

Analysis of Cloud-to-Ground Lightning on the Olympic Peninsula

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Acknowledgment

Our appreciation, especially to Kelvin Li for assembling a uniform lightning data set for the Olympic Peninsula, and to Don Estberg for help with various computer issues.

Summary

A 25 year record from 1985-2009 of cloud-to-ground lightning strikes on the Olympic Peninsula from the National Lightning Detection Network was analyzed in order to develop a first lightning climatology of this region. Additional strike data from Western North America was also used to develop this climatology. The primary source of atmospheric data used to develop this climatology was from the North American Regional Reanalysis.

Statistical distributions of the annual cycle were developed revealing a primary warm season maximum dominated by negative polarity strikes in August and a secondary wet season maximum dominated by positive polarity strikes in November.

Statistical distributions of the warm season diurnal cycle revealed a primary afternoon maximum and additional secondary maximum associated with singular intraseasonal events whose timing was dictated by their spatial and temporal origins.

Statistical elevation distributions revealed a primary warm season elevation maximum at 1350m related to cloud base heights. Several secondary maximums and minimums related to orography and the temperature field were also revealed. Positive and negative polarity strikes had distinctly different distributions attributed to the vertical charge structure within the thunderstorm cell. The wet season distribution differed from that of the warm season; these differences were related to the contrasting winter temperature field and thunderstorm origins.

A case study and statistical analysis of the major warm season intraseasonal events revealed the importance of tropical moisture origins and subsequent dynamic evolution. The 700mb behavior appears to be an important indicator of this evolution. The influence of a cyclonic vortex typically in the mid latitude eastern Pacific Ocean was a critical factor in determining the likelihood of the development of an Olympic Peninsula lightning event.

Storm motion was examined through case studies of major warm season events, and warm season events which occurred in the afternoon. Major events generally entered the Olympic Peninsula from the south although some differences in direction and entry location were influenced by details of

the tropical moisture source dynamics responsible for the vertical instability. Strike motion through the Olympic Peninsula was well represented by the 700mb wind direction and speed. The cloud base ceiling was also a factor in determining the progression of events through the Peninsula. Some of the afternoon events progressed across the Peninsula in different directions, but all were consistent with the 700mb wind direction. On shore 700mb cyclonic vortices were responsible for two events moving from north to south. The two largest wet season events were also examined. Storm motion was from the southwest and associated with the progression of wet season frontal boundaries on shore.

Interannual behavior on the Olympic Peninsula was also examined without attempting rigorous statistical analysis because of the limited length of the study period. The beginning dates for the warm season lightning showed no definite trend over the 25 years of observations. The annual strike count of afternoon warm season events appeared to be correlated with the total annual strike count of all warm season events. The time series of these totals was correlated with the warm season tropical ocean temperature averages used as a measure of El Nino activity. The annual average near surface specific humidity was correlated with the total annual wet season strike count. The warm season strike totals were correlated with the wet season totals a year later.

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Introduction

The development of ground based remote sensing lightning detection networks (Rakov and Uman 2003) has resulted in many cloud-to-ground regional lightning climatology studies throughout the world; a partial summary appears in Williams (2005). Using the broadest definition of the Pacific Northwest (including Alaska, and Western Canada), several studies for this region have been published (Dissing and Verbyla 2003, Nash and Johnson 1996, Rorig and Ferguson 1999, Van Wagtendonk and Cayan 2008). Some of the detection networks have been established for a long enough period of time that statistical analysis of the data generated by them is becoming feasible. In this paper we present the analysis of the 1985-2009 cloud-to-ground lightning data from the National Lightning Detection Network (NLDN) for the Olympic Peninsula (OP) and its surrounding waters. This area is bounded by latitudes from 47° N to 48.5° N and longitudes from 122.5° W to 125° W.

Conifers dominate the OP ecosystem. In the central mountainous region (roughly within the non-coastal boundaries of the Olympic National Park), they remain relatively unaltered by human influences. Much of this area is in a climatic regime that has been classified as “Mediterranean” (Peel et al 2007). The conifers function as poorly grounded lightning rods, and when struck by lightning during the warm season, can lead to forest fires creating catastrophic disturbance of the forest ecosystem (Lutz et al 2009). While analysis of these events on the OP has led to frequency estimates of which are relatively low in comparison to other forested areas, their impact on the forest ecosystem is significant (Huff 1995, Pickford et al 1980, Gavin and Brubaker 1999, Fonda and Binny 2011).

As detection arrays have expanded and improved measures of accuracy have been established, inter comparison of regional strike measurements have become feasible. Figure 1 is a display of the annual strike intensity from the NLDN for the contiguous US from 2001 through 2009 (Orville et al 2011). In this paper intensities are calculated in units of strikes/area · time; strikes have the same meaning as flashes in Orville et al. Expressing time in units of 1 year, Florida is the region of highest intensity and the OP region of least. However, intensity calculations based on polarity and smaller time and area units give a very different regional perspective with highest intensity in various regions of the central US (Zajac and Rutledge 2001, Makela et al 2011). The measure of percentage of positive polarity strikes (Figure 2) gives a contrasting perspective to that of Figure 1 (Orville et al 2011). A

more detailed plot of the data in Figure 2 reveals the highest values in the coastal regions of the OP (Ely and Orville 2005) with some of the lowest values in Florida. Coastal events have also been observed over other ocean waters and the higher cloud-to-ground positive current strikes have been associated with transient luminous events (TLEs) above the thunderstorms such as sprites and elves (Soula et al 2010, Adachi et al 2005, and Ganot et al 2007).

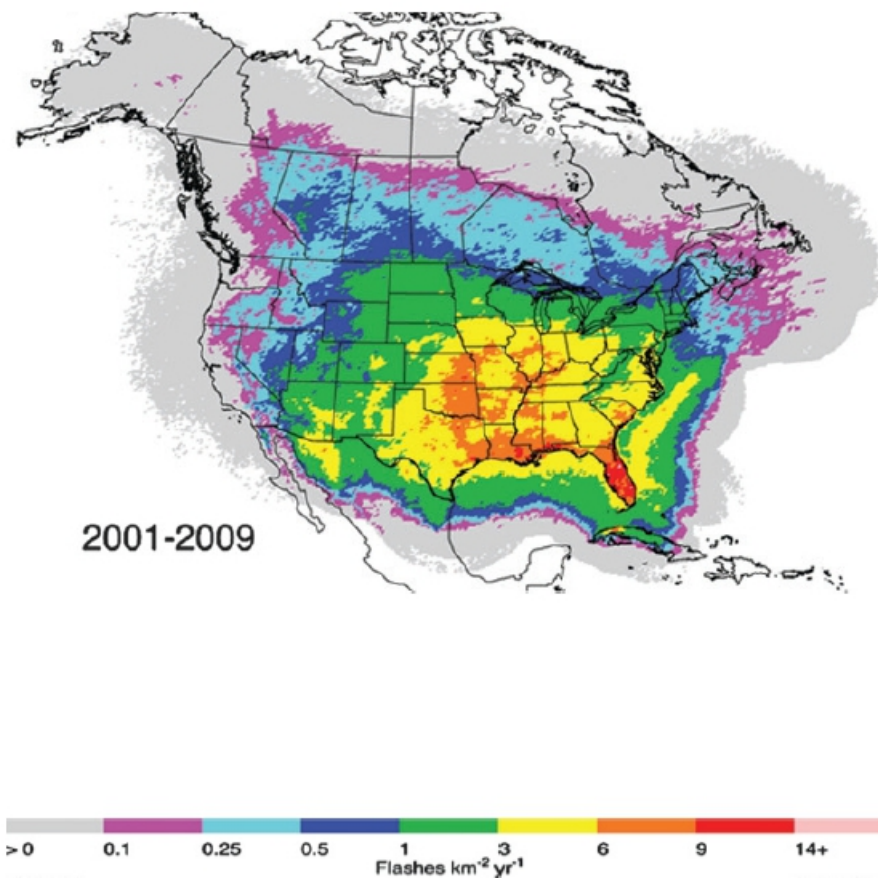


Figure 1. Mean annual strike intensity in North America, 2001-2009, in units of strikes/ km^2yr . Adapted from Orville et al 2011, Figure 2j.

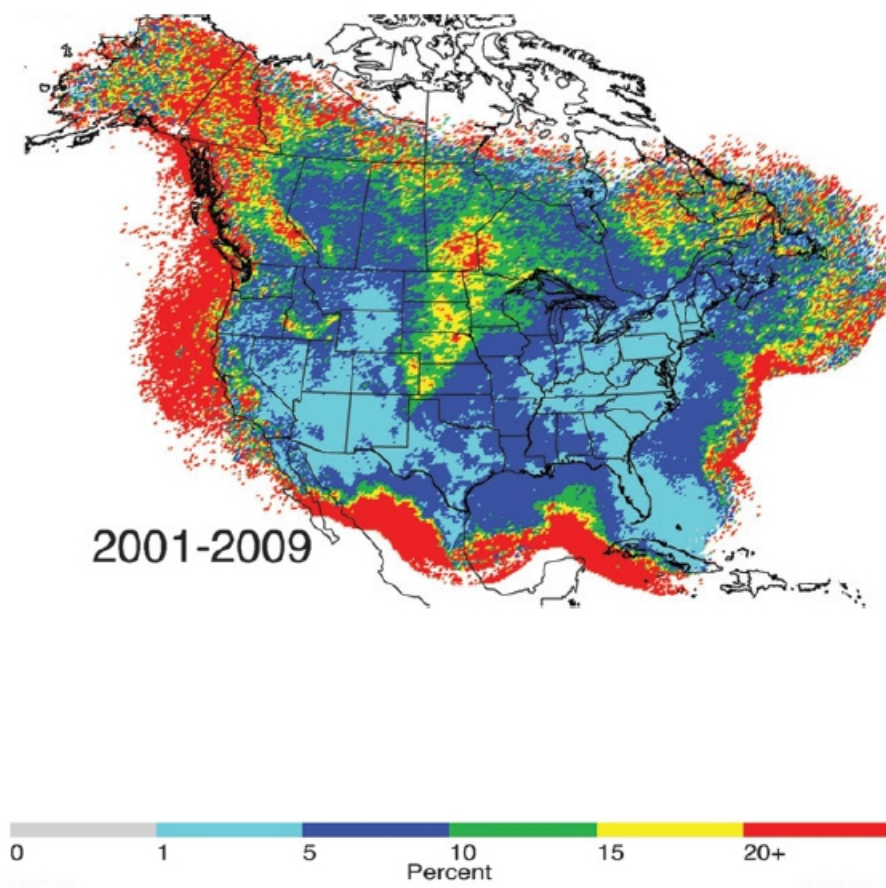


Figure 2. Mean Annual positive percentage in North America, 2001-2009. Adapted from Orville et al 2011, Figure 3j.

Lightning Data

Lightning data for this research is currently provided by the Olympic National Park and the National Interagency Fire Center. Since this agency began using strike data from a sensor network other than that of the NLDN in 2010 and because efficiency comparisons with the newer network are currently being studied (Thompson and Bateman 2013), only data through 2009 from the NLDN is analyzed in this study. Prior to August, 2000 the data was provided by the Climate Research Institute, Scripps Institution of Oceanography.

The NLDN is currently owned and operated by Vaisala, Inc. It has undergone several detection efficiency upgrades and cloud-to-ground strike accuracy improvements since 1985 (Cummins et al 1998). In order to include the earliest data in our analysis, a correction factor was computed for strike data measured prior to the most significant efficiency upgrade in 1994. A correction factor of 1.71 was computed for the OP from the ratio of strikes detected from 1994 through 1996 to the strikes detected at the earlier efficiency but for this same time period. This factor was multiplied by the pre 1994 strike counts to estimate the strike counts that would have been measured at the post 1994 efficiency. Data prior to 1994 was not included for analysis requiring actual strike locations. The current cloud-to-ground strike efficiency and location accuracy is estimated to be greater than 95%

(<http://www.vaisala.com/en/products/thunderstormandlightningdetectionsystems/Pages/NLDN.aspx>). Several ground truthing measurements of the actual detection efficiencies and strike location accuracy have been made (Biagi et al 2007, Maier and Wilson 1996, Idone et al 1998). None of these studies were conducted in mountainous regions such as those of the OP.

Additionally, as described in more detail in the polarity analysis section below, some early data was excluded in our analysis whose polarity was not measured. A correction was also considered by removing low current (≤ 10 kA) positive polarity strikes which might have been misidentified as cloud-to-ground strikes, but were cloud-to-cloud discharges (Orville, 2002; Cummins et al 1998). We performed a low current count of lightning strikes for data from 1994 to 1999. We found 18 low current positive polarity strikes among the 8028 strike 1994-1999 data set; this is less than 0.002% of the 1994-1999 data. We also checked low current strikes by season and found no low positive current strikes in the wet season, 1 strike in Spring and 17 in the warm season out of 718 total positive warm

season events. However, 13 out of 17 low current strikes are from August 4-5, 1999. Due to the small number of low current strikes as a percentage of the total data – with the exception of the August 5th 1999 outlier event - we decided to keep the low current strikes in our lightning data set.

Except for the **Interannual Behavior** section, where annual comparisons are based on total OP strike counts, lightning strike activities are calculated in units of strikes/area/time – using standard units for area and time. This has been done to allow comparisons with the results of other studies done at different locations and times.

Results

A. Distributions

As a starting point in our investigation, the average strike intensity on the Olympic Peninsula was calculated to be 0.025 strikes/(km²year). For the diurnal, annual and elevation analysis, several distributions were created to estimate average lightning intensity in discrete intervals characterizing the temporal or spatial range being investigated.

The lightning data was first subdivided into positive and negative polarity strikes. For polarity analysis, only data from the years 1987 to 2009 were kept in each distribution since the data for 1985 and 1986 did not have polarity values. There were also 5 strikes in July 1987 that had undefined polarity. These strikes were assigned negative polarity values since approximately 89% of warm season strikes have negative polarity. Distributions were created for all lightning strikes, negative polarity strikes and positive polarity strikes separately.

In addition, the lightning data was further subdivided into categories suggested by the climatic analysis of the data itself. For example, based on the analysis of the annual distribution, the strike data was subdivided by season.

Annual Distribution

Method

Lightning strike intensities were calculated by first computing an OP strike count for each month for the entire duration of the lightning data set (January 1987 to December 2009). Strike intensity for each month was defined as the strike count for that particular month divided by the entire area of the Olympic Peninsula (in units of 10^4 km^2) to give intensity units of strikes / ($10^4 \text{ km}^2\text{month}$). The strike intensity for every month was calculated and then the 23-year average strike intensity for that month was found. In the distribution, the standard deviation of the mean was estimated and used as the error bars for each month's average strike intensity.

All strikes

The annual distribution of lightning intensity over monthly intervals was computed first for all positive and negative polarity strikes. As can be seen from Figure A1, the distribution is characterized by a primary peak in August, and a secondary peak in November. This suggests two different mechanisms for lightning generation. The August peak is characterized by mesoscale convective system development during the warmest and driest months of the year. This has been well documented in other lightning studies (Zajac and Rutledge 2001). The November peak reflects synoptic scale systems generated primarily in winter months (Joseph et al 2000). The Pacific Coast – unlike the continental United States - exhibits this secondary peak in lightning activity in the winter season (Zajac and Rutledge 2001). Corresponding seasonal designations are made to distinguish these two types of events. The warm season can be distinguished by the 4 months of highest average temperature and lowest average precipitation. These months are June, July, August and September (JJAS) and they also correspond to the 4 months of highest lightning activity. They will be referred to as the Warm Season for the remainder of this study. The winter events are best characterized by the 4 months of highest average precipitation and lowest average temperature. These wet season months are November, December, January and February (NDJF) and will be referred to as the Wet Season. Data for average monthly precipitation and temperature is from NOAA's Monthly Weather Summary for the Seattle-Tacoma International Airport (nws.noaa.gov); see Table A1.

