cut-off; significant flooding in CO
7.	13 February 1960	4.399	Arctic intrusion into the central U.S.
8.	22 August 1968	4.395	Strong trough along west coast; locally heavy rain in northern CA
9.	01 May 1951	4.384	Deep cold southwest U.S. trough
10.	09 November 1955	4.316	Upper low over Texas; early season Texas snow

Table 2b. Top 10 normalized M_{TEMP} events for the period 1948-2006

	Date	M_{WIND}	Description
1.	02 July 1997	4.962	Strong summer trough; >1” (25 mm) rain in northern CA and OR
2.	26 June 1996	4.701	Deep trough; severe weather outbreak in MT
3.	17 July 1987	4.684	Record rain OR/ID/MT; Yellowstone F4 Tornado
4.	13 October 1962	4.663	Intense low – Columbus Day windstorm - northern CA to the Pacific NW
5.	10 July 1979	4.590	Unseasonably strong trough into the Pacific Northwest
6.	16 November 1986	4.578	Cut-off near Baja; 1-2” (25-50 mm) rain southern CA
7.	24 December 1983	4.561	Significant windstorm in lee of Cascade Mountains, WA
8.	26 June 1969	4.545	Heavy rain from the Pacific NW o MT and ND
9.	22 August 1968	4.539	Strong trough along west coast; locally heavy rain in northern CA
10.	18 January 1988	4.532	Major winter storm; Great Basin into the Northern Plains

Table 2c. Top 10 normalized M_{WIND} events for the period 1948-2006

Date	M_{MOIST}	Description
1. 10 February 1972	9.459	Heavy rain and record flooding in the Pacific Northwest
2. 23 February 1972	9.425	Heavy rain and record flooding in the Pacific Northwest
3. 14 February 1972	7.995	Heavy rain and record flooding in the Pacific Northwest
4. 18 May 1956	6.995	Moisture surge into southern CA;
5. 01 August 1952	6.985	Locally heavy rain southern CA, AZ, NM
6. 23 March 1954	6.753	Heavy rain in southern CA…10-12" (250-300 mm) in CA mountains…32" (81 cm) snow in 24 hrs in Bright Angel AZ
7. 01 January 1997	5.965	Heavy rain and severe flooding in CA and Pacific Northwest
8. 31 March 1964	5.939	West Coast trough
9. 24 December 1955	5.851	Record rain and flooding across northern CA and Oregon; significant Pacific Northwest windstorm
10. 31 July 1952	5.758	Summer rain event in northern California

Table 2d. Top 10 normalized M_{MOIST} events for the period 1948-2006