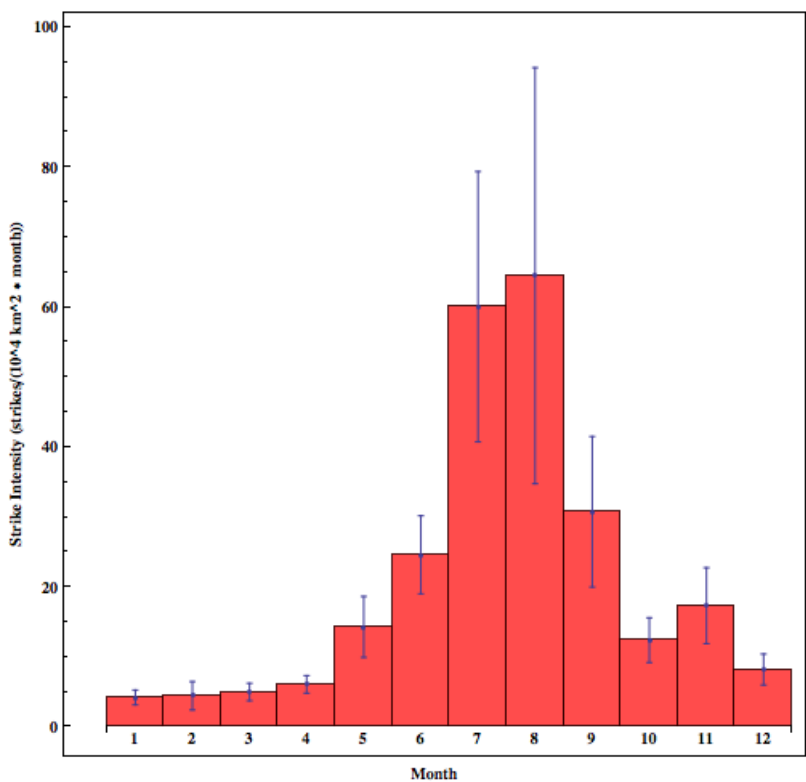


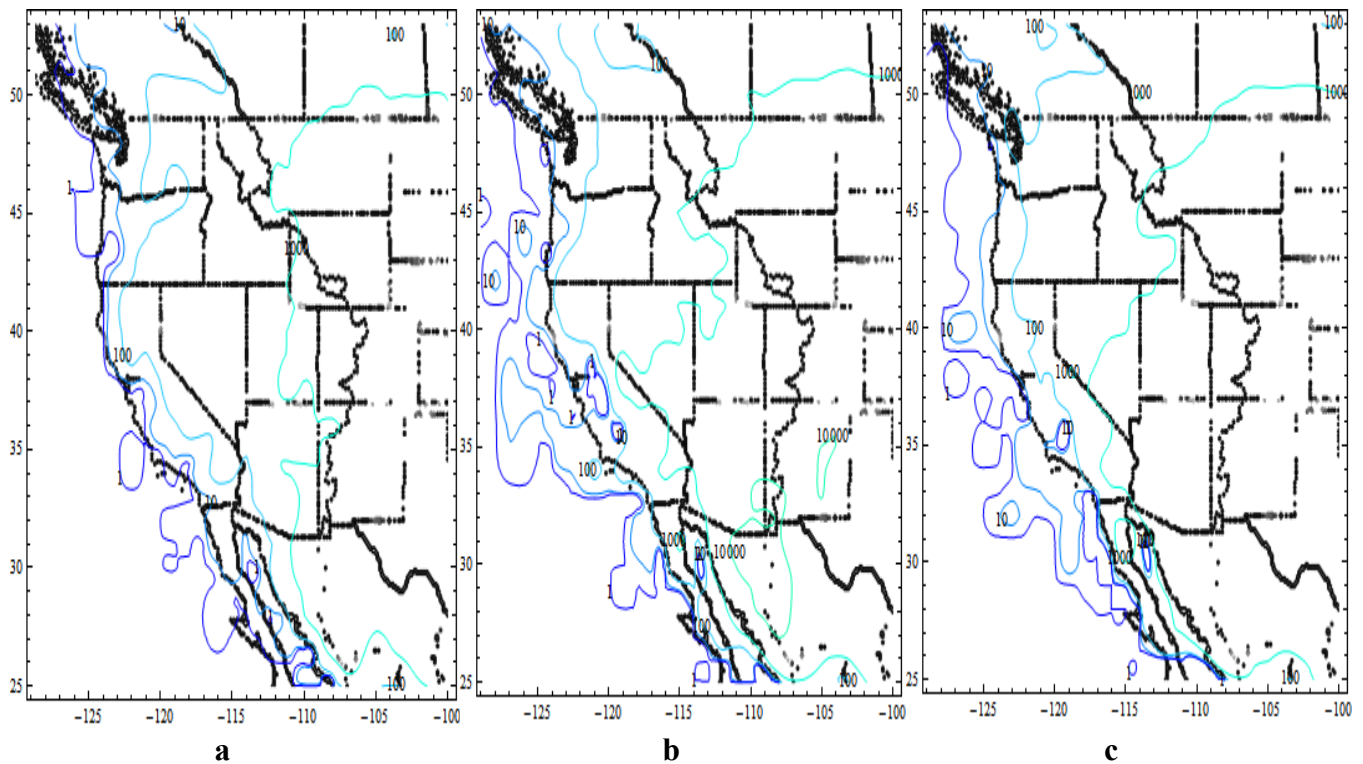
Figure A1. Mean monthly distribution of strike intensity on the Olympic Peninsula (OP), 1987-2009, in units of strikes/10⁴km²mo. Error bars are standard deviation of the mean.

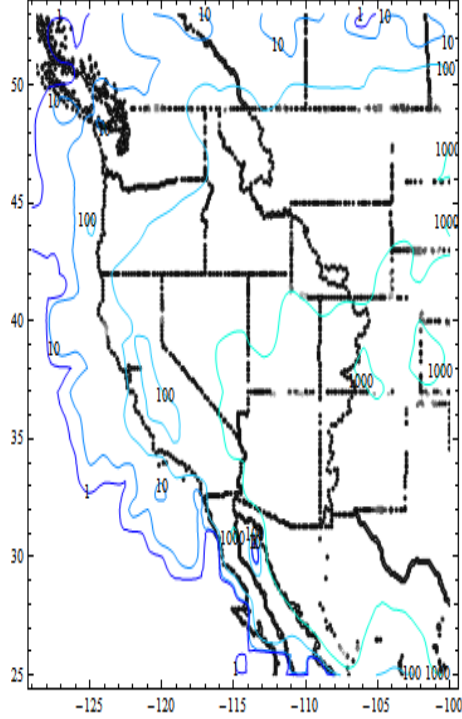
	Precipitation Totals (In)	Mean Temperature (F)	Years Averaged Over
January	5.57	42.0	1981-2010
February	3.50	43.4	1981-2010
March	3.72	46.5	1981-2010
April	2.71	50.3	1981-2010
May	1.94	56.0	1981-2010
June	1.57	60.9	1981-2010
July	0.70	65.7	1981-2010
August	0.88	66.1	1981-2010
September	1.50	61.3	1981-2010
October	3.48	52.8	1981-2010
November	6.57	45.4	1981-2010
December	5.35	40.6	1981-2010

Table A1. Average monthly precipitation and temperature for the Seattle-Tacoma International Airport (nws.noaa.gov).

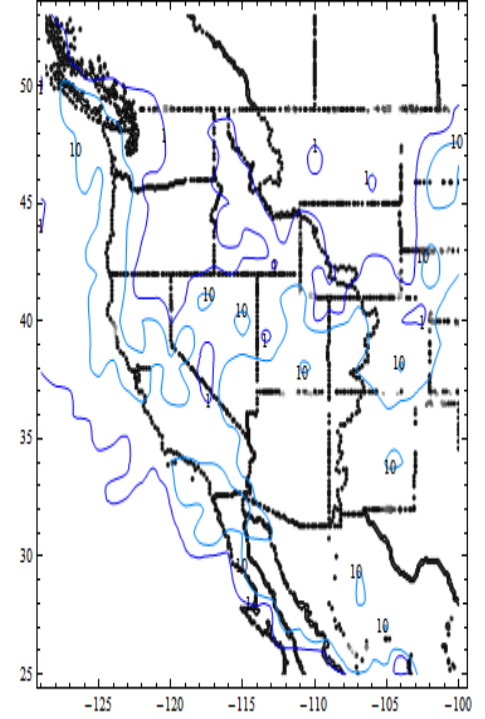
Season and polarity

The evolution of the warm season convective lightning activity for Western North America (WNA) is illustrated for the June-September mean monthly intensities for the period 1994-2005 (Figures A2a-d). During the warm season, lightning events progress both north and west, peaking in August. It is clear from Figure A2d that September also exhibits this trend, hence the reason for its inclusion in the Warm Season definition. The wet season synoptic event lightning activity is illustrated for the November-February months with intensities progressing south along the West Pacific Coast as expected from the seasonal progression of the polar front jet (Figures A2e-h).

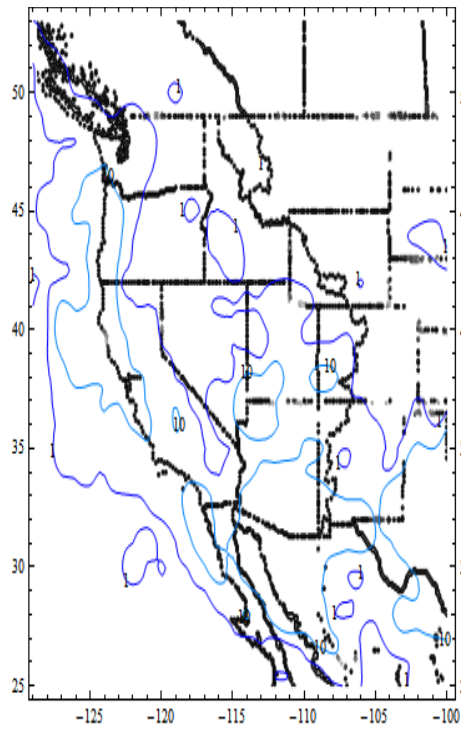




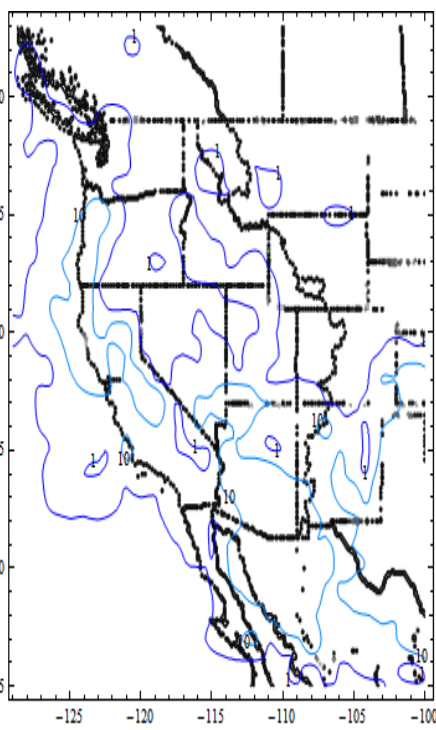
d



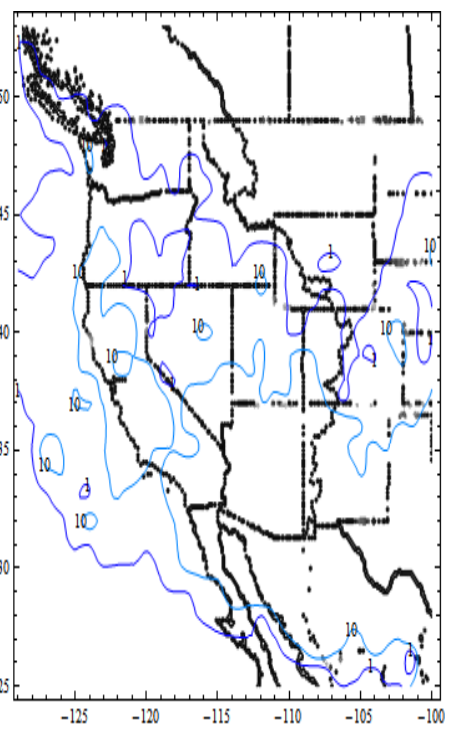
e



f



g



h

Figure A2. Contours of mean monthly strike in Western North America (WNA), 1994-2005, in units of strikes/ $10^4\text{km}^2\text{mo}$. Labeled contour intervals in powers of 10. Strike intensities for (a) June, (b) July, (c) August, (d) September, (e) November, (f) December, (g) January, (h) February.

During the warm season the monthly negative strike distribution (Figure A3) is almost completely characterizes the distribution for all strikes (Figure A1). The monthly positive strike distribution (Figure A4) also largely characterizes the wet season peak centered around the month of November – the month of highest precipitation. These distribution differences reflect the relatively enhanced positive to negative strike ratio in the wet seasons and the reversed ratio in warm season events. Only 13.70% of warm season strikes have positive polarity while 64.32% of wet season strikes have positive polarity. In previous studies, cold season lightning was found to have a high percentage of positive polarity strikes (Zajac and Rutledge 2001).

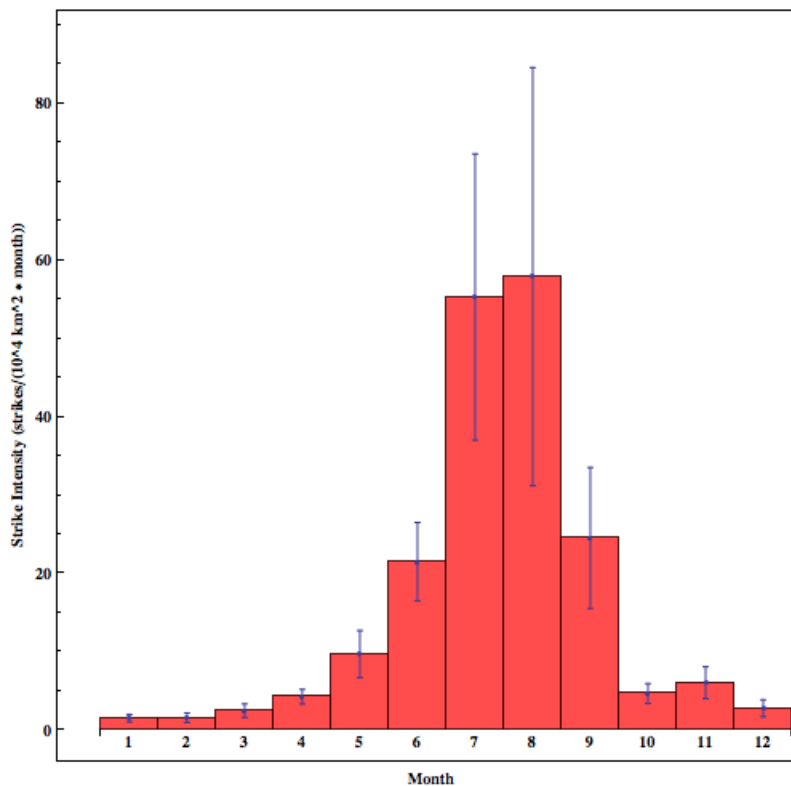


Figure A3. Mean, negative, monthly strike intensity on the OP, 1987-2009, in units of strikes/10⁴km²mo. Error bars are standard deviation of the mean.

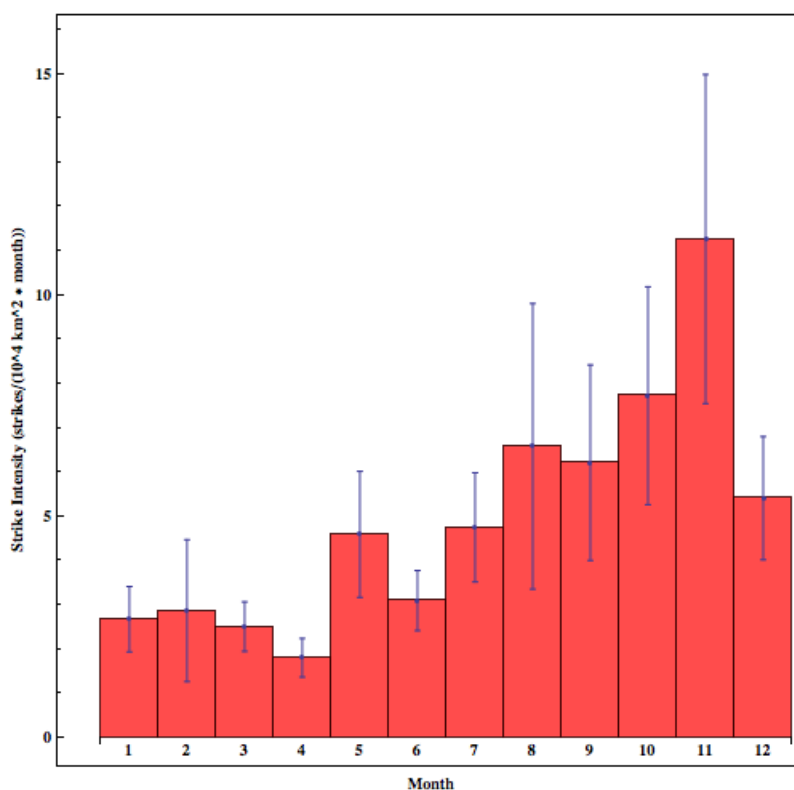


Figure A4. Mean, positive, monthly strike intensity on the OP, 1987-2009, in units of strikes/ 10^4 km ^{2} mo. Error bars are standard deviation of the mean.

Diurnal Distribution

Method

Lightning strike intensities were calculated by first determining an OP strike count for each hour for the entire duration of the lightning data set (January 1987 to December 2009). The OP strike intensity for each hour was defined in an analogous manner to the monthly intensity in units of strikes/ 10^4 km ^{2} hour. Subsequently, the strike intensity for every hour was calculated and then the 23-year average strike intensity for that hour. An estimate of the standard deviation of the mean was used as the error bars for each hour's average strike intensity.

All strikes

The breakdown of notable average hourly intensity patterns is as follows. The total hourly distribution – including all months and both negative and positive polarity strikes – has a lightning activity peak in the afternoon (Figure A5). This is due to convective instability caused by afternoon surface heating and supports previous findings that peak diurnal lightning occurs in the afternoon in the western United States (Zajac and Rutledge 2001). In the morning hours, from 6 to 11 am and peaking at 8 am, there is a broad maximum that smooths out the afternoon peak. In the evening hours, peaking around 10 pm, there is another maximum. The large standard deviations for these two peaks led us to believe that those two maximums may have been result of a few large events that skewed our results.

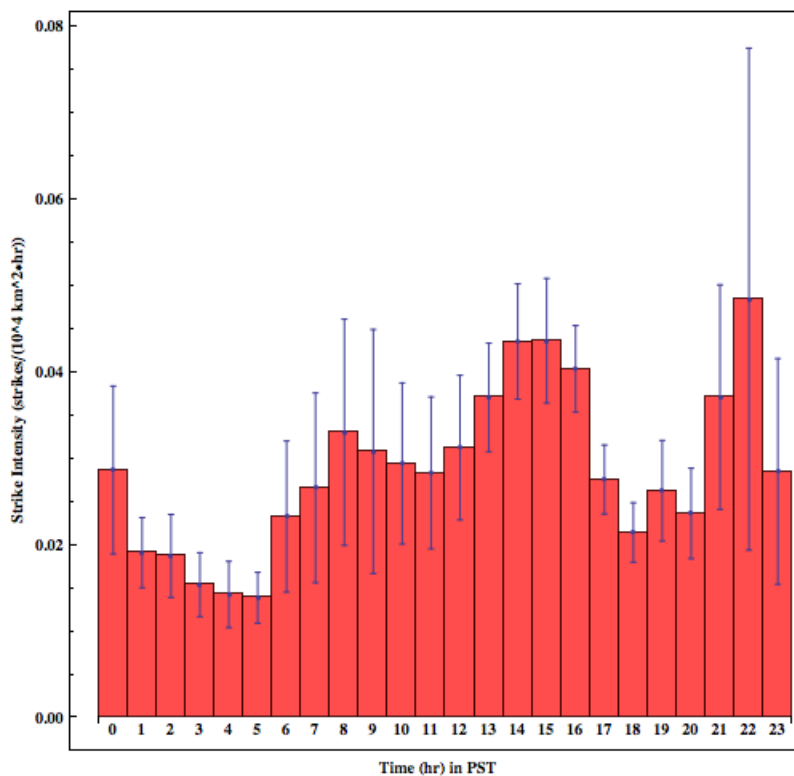


Figure A5. Mean hourly strike intensity on the OP, 1987-2009, in units of strikes/10⁴km²hr. Error bars are standard deviation of the mean.

Three major events

To see if our hourly distribution was skewed by several single events, we isolated all days with 100 or more lightning strikes to see if any major events appeared (Table A2). July 5th 1997 with 1264 strikes, August 6th 1997 with 832 strikes, and August 4th 1999 with 1630 strikes stood out clearly from the other maximum days. These event days can be explained by the very strong 1997 and 1999 lightning seasons; (see the Interannual Behavior discussion section). Hourly distributions were created for these three days to see if they contributed significantly to the morning and evening maxima. The lightning events on July 5th 1997 peak from 6 am to 10 am, and the events on August 6th 1997 peak from 8 am to 1 pm (Figures A6 and A7). These events correspond to the broad morning maximum seen in the total hourly distribution. The lightning events on August 4th 1999 peak from 9 pm to 11 pm which is consistent with late night peak in the total hourly distribution (Figure A8). Removing these three events from the hourly distribution results in a more pronounced afternoon peak (Figure A9). In the early morning hours before sunrise a broad minimum is now visible; at this time the surface temperature is at its diurnal minimum and the surrounding atmosphere is stable. There is still a broad late night maximum, however, peaking at 9 pm and again at 12 am. From Figure A9, one can see that from 9 pm to 1 am the hourly distribution has high strike intensities with large standard deviations – lending credibility to our belief that these high values are due to strong, independent lightning events that have not been isolated. The existence of a late night peak suggests that there may be an underlying climatological cause of nighttime lightning in the Olympic Peninsula. For example, Pitchford and London (1962) found an association between the low-level jet and thunderstorms in the Midwest.

Year	Month	Day	Strike Count
1989	7	30	116.42
1989	7	31	174.62
1990	7	5	106.14
1991	7	24	558.11
1991	8	1	121.55
1992	6	28	304.74
1992	7	20	338.98
1992	8	22	181.47
1993	5	28	164.35
1994	8	3	243
1994	8	28	177
1995	9	4	590
1997	7	5	1264
1997	8	6	832
1997	9	15	125
1997	9	25	163
1997	9	26	169
1998	11	21	133
1999	8	3	186
1999	8	5	1630
1999	8	7	109
2000	7	22	134
2003	6	29	120
2004	9	1	104
2005	6	21	199
2005	9	9	100
2008	11	12	104
2008	7	3	302
2008	8	17	304
2009	7	12	290

Table A2. Dates and strike counts of major daily lightning events on the OP (100 or more lightning strikes) during study period.

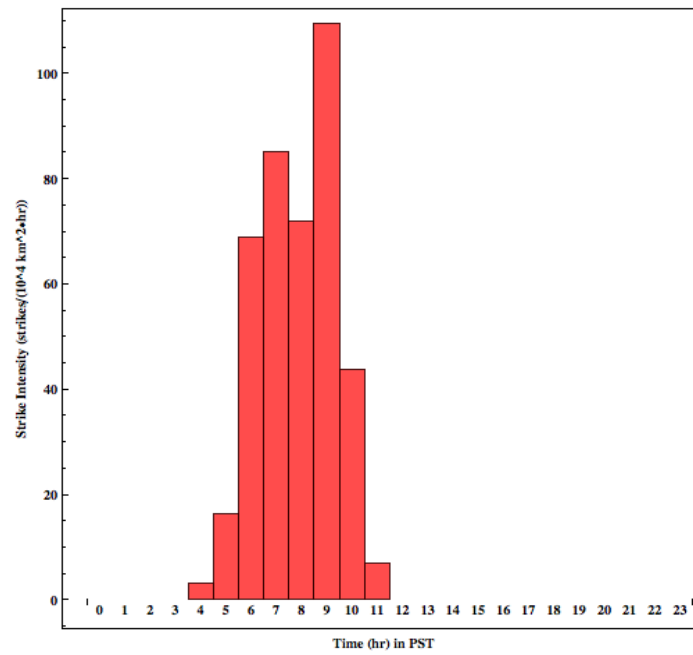


Figure A6. Hourly strike intensity on the OP, July 5th, 1997, in units of strikes/10⁴km²hr.

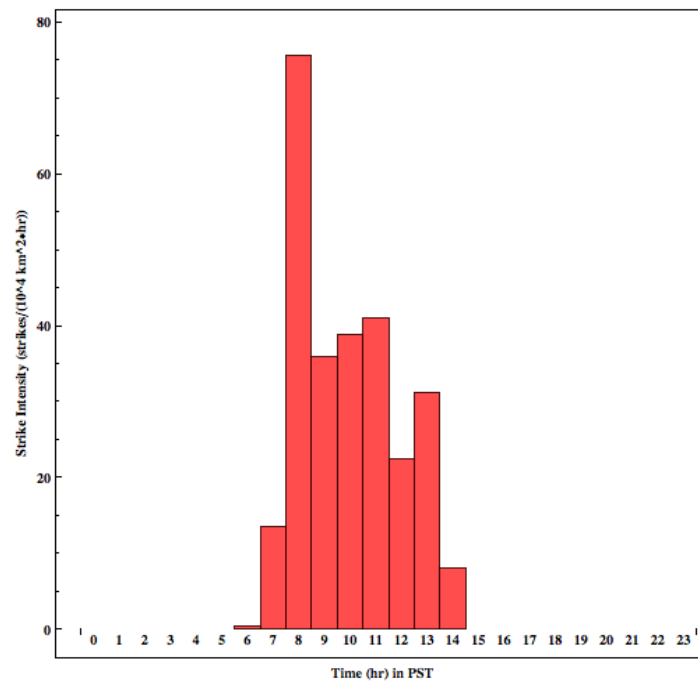


Figure A7. Same as Figure A6 except for August 6th, 1997.

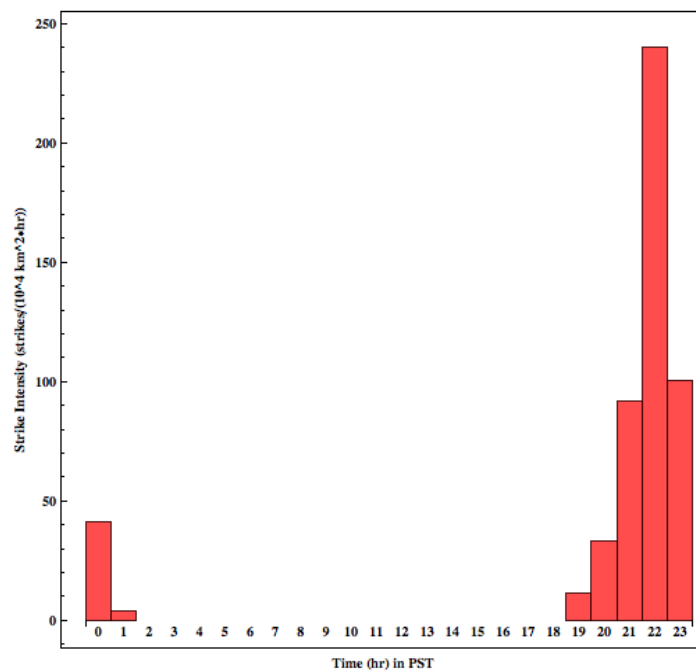


Figure A8. Same as Figure A6 except for August 5th, 1999.

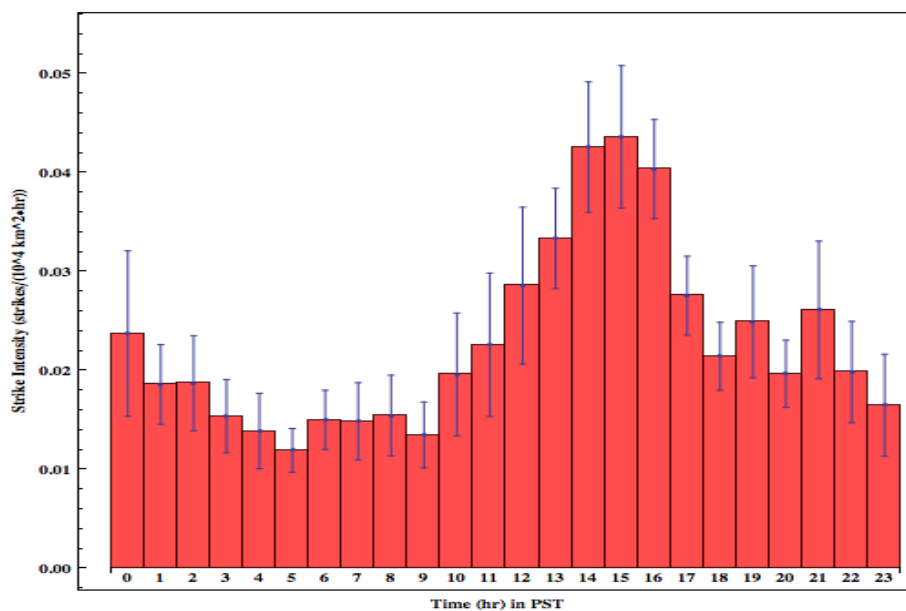


Figure A9. Mean hourly distribution of strike intensity on the OP, 1987-2009, in units of strikes/10⁴km²hr – with strikes for July 5th, 1997, August 6th, 1997, and August 5th, 1999 removed. Error bars are standard deviation of the mean.

Season and Polarity

The following discussion of diurnal distributions includes the three major events in the previous section.

As can be seen from Figures A5, A10 and A11, the warm season dominates the total hourly distribution with strike intensities that are an order of magnitude larger than the wet season. There are approximately 5.3 times more lightning strikes in the warm season than in the wet season. Comparing Figures A10 and A11 suggests that the late night peak originates from events in the warm season (eg, the August 4th 1999 event). The warm season exhibits an afternoon peak and morning minimum consistent with the total hourly distribution.

The wet season exhibits less clear extrema than the warm season. The standard deviations of the wet season distribution are large and the only definite maxima are the afternoon peak and a nocturnal peak around 8 pm (Figure A11). Since the wet season months are the peak precipitation months on the OP we hypothesized that there might be a relationship between the 8 pm nocturnal maximum and the wet season diurnal precipitation pattern. We tested this conjecture but did not find any significant relationship between the diurnal precipitation and lightning distributions. Wallace (1975) has also observed a nocturnal lightning maximum in winter in the northern United States. At this time we do not know the cause of the wet season nocturnal peak though it is a topic for further investigation. The wet season 3 pm maximum might be due to occasional afternoon solar heating. The Olympic Peninsula experiences mild temperatures during the wet season so a midday peak due to several convection-driven lightning events is not unexpected. The large error bars surrounding the afternoon peak confirm our belief that this feature is due to several singular events (Figure A11). Because wet season events are driven by synoptic scale activity, large hourly variations are not expected. Indeed, aside from the aforementioned shallow afternoon and nighttime peaks, there is very little hourly variation in the wet season compared to the warm season.

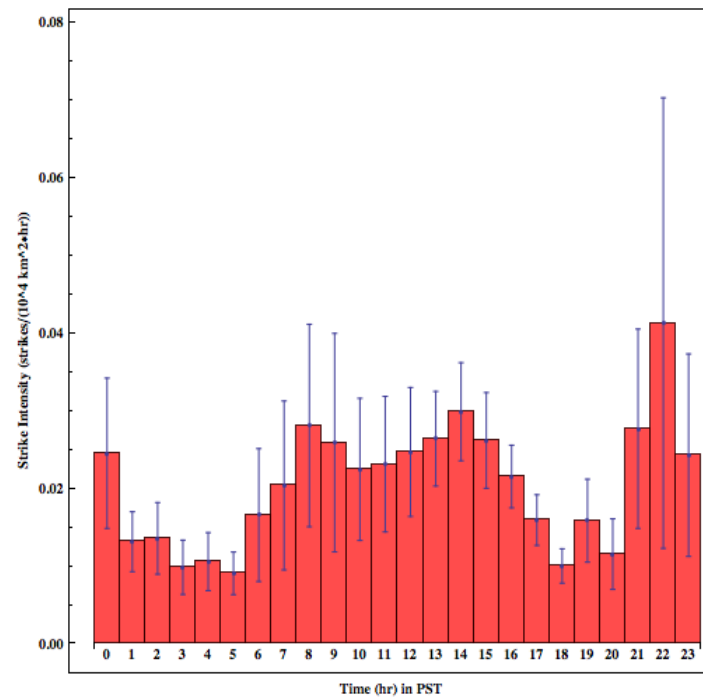


Figure A10. Mean, warm season, hourly distribution of strike intensity on the OP, 1987-2009, in units of strikes/ $10^4\text{km}^2\text{hr}$. Error bars are standard deviation of the mean.

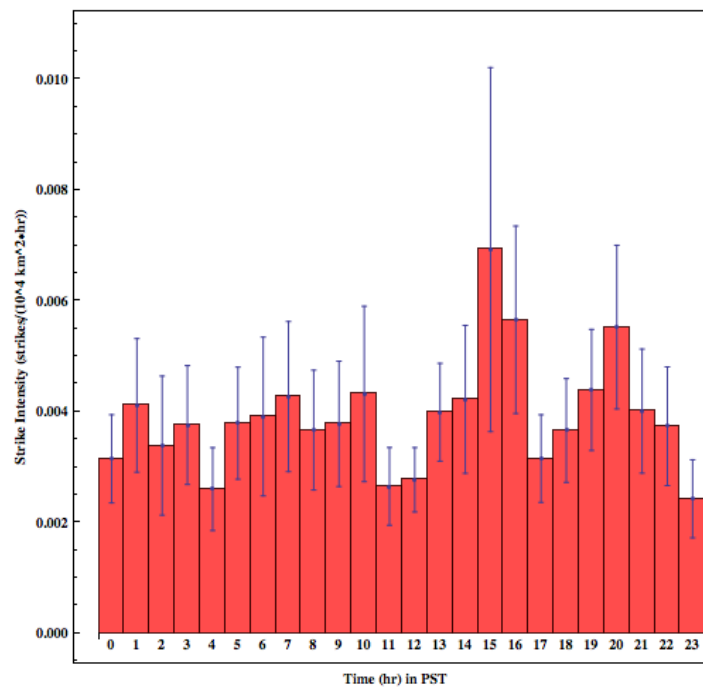


Figure A11. Mean, wet season, hourly distribution of strike intensity on the OP, 1987-2009, in units of strikes/ $10^4\text{km}^2\text{hr}$. Error bars are standard deviation of the mean.

Negative polarity strikes dominate the diurnal lightning picture (Figures A5&A12). There are approximately 3.3 times more negative polarity strikes than positive polarity strikes total. We have already seen in the annual distribution that warm season events are dominated by negative polarity strikes. This result can be seen in the warm season diurnal distribution comparing Figures A10, A13, and A14. We have also seen that positive polarity strikes dominate the wet season, and this can be seen in the diurnal distribution comparing Figures A11, A15, and A16.

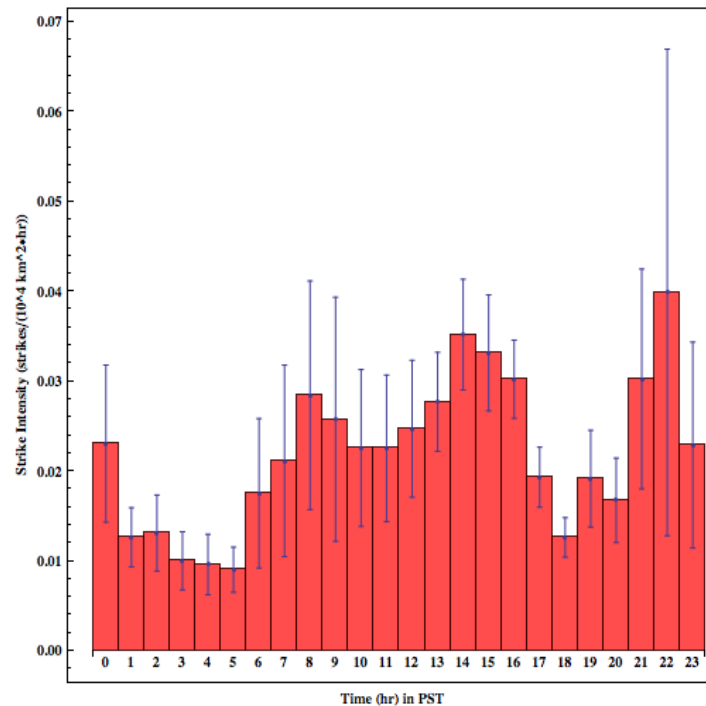


Figure A12. Mean, negative, hourly distribution of strike intensity on the OP, 1987-2009, in units of strikes/10⁴km²hr. Error bars are standard deviation of the mean.

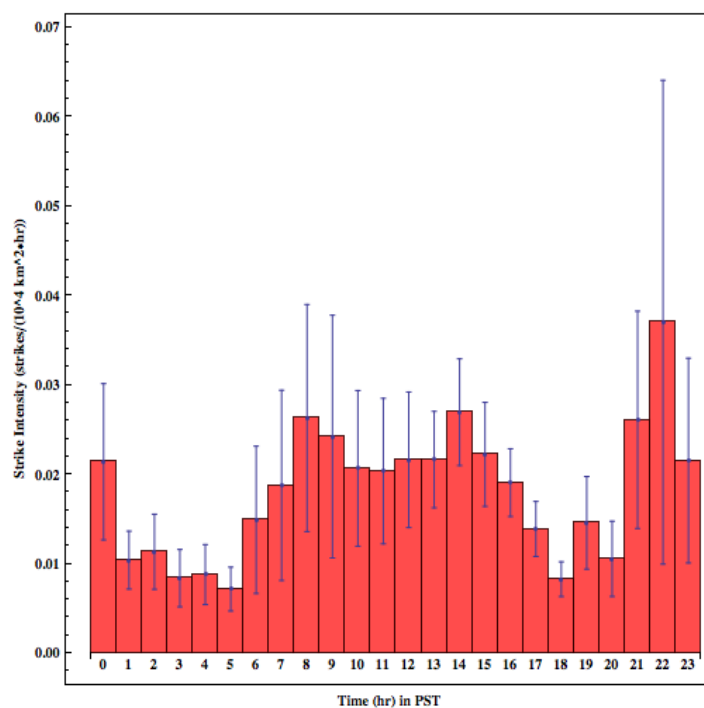


Figure A13. Mean, warm season, negative, hourly distribution of strike intensity on the OP, 1987-2009, in units of strikes/ $10^4\text{km}^2\text{hr}$. Error bars are standard deviation of the mean.

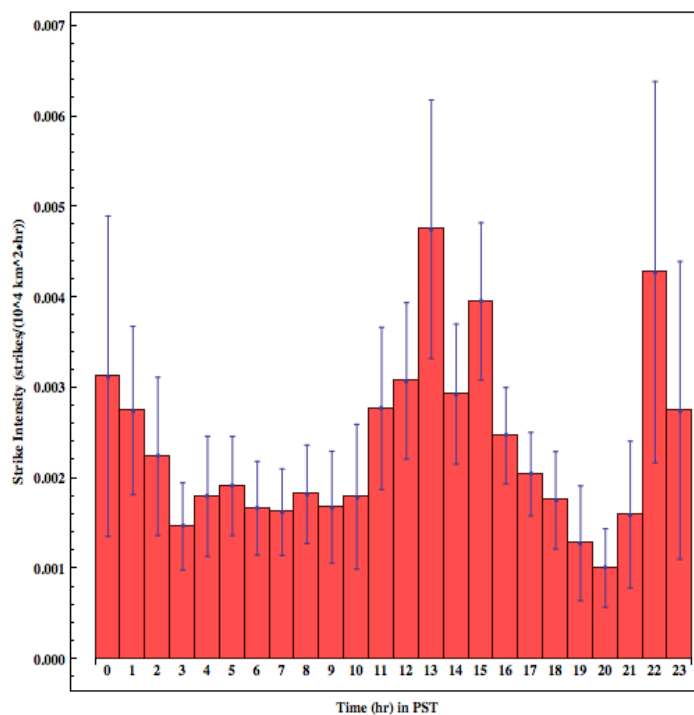


Figure A14. Mean, warm season, positive, hourly distribution of strike intensity on the OP, 1987-2009, in units of strikes/ $10^4\text{km}^2\text{hr}$. Error bars are standard deviation of the mean.

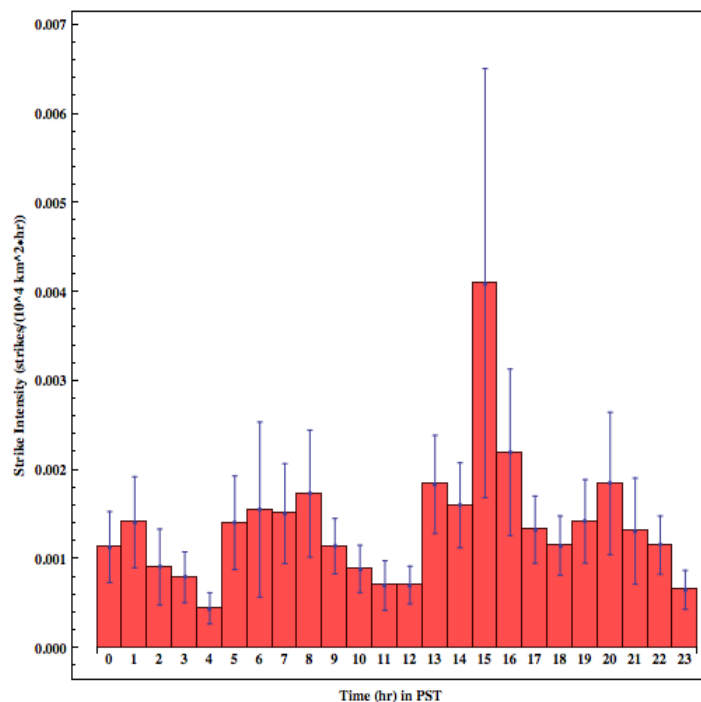


Figure A15. Mean, wet season, negative, hourly distribution of strike intensity on the OP, 1987-2009, in units of strikes/ $10^4\text{km}^2\text{hr}$. Error bars are standard deviation of the mean.

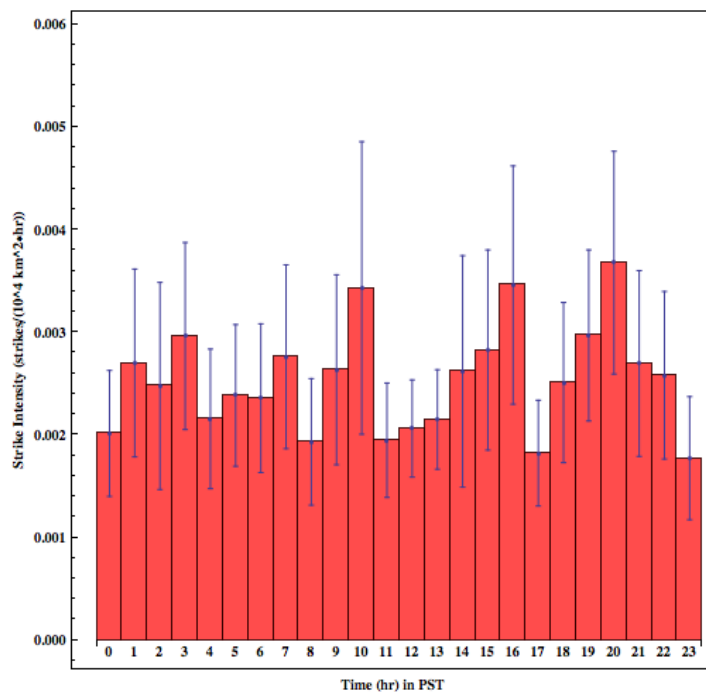


Figure A16. Mean, wet season, positive, hourly distribution of strike intensity on the OP, 1987-2009, in units of strikes/ $10^4\text{km}^2\text{hr}$. Error bars are standard deviation of the mean.

The Spring Quarter (March, April, May) distributions exhibit an unusual and notable pattern. The spring afternoon peak (Figure A17) is much more distinct than in the warm or wet season (Figures 17 and 18). The Spring Quarter months have the highest temperature increase of the year (Shinker 2010). Since the afternoon is the warmest time of the day, large temperature increases from the morning hours to the afternoon hours in the spring would be expected. This distinct warming trend can set up local instabilities that cause thunderstorms to form in the late afternoon. There also exists a broad evening peak centered around 8 pm in both the negative polarity and positive polarity distributions (Figures A18 and A19). This peak is probably due to wet season storms persisting well into spring. The wet season distributions also exhibit the same evening peak centered at 8 pm and it is likely that winter-like weather is the cause of the spring quarter evening peak, as well (Figures A11, A15, A16).

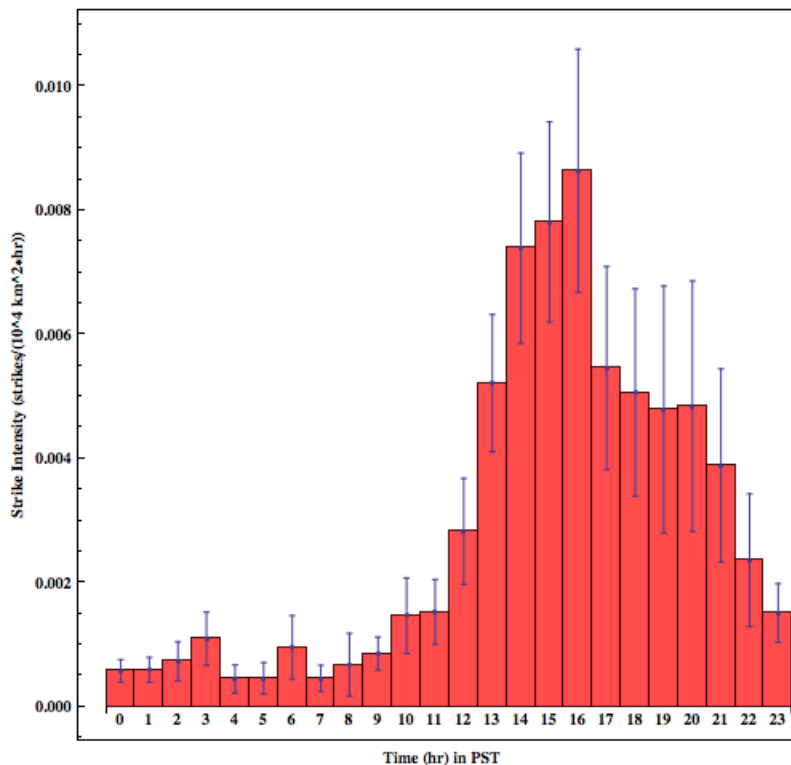


Figure A17. Mean, spring season, hourly distribution of strike intensity on the OP, 1987-2009, in units of strikes/10⁴km²hr. Error bars are standard deviation of the mean.

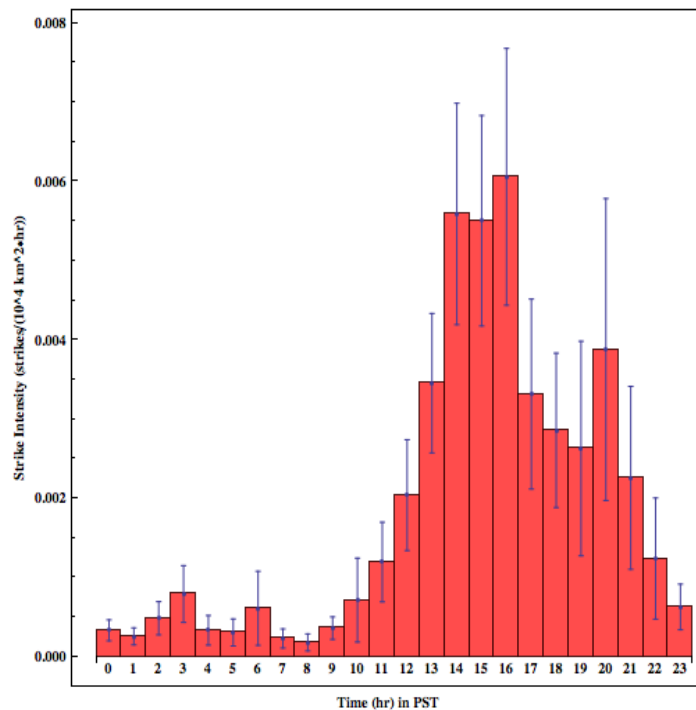


Figure A18. Mean, spring season, negative, hourly distribution of strike intensity on the OP, 1987-2009, in units of strikes/10⁴km²hr. Error bars are standard deviation of the mean.

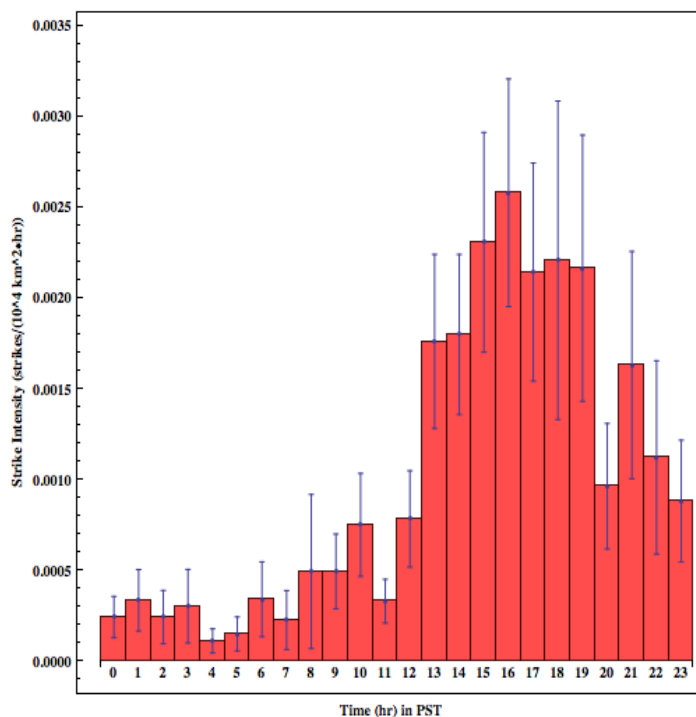


Figure A19. Mean, spring season, positive, hourly distribution of strike intensity on the OP, 1987-2009, in units of strikes/10⁴km²hr. Error bars are standard deviation of the mean.

Elevation Distribution

Method

The elevation data used for the elevation distribution comes from the USGS' GTOPO30 data set (<https://lta.cr.usgs.gov/GTOPO30>). We truncated the GTOPO30 data to the OP latitude-longitude range. The elevation data is given in meters for every 1/120 degree latitude-longitude. The size of the spatial grids is on the same order of magnitude as the median error of the National Lightning Detection Network

(<http://www.vaisala.com/en/products/thunderstormandlightningdetectionsystems/Pages/NLDN.aspx>). For each 1/120 degree latitude-longitude spatial grid the length of one side is approximately between 500 m and 1000 m. The 500 m NLDN median location error suggests that the majority of strikes will be correctly counted in the spatial grid containing the actual stroke location. (This issue is discussed further in **Appendix 4**.)

Each lightning strike in the 23 year data set (January 1987 through December 2009) was assigned the elevation of the 1/120 degree by 1/120 degree spatial grid that it occurred in. We also found the area and total strike count for each spatial grid and added the results to the spatial array. Spatial grids with no lightning strikes were assigned a zero-strike count. We defined the strike intensity of each spatial grid as the total strike count for that spatial grid over the entire 23 year period divided by the spatial grid's area and 23 years to give units of strikes/km²year. The seasonal elevation distributions have spatial grid strike intensities in units of strikes/km²season, where “warm” and “wet” season is defined as a 4 month span (spring season is the conventional 3 month span).

Finally, we grouped the spatial grids into elevation bins from 0 to 2300 m by 50 meter increments. Sea-level strikes (0m) were grouped as one elevation bin to distinguish them from the 0-50 m land strikes. We calculated the average strike intensity and its standard deviation for each elevation bin and used these values to determine the elevation distribution. The standard deviation of the mean was used as the error bar for each elevation bin's average strike intensity value. Several other studies utilized a similar method of assigning strike intensities to elevation ranges (Randerson et al 2004; Dissing and Verbyla 2003; Lopes et al 2011). We created elevation distributions for the relevant subsets of data as follows.

All strikes

As can be seen from Figure A20, the distribution is characterized by a primary peak at 1350 m, a secondary peak 50 m, a sharp minimum at sea-level and a broad minimum centered around 400 m. The large strike intensity errors for the highest elevations are the result of a few lightning strikes occurring over a very small area. The bin areas for elevations around 1700 m and higher become very small so the addition of a few lightning strikes can increase the strike intensity considerably. The standard deviations for these strike intensities are large and therefore these results are not statistically robust. At 2100 m and above, each elevation bin contains only one or two strikes. Randerson et al (2004) reported a similar issue with high strike intensities but lack of statistical significance for their highest elevation bins in Nevada. Kilinc and Beringer (2007) also found variable strike intensities for high elevation bins with small areas in Australia's Northern Territory. The key elements of this distribution will be analyzed in order of increasing elevation in the following **Season** section. (They can all be interpreted from the perspective of warm and wet season events). The spring elevation distribution is discussed separately at the end of this section.

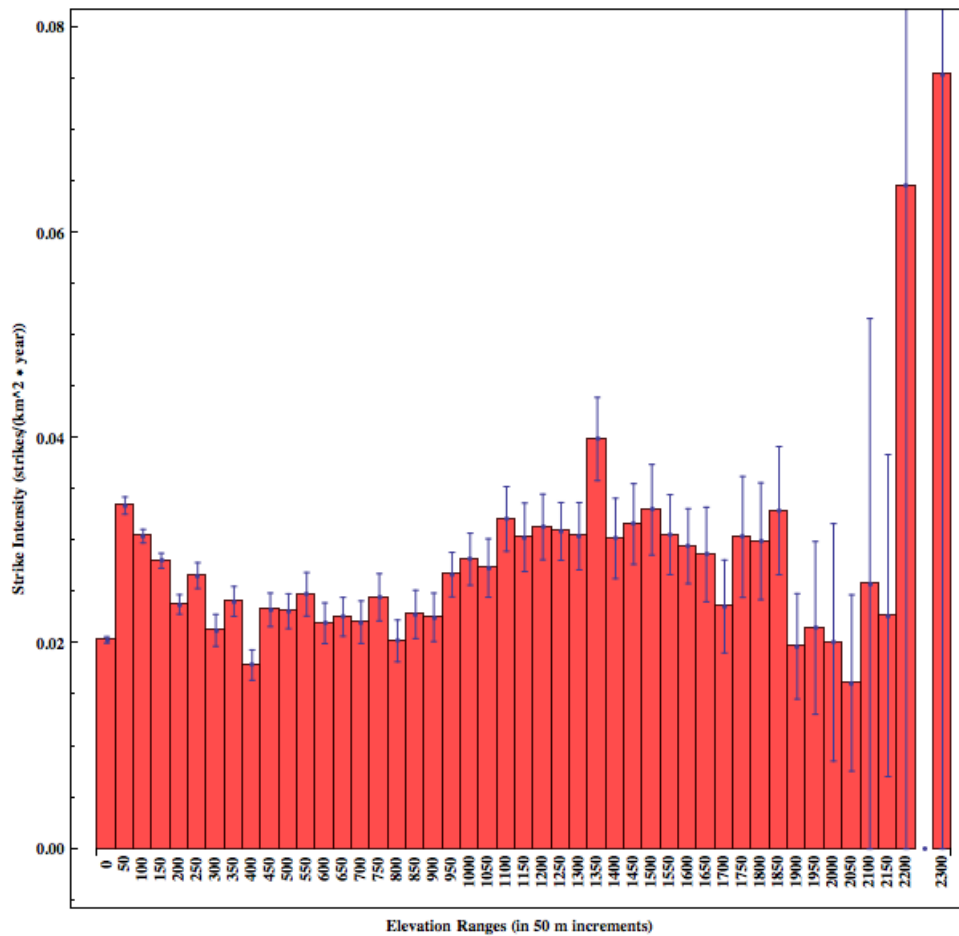


Figure A20. Mean elevation distribution of strike intensity on the OP, 1987-2009, in units of strikes/km²yr. Error bars are standard deviation of the mean.

Seasonal Distributions

Sea-Level Minimum

The sea-level minimum originates in the warm season (Figures A20 and A21). In the summer, the land is warmer than the ocean and the majority of vertical instabilities form over land. In the wet season we see this pattern reversed. The ocean is warmer than the land and there is a corresponding maximum of strikes at sea-level (Figure A22).

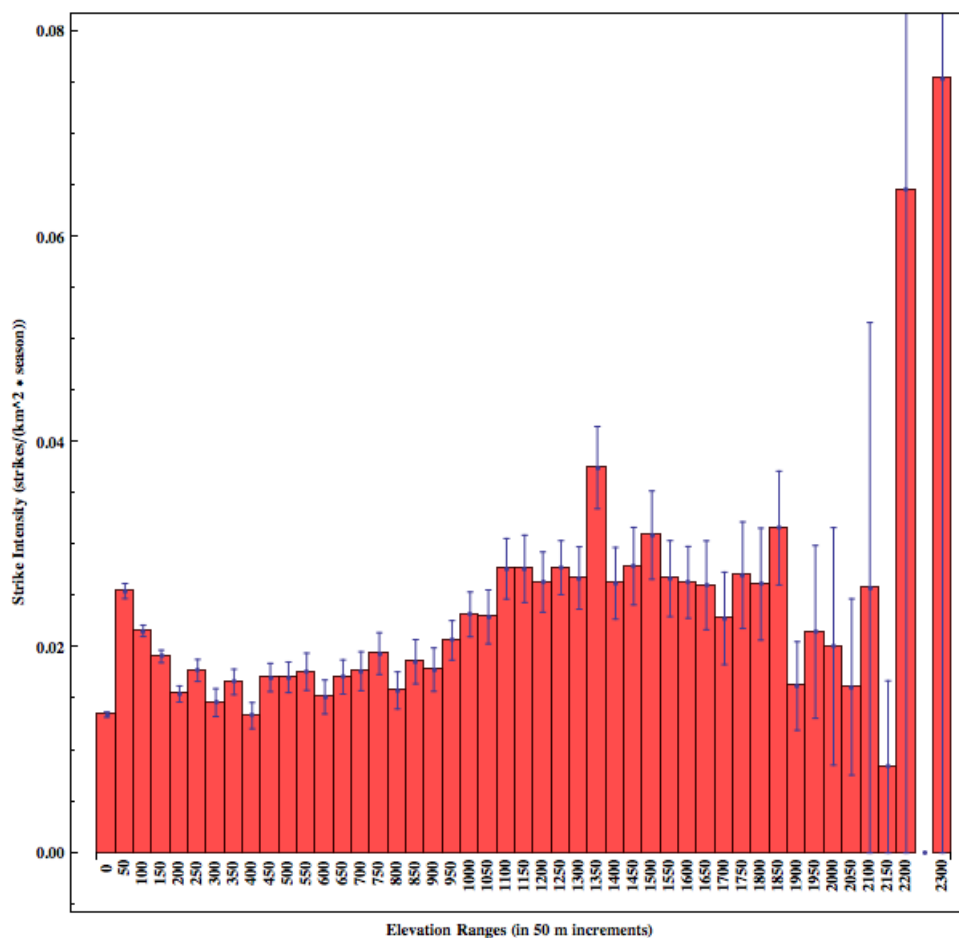


Figure A21. Mean, warm season, elevation distribution of strike intensity on the OP, 1987-2009, in units of strikes/km²season. Error bars are standard deviation of the mean.

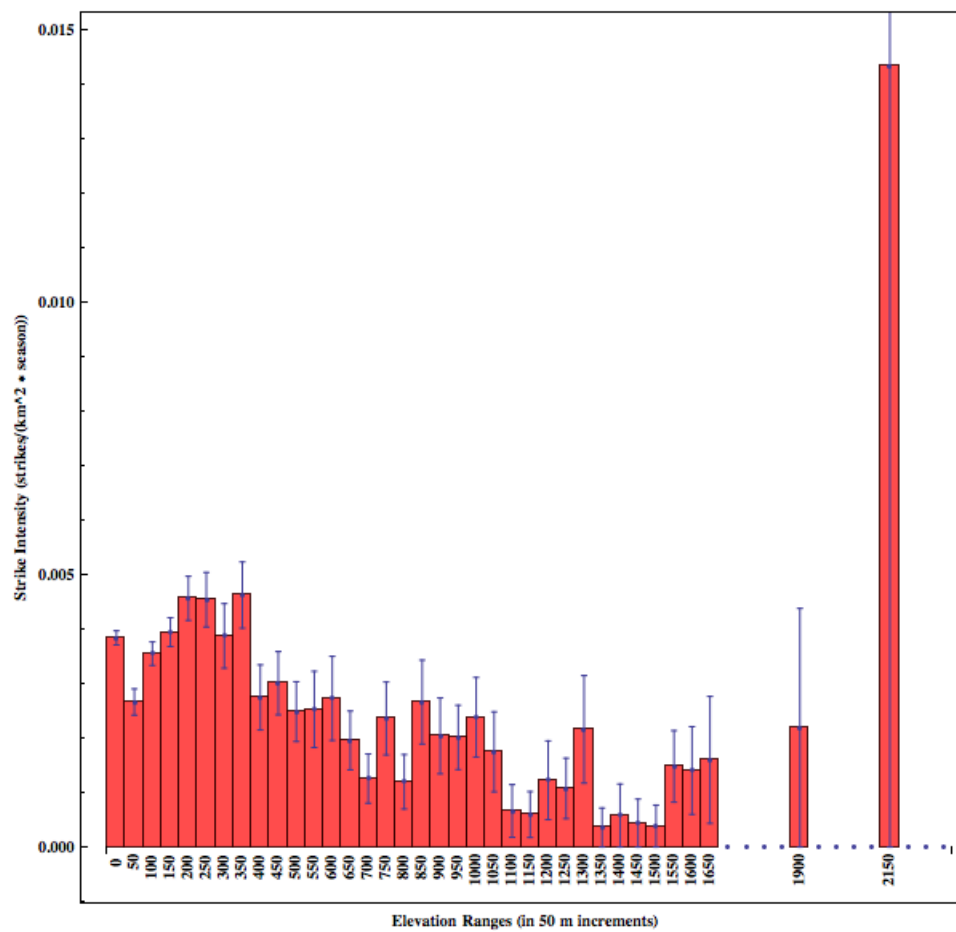


Figure A22. Mean, wet season, elevation distribution of strike intensity on the OP, 1987-2009, in units of strikes/km²season. Error bars are standard deviation of the mean.

Low-Level Maximums and Minimums

The low elevation maximum from 50 to 150 m also originates in the warm season (Figures A20 and A21). Many warm season thunderstorms on the Olympic Peninsula move from south to north / northeast in the Hood Canal region of the Kitsap Peninsula. The majority of the topography near the east side of the Hood Canal is in the 0-100 m elevation range which would be the maximum for those elevations.

During the warm season the North Pacific High is usually located off the coast of the Olympic Peninsula. Due to this high pressure region very few thunderstorms come off of the Pacific Ocean and across the west side of the Olympic Mountains; this causes warm season lightning activity on the west face of the Olympics to be sparse. This could be related to the lightning activity minimum at 400 m. Figure A23 shows that the majority of elevations from 300-500m occur on the west side of the Olympics whereas the east side of the Olympic has a much steeper incline. (In this elevation range, the west side has approximately 30% more area than the east side.) Therefore, the majority of the 300-500m elevation range is in a location that does not receive much warm season lightning and the elevation distribution appears to have a minimum at 400 m.

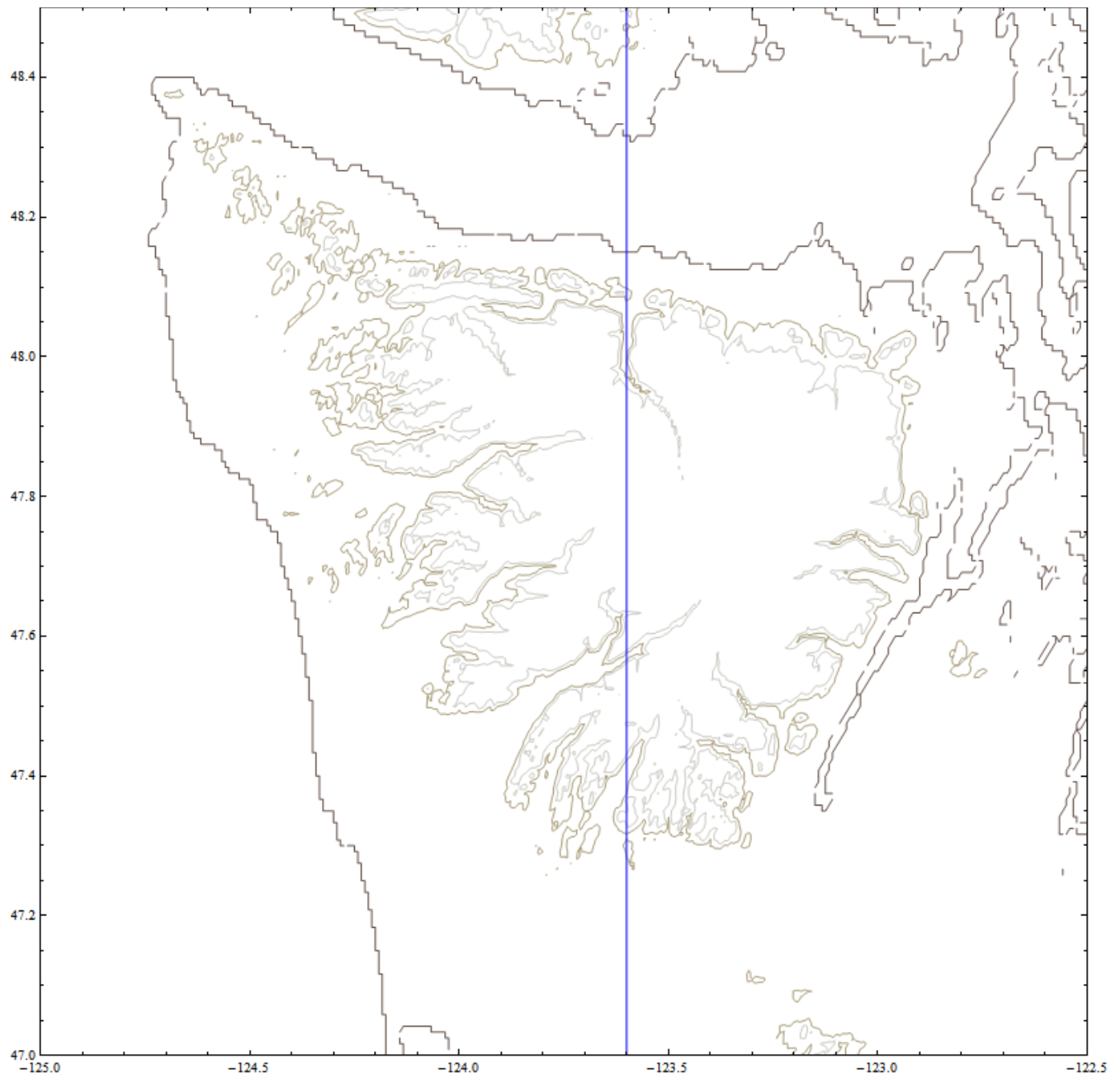


Figure A23. Elevation contours on the OP: 0m, 300m, 5000m. The vertical blue line represents the dividing line from which the east and west 300-500m elevation range areas were calculated.

In the wet season the situation is reversed. The low level maximum is now the minimum and the 400m warm season minimum is now near the wet season local maximum 200-350m (Figures A21 and A22). All of these low level characteristics can be explained by seasonal storm direction and intra-cloud charge distribution; this is discussed in the following Polarity section.

1350m Maximum

This maximum is exclusively a warm season event (Figure A21). To explain the 1350 m peak we first investigated a possible relationship between lightning activity and vegetation as some authors have claimed (Dissing and Verbyla 2003, Knowles 1993, O'Neal 1996, Wells and McKinsey 1993, Kotroni and Lagouvardos 2008, Kilinc and Beringer 2007). We examined lightning strikes from 1994 through 2005 overlaid on a dominant vegetation plot within the Olympic National Park (not shown). No significant relationship was discovered. Nonetheless, we did observe that mountain hemlock was present at several high strike intensity locations. In northern Washington mountain hemlock tends to grow in an elevation range of 1300 to 1700 m which explains its presence around the 1350 m strike intensity peak (Means,

http://www.na.fs.fed.us/spfo/pubs/silvics_manual/Volume_1/tsuga/mertensiana.htm).

Several studies have found peaks in lightning strike intensity with higher mean elevation than 1350m. (Dissing and Verbyla 2003; Randerson et al 2004; Reap, 1986, Fosdick and Watson 1995; Van Wagendonk and Cayan 2008). Lopes et al (2011) reported a peak in lightning activity between 750 to 1000 m and a decrease for higher elevations. Reap (1991) also found a rapid decrease in lightning in Alaska, after the 700 to 800 m peak. Schulz and Diendorfer (1999) reported an increase in strike intensity from 500 m to 1800 m in the Austrian Alps, and a subsequent decrease above 1800 m. Furthermore, the Schulz and Diendorfer study proposed that the regions with high altitudes and low strike intensities are inside or close to the thunderstorm clouds and therefore only some of those strikes are located by the lightning detectors.

We propose that warm season thunderstorm cloud bases do occur at or above the 1350m peak intensity altitude on the Olympic Peninsula. Therefore, the shortest distance – and consequently the highest electric field strength – between the base of the cloud and the ground is near 1350 m, which results in a discharge at that elevation relative to lower elevations. Elevations higher than 1350 m are

frequently located in the thunderstorm cloud - perhaps resulting in lower field strengths or possibly reduced detection efficiency of the ground based detectors. To verify this claim we calculated the average cloud base height for the Olympic Peninsula on lightning days (see **Appendix 1** for details).

The average cloud base for the Olympic Peninsula is 1450 ± 71 meters. Our result for the average cloud base height supports our theory that the lightning maximum at 1350-1400 m is due to the cloud base's location near that height. The elevations 1350-1400 m fall mostly within the uncertainty for the average cloud base height and uncertainty of the lightning distribution peak. We further investigated the relationship between cloud base, lightning and time of day in the following Diurnal – Elevation Distribution section and Appendix 2. Our cloud base hypothesis can also explain the elevation peaks in lightning strike intensity of other regional lightning studies. A listing of the studies we examined appears in Table A3.

Lightning Study: Latitude vs Elevation of Lightning Strike Intensity Maximum:				
Study Date and Author:	Study Location:	Study Duration:	Approximate Latitude (deg N):	Elevation Peak (m):
Dissing et al, 2003	Alaska – Interior	1986-1999	65	1150
Reap et al, 1991	Alaska	1987-1989 summer	65	750
Olympic Peninsula	Olympic Peninsula	1987-2009 summer	48	1450
Schulz and Diendorfer, 1999	Austria	1995-1998	47.5	1800
Lopes et al, 2011	Portugal	2003-2009	39.5	875
van Wagtenonk et al, 2008 & 1993	Yosemite National Park	1985-1990	38	2850
Randerson et al, 2004	Southern Nevada	1993-2000 summer	37	2670
Wells et al, 1995	San Diego County	1985-1990	33	1980

Table A3. Approximate latitude and average elevations of peak lightning counts for 8 different lightning strike studies.

Cloud base height depends on the two interrelated atmospheric variables – atmospheric temperature and moisture. The lifted condensation level - used here to approximate the cloud base height - is determined by the difference between the air temperature and dew point temperature. As the surrounding temperature increases, the difference between the temperature and dew point becomes greater and the cloud base increases (**Appendix 1: Cloud Base Calculation**).

Because temperature generally increases with decreasing latitude we can expect to see cloud base heights increasing with decreasing latitude. To test this hypothesis we compiled a list of lightning

studies along the west coast of the United States whose study locations were at approximately the same longitude as the Olympic Peninsula; studies with a similar longitude were used to decrease the potential effects of a longitude-lightning relationship. We compared the elevation where the maximum lightning strike intensity occurs versus the approximate latitude of the study's location. Since each study used different elevation ranges, for each study we calculated the mean elevation with peak lightning and used that elevation in Table A3. Likewise, we approximated the median latitude for each study region in the Table. In addition to our own OP data, the five lightning studies we used were Dissing and Verbyla (2003); Reap (1991); Van Wagtendonk and Cayan (2008); Randerson et al (2004) and Wells et al (1995). It is clear from Figure A24 that peak lightning elevation does increase with decreasing latitude.

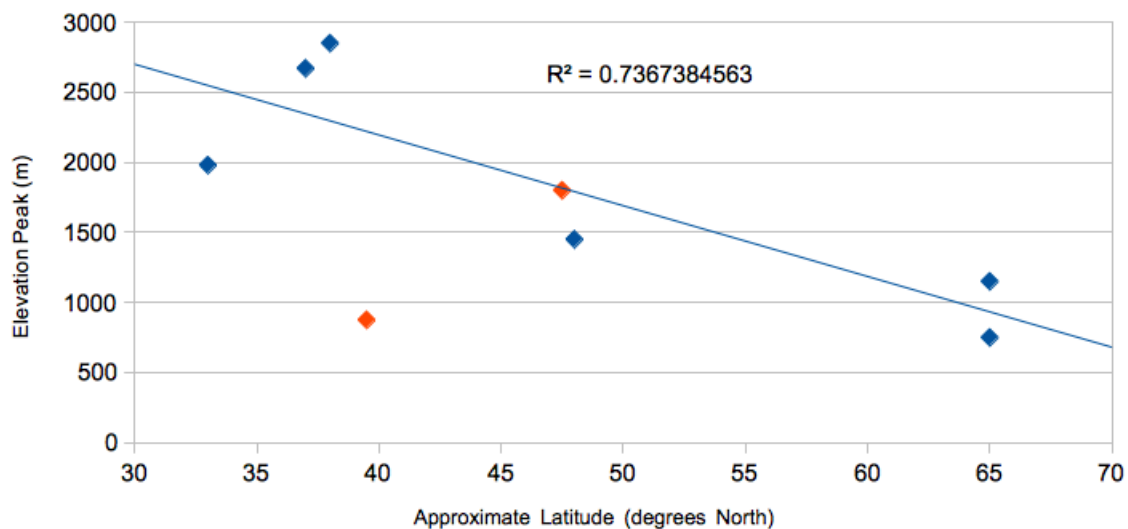


Figure A24. Plot of mean elevation of peak lightning as a function of mean latitude for 6 sites in WNA of approximately the same longitude (blue). Two additional data points from two sites in Europe (red). Data values appear in Table A3.

Since both atmospheric temperature and atmospheric moisture determine the cloud base height, the relationship between cloud base height and location must be more complex than this result

suggests. We know that a humid area like Florida will have lower cloud bases compared to an arid region at a similar latitude like Arizona or New Mexico (Williams et al 2005). This effect should be most pronounced at lower latitudes where greater differences in air and dew point temperatures are possible. To further illustrate this effect, we included Schulz and Diendorfer (1999) data for Austria and Lopes et al (2011) data for Portugal as separate data points in Figure A24. As expected, the most extreme departures from the general trend of decline of peak lightning elevation occur at the lowest latitudes – the coastal lightning climatology of Portugal represents the most extreme negative departure from this inverse relationship.

Spring Quarter Elevation Distribution

The Spring Quarter elevation distributions exhibit a pattern very different from the wet season and warm season months. There is a lack of an apparent relationship between lightning occurrence and elevation. The total Spring Quarter distribution in Figure A25 demonstrates the sea-level minimum, low elevation (50-150 m) maximum and 400 m minimum that are also present in the warm season (Figures A21 and A25). At higher elevation several maxima and minima not found in the warm or wet season appear. It is possible – as introduced in the diurnal discussion – that the many maxima and minima present in the spring lightning distribution represent individual lightning events. As seen from Figures A26 and A27, the ratio of negative to positive polarity strike intensities is not as large as for the warm season but not reversed as in the wet season. This suggests that the spring events arise from a combination of warm season and wet season atmospheric influences.

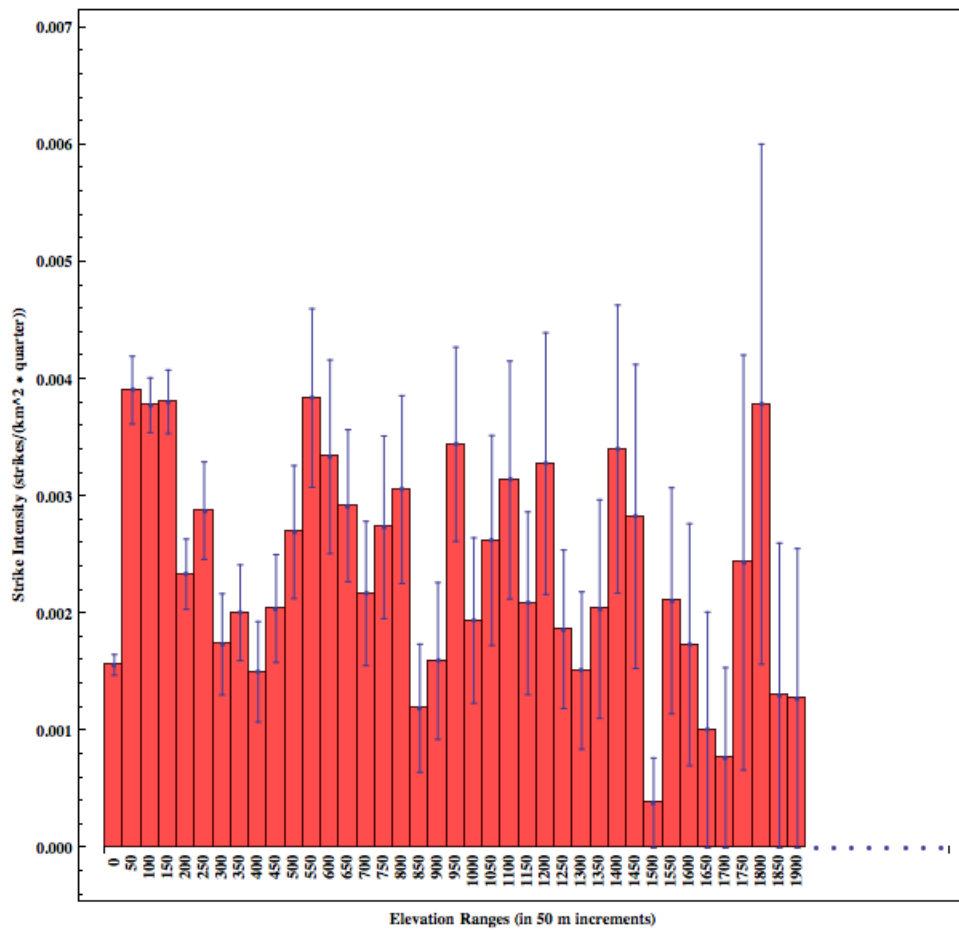


Figure A25. Mean, spring season, elevation distribution of strike intensity on the OP, 1987-2009, in units of strikes/km²season. Error bars are standard deviation of the mean.

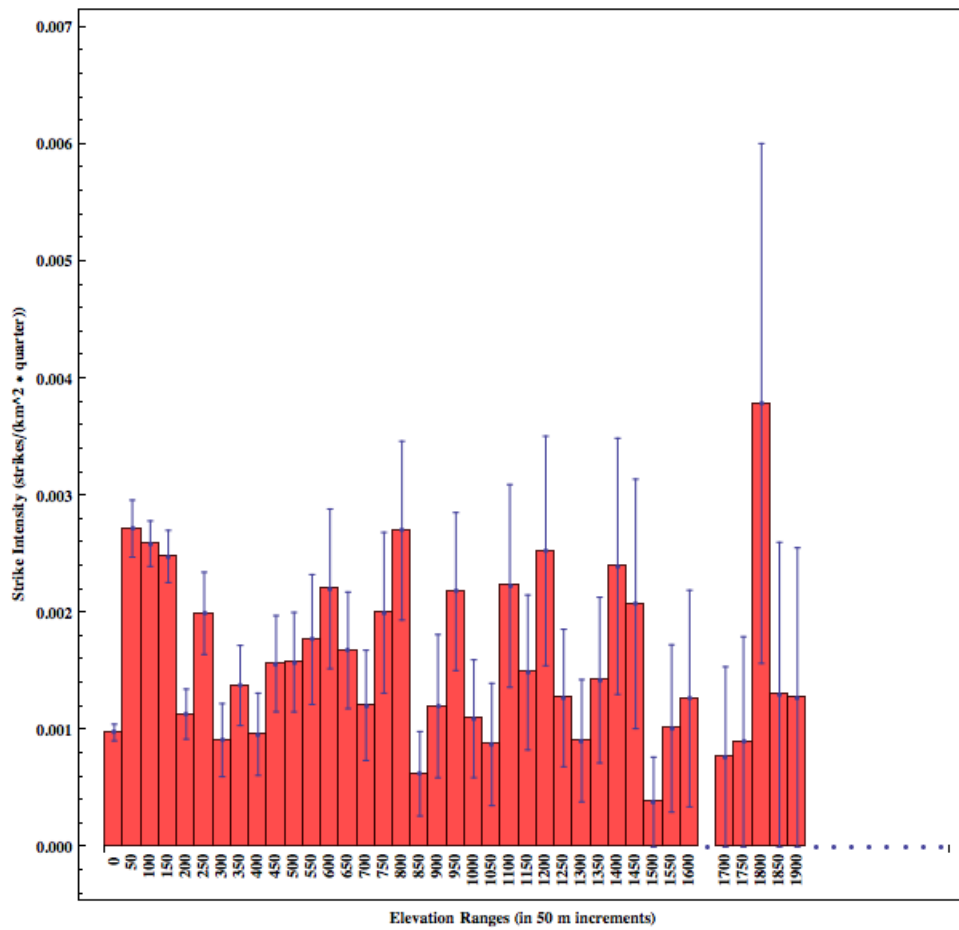


Figure A26. Mean, spring season, negative, elevation distribution of strike intensity on the OP, 1987-2009, in units of strikes/km²season. Error bars are standard deviation of the mean.

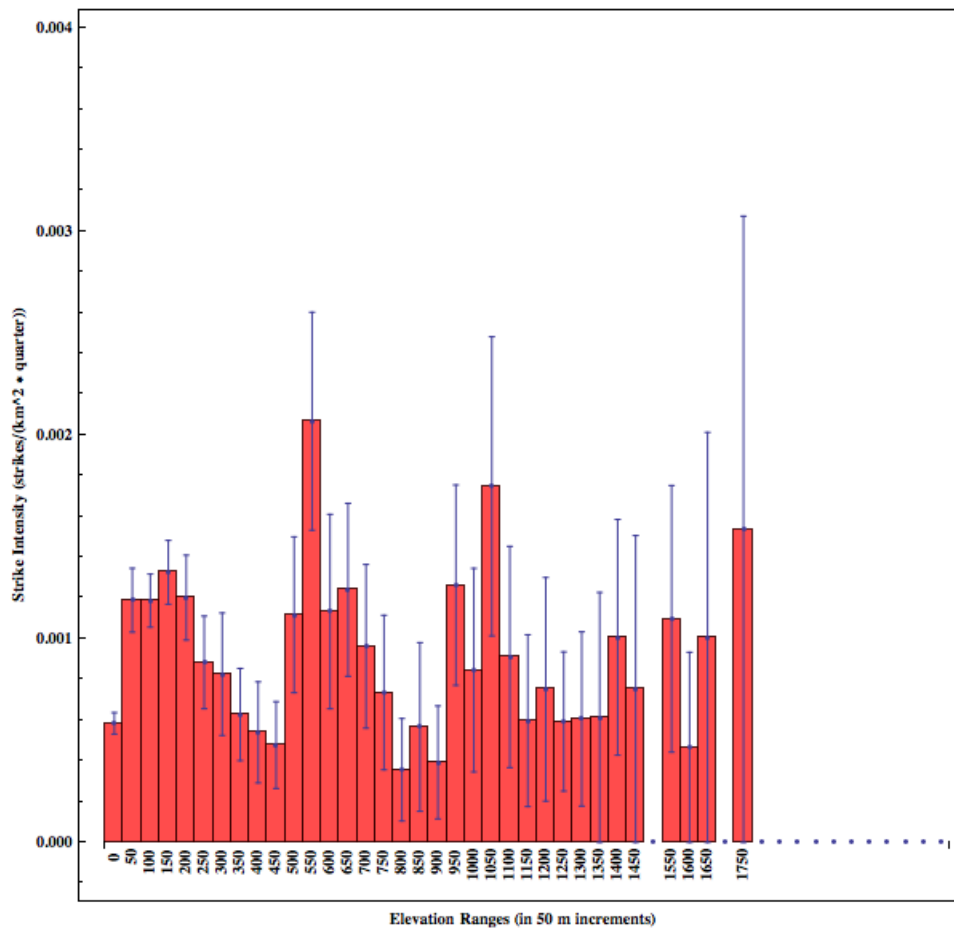


Figure A27. Mean, spring season, positive, elevation distribution of strike intensity on the OP, 1987-2009, in units of strikes/km²season. Error bars are standard deviation of the mean.

Polarity

As discussed in the temporal analysis, the warm season is almost entirely composed of negative polarity strikes. Consequently the negative polarity elevation distribution almost completely characterizes the warm season all strike distribution (Figures A21 and A28). In contrast to this distribution, positive polarity strike intensity increase with elevation throughout the whole elevation range (Figure A29). Recent advances in lightning detection technology employing Lightning Mapping Arrays (LMAs) are beginning to make measurements of charge distributions within thunderstorm clouds as well as lightning discharge origins within the cloud (MacGorman et al 2008). However, because of the relative lack of positive polarity strikes in typical low to medium current

mesoscale warm season events, and because of problems locating positive strike leaders, this technology has not yet been used for locating positive strike origins within thunderstorm clouds (Bruning et al 2007). Earlier measurements with less precise location technology suggest that many of these strikes do originate from the upper anvil region of the thunderstorm cloud (Rust et al 1981). If this earlier data is shown to be correct, it would imply that the shortest distance between the point of origin of the positive polarity lightning leader and the ground would occur at the highest elevations. If this is the case it would be plausible to expect an increase in positive polarity strikes with increasing elevation during the warm season.

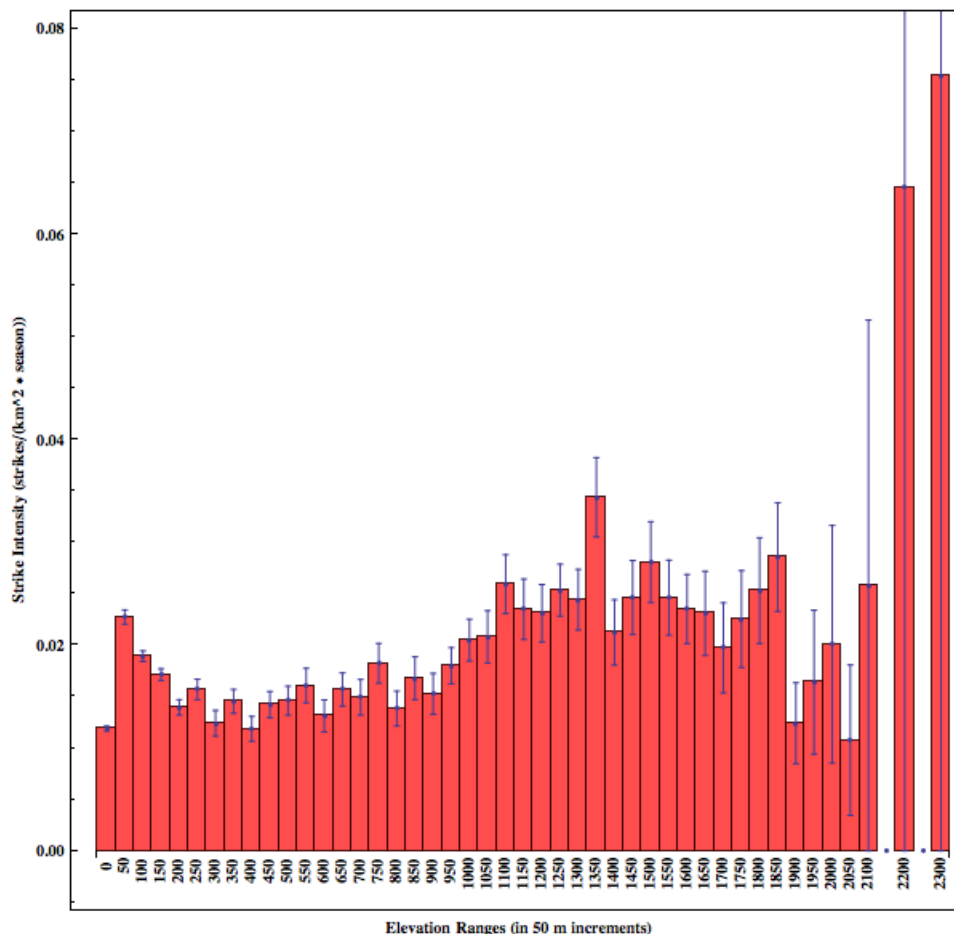


Figure A28. Mean, warm season, negative, elevation distribution of strike intensity on the OP, 1987-2009, in units of strikes/km²season. Error bars are standard deviation of the mean.

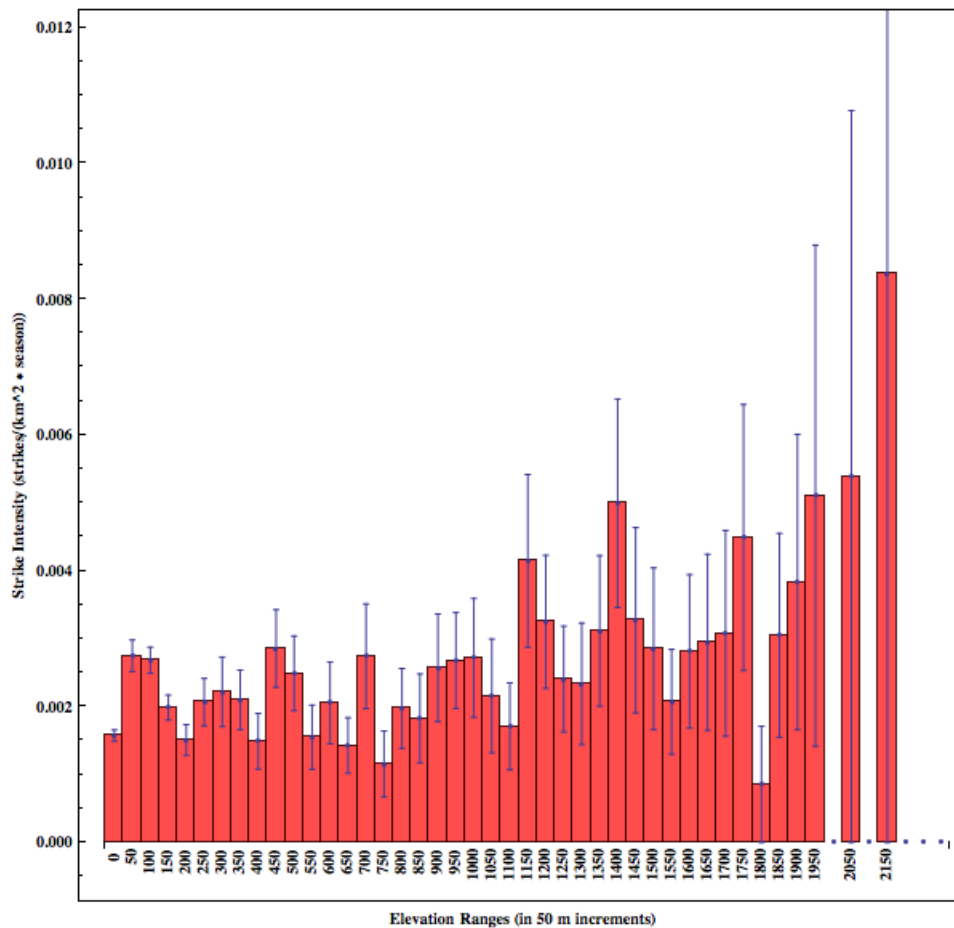


Figure A29. Mean, warm season, positive, elevation distribution of strike intensity on the OP, 1987-2009, in units of strikes/km²season. Error bars are standard deviation of the mean.

The wet season distributions present a very different picture. There is a peak in lightning at sea-level, a minimum at 50 m, a broad peak from 0 to 350 m and then a decline in lightning activity for higher elevations (Figure A22). As expected from their dominance in the wet season, the positive warm season distribution (Figure A30) is similar to that of Figure A22. This decline with elevation is in contrast to the increase with elevation during the warm season (Figure A29) – suggesting different intracloud charge distribution and discharge mechanisms for the two seasons. This wet season pattern is most pronounced along the coastal OP but extends all along the west coast (Ely and Orville 2005). It is also interesting to note that, in contrast to the warm season, the wet season negative polarity elevation distribution (Figure A31) is diminished in intensity, but exhibits a similar pattern to the positive strike pattern.

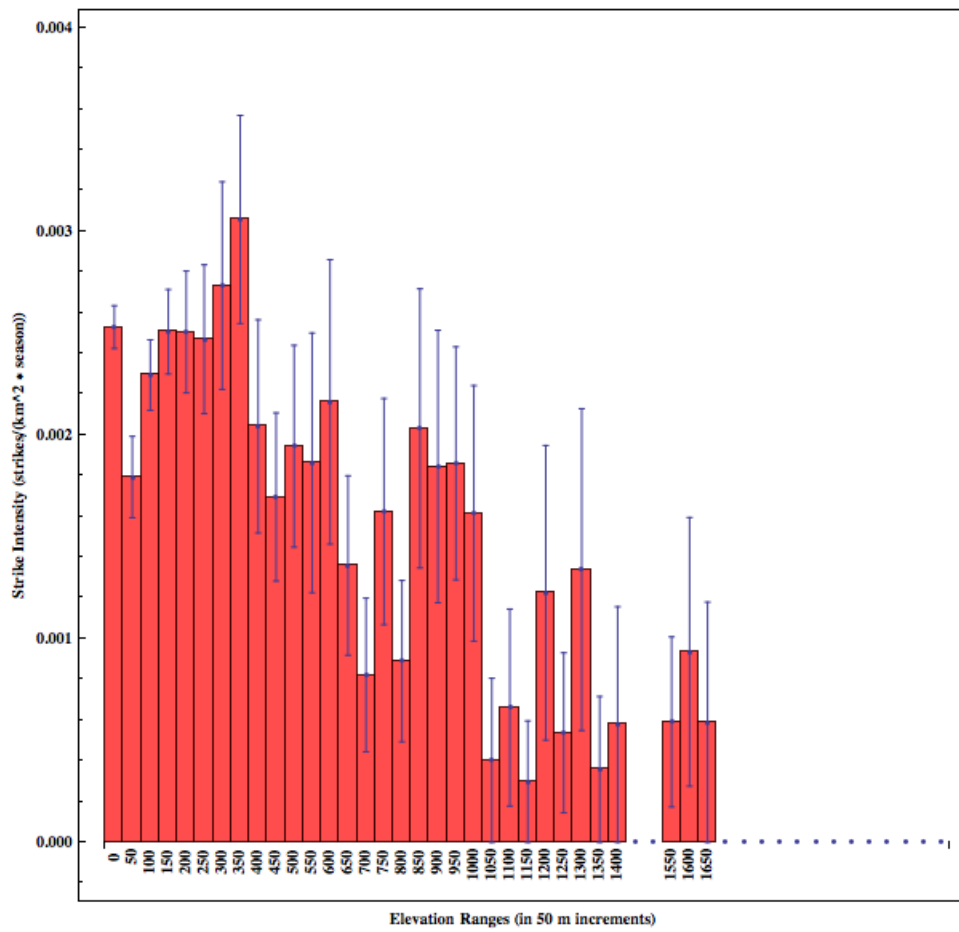


Figure A30. Mean, wet season, positive, elevation distribution of strike intensity on the OP, 1987-2009, in units of strikes/km²season. Error bars are standard deviation of the mean.

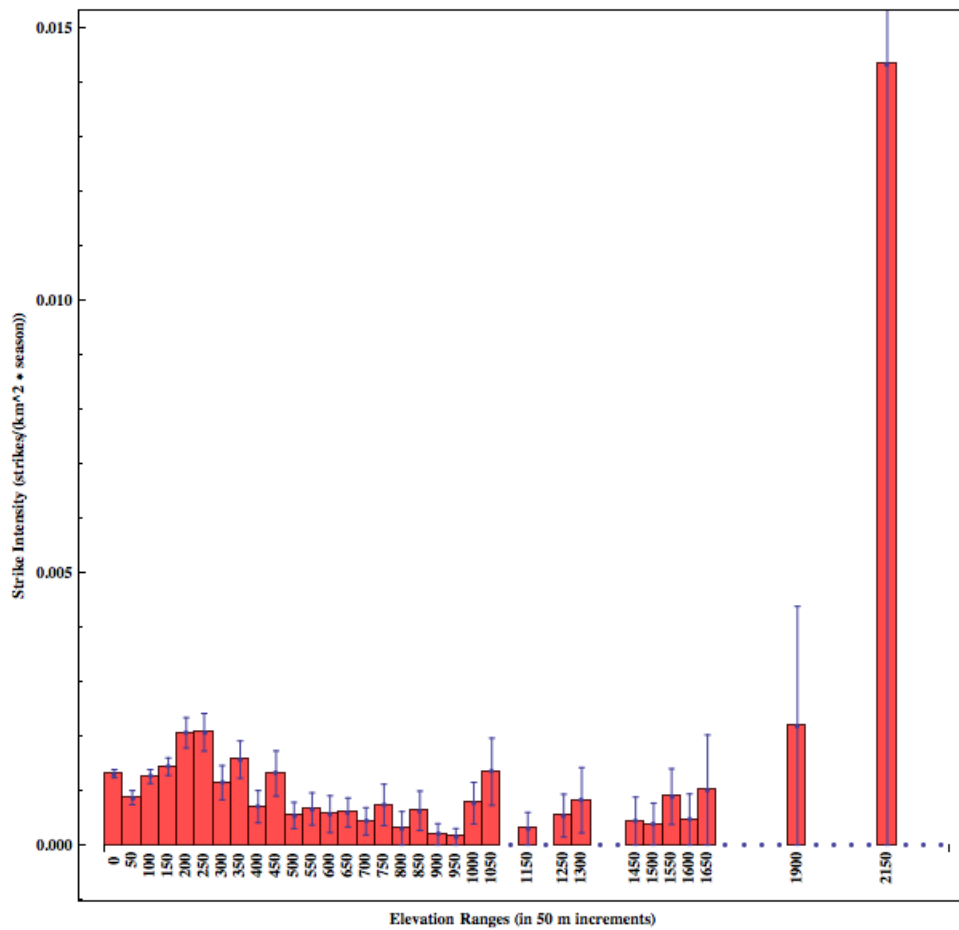


Figure A31. Mean, wet season, negative, elevation distribution of strike intensity on the OP, 1987-2009, in units of strikes/km²season. Error bars are standard deviation of the mean.

It is known that the majority of wet season thunderstorms are synoptic processes, reaching land from the Northeastern Pacific Ocean (McMurdie 2013, Lang et al 2011). The intra-cloud charge structure has not yet been directly investigated over the ocean. However, a recent study of high energy storms dominated by large current positive polarity events over the central United States (a situation where the application of LMA technology is feasible) indicates that the cloud charge structure is inverted from the negative dominated strike cloud structure (Lang and Rutledge 2011).

One possible explanation for our observations of the wet season distributions would be that because of the different mechanism of generation than for warm season events, there is a much higher percentage of reversed charge distributions embedded in these clouds than in warm season clouds. If a relatively high percentage of the thunderstorm clouds had an inverted cloud charge structure, but the

cloud base for all of the clouds were near the 0-350m elevation regardless of charge structure, then, a similar explanation of the wet season 0-350m distribution peak to that of the 1350m warm season peak would be possible. While resolving the uncertainties associated with wet season events is beyond the scope of the present study, recent discoveries relating to TLEs and their association with high current positive cloud to ground strikes should provide an incentive for further investigations.

Diurnal – Elevation Distribution

Reap (1986) hypothesized that there is a correlation between terrain elevation and the hour of maximum frequency of lightning. We investigated this relationship for Olympic Peninsula. Our analysis suggests that this correlation represents only a portion of a diurnal cycle of lightning strike elevations. The diurnal cycle of the cloud base height is the probable cause. The analysis is somewhat complex and the details are presented in **Appendix A2**.

B. Intraseasonal Behavior During the Warm Season

We took the initial year of this intraseasonal study to begin in 1994 – the year of significant efficiency upgrade of the lightning detection network. We took the last year to be 2005; this was done because lightning data for all of the western United States was available through this year. This more extensive data set made it possible to identify characteristics responsible for the lightning events whose scale extended beyond the OP. We also used an empirical definition of the beginning and end of the active lightning season rather than the calendar month designation of the warm season used to describe the annual cycle statistical distribution. This enabled us to define a variable season length which includes major mesoscale convective system events which occurred in the spring quarter. The Pacific North West (PNW) lightning season was defined to begin two days before the first day of the calendar year that the PNW daily activity reaches 5,000 strikes and to end two days after the last day that 5,000 strikes occurs. The PNW for this study is bounded by 40° N to 49° N and 115° W (Estberg et al 2008).

Major lightning events on the OP are a relatively small subset of the events in the PNW lightning season. For example, only 2 events occurred on the OP with peak activity of ≥ 100 strikes in compared to 28 events with ≤ 1 OP strikes and comparable PNW activity. In this section we identify causal characteristics that could be used to distinguish events that do occur on the OP from those that do not.

We imported data from two major reanalysis data sets to estimate atmospheric conditions associated with lightning activity. For global scale upper troposphere wind conditions, data from NCEP-DOE Reanalysis 2 was used (Kanamitsu et al 2002). For regional atmospheric conditions, data from North American Regional Reanalysis (NARR) was used (Mesinger et al 2006). Both data sources were provided by NOAA/OAR/ESRL PSD, Boulder, CO <http://www.esrl.noaa.gov/psd/>. Some problems with the NARR data have been reported regarding North American Monsoon measurements of atmospheric behavior including moisture (Chan and Misra 2011, Mo et al 2005). However, it is the best information available for the period of this study and it appeared to provide a consistent relationship with the lightning data in the analysis that follows.

Major PNW Event With Insignificant Activity on the OP

We first examined a case study of a major warm season PNW event for which little activity occurred on the OP. The event which had a PNW daily peak activity of 10,039 strikes on July 11, 2001 was chosen for this case study; we examined a 5 day sequence of this event centered about July 11th. It was a major PNW event (the 8th largest event for which the lightning strikes on the OP were ≤ 1).

We initially focused on the 250mb horizontal divergence as a primary upper troposphere atmospheric characteristic related to lightning strike activity. (The background and reasons for this choice, involving investigation of a considerably larger study area will be published separately). Contour plots of the average daily lightning intensity were overlaid on contours of the daily averaged 250mb wind divergence for July 9th through the 13th (Figures B1a-e). The development of this sequence can best be interpreted through the 5 day progression of the jet stream. The 250mb winds are plotted in Figures B2a-e. The jet during this event maintains a northern and southern branch. On July 9th two areas of divergence are approaching the west coast associated with these two branches. By July 11th a single area has strengthened on shore east of the California/Oregon border coinciding with the merger of the two jet branches over the PNW. Lightning activity which had previously been centered over the Desert Southwest has been pulled into an area which coincidences reasonably well with this area of divergence. By July 13th the region of jet merger and divergence has moved northeast through the PNW along with the lightning activity. An area of convergence has moved onto the OP coinciding with a region of no lightning activity. While lightning activity is reasonably well associated with the divergence, the exceptions suggest that more complex processes occurring in the lower troposphere need to be considered – especially when attempting to characterize the lightning activity in sub regions of the PNW such as the OP.

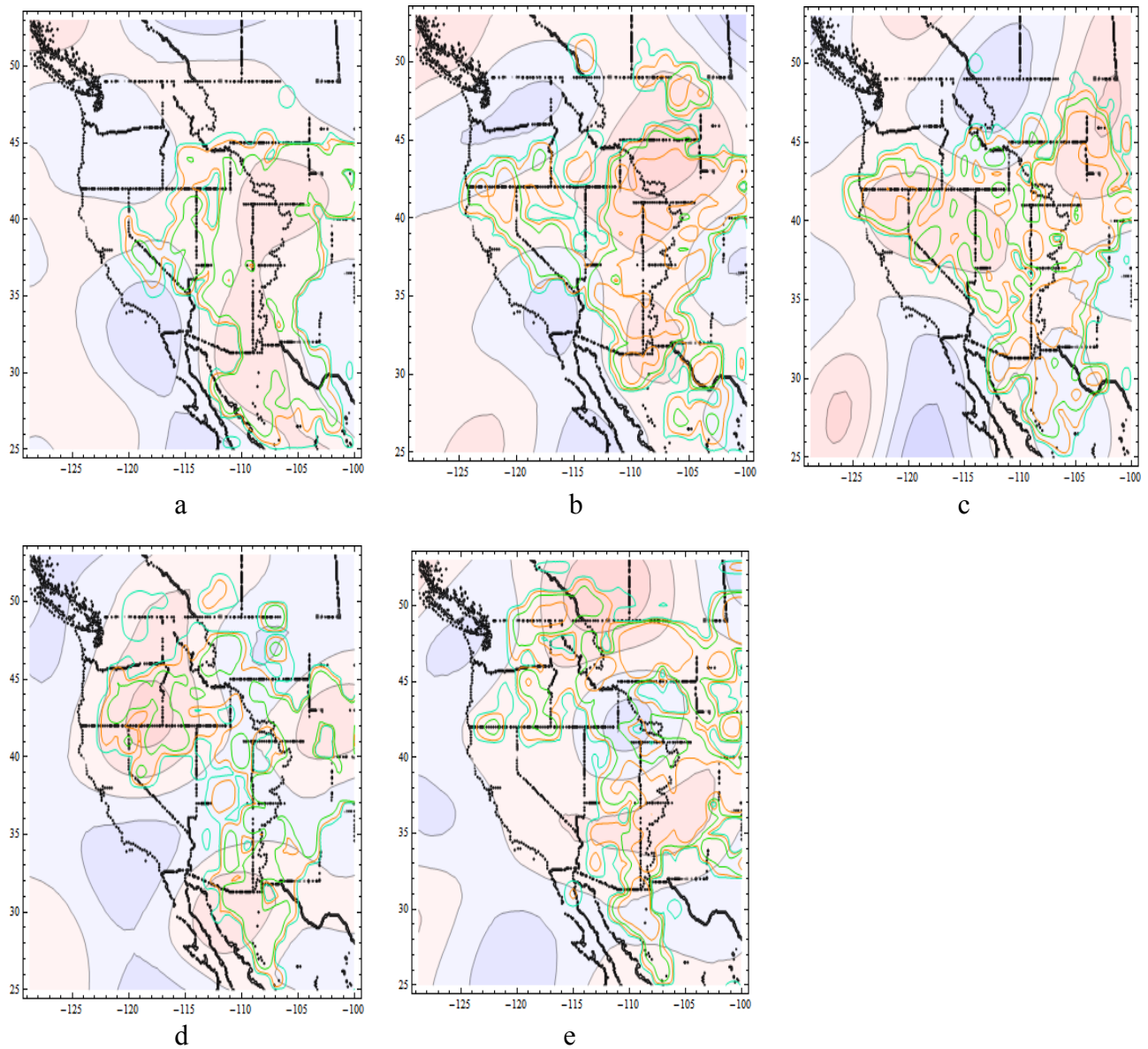
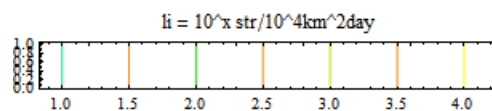
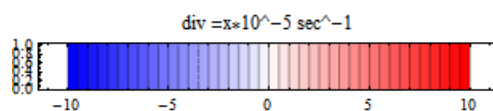


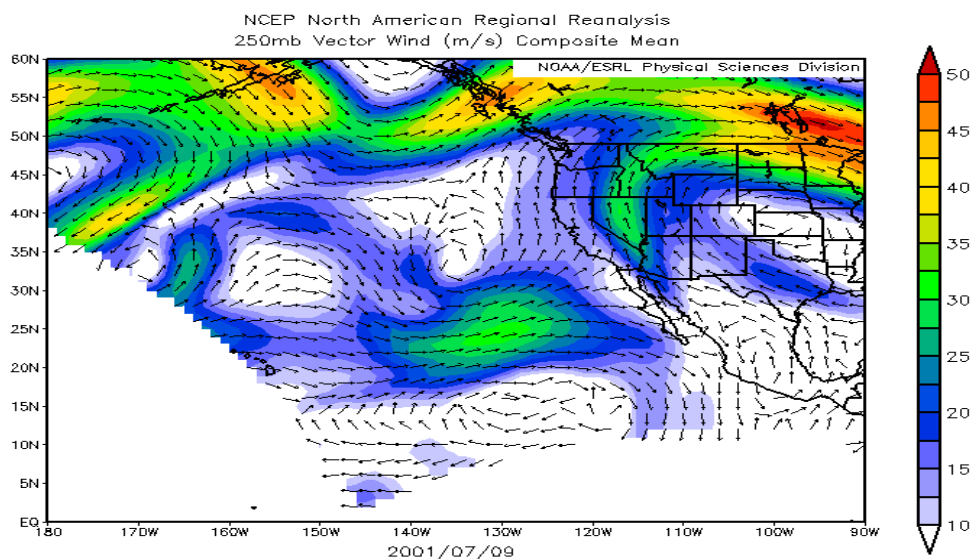
Figure B1. Five day sequence of lightning intensity and 250mb horizontal divergence centered about July 11, 2001 (2001 case study). The legend for the lightning intensity contour values is shown for units of powers of 10 strikes/ $10^4 \text{ km}^2 \text{ day}$ (horizontal axis). For example, if the color is yellow corresponding to an x value of 4, the value of this contour is $10^4 \text{ strikes}/10^4 \text{ km}^2 \text{ day}$.



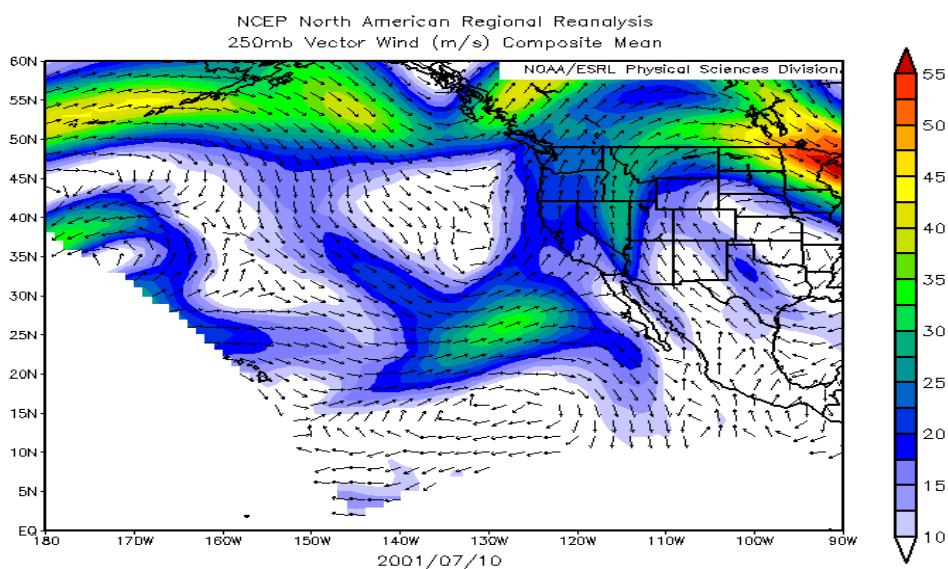
The legend for divergence shading is shown in units of 10^{-5}sec^{-1} (horizontal axis). For example, the deepest color of red corresponds to a divergence of $+10 \times 10^{-5}\text{sec}^{-1}$.



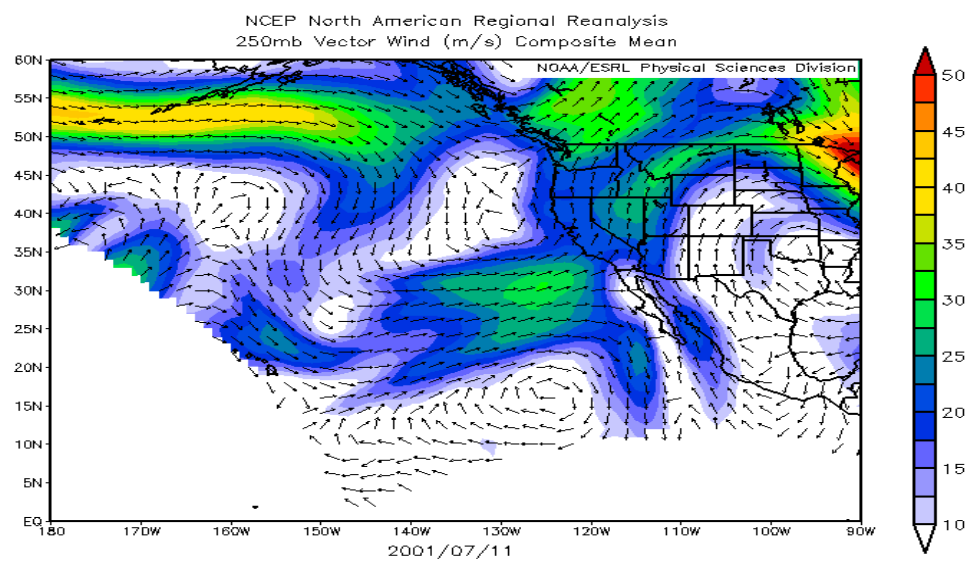
Plots for (a) June 9th, (b) June 10th, (c) June 11th, (d) June 12th, (e) June 13th.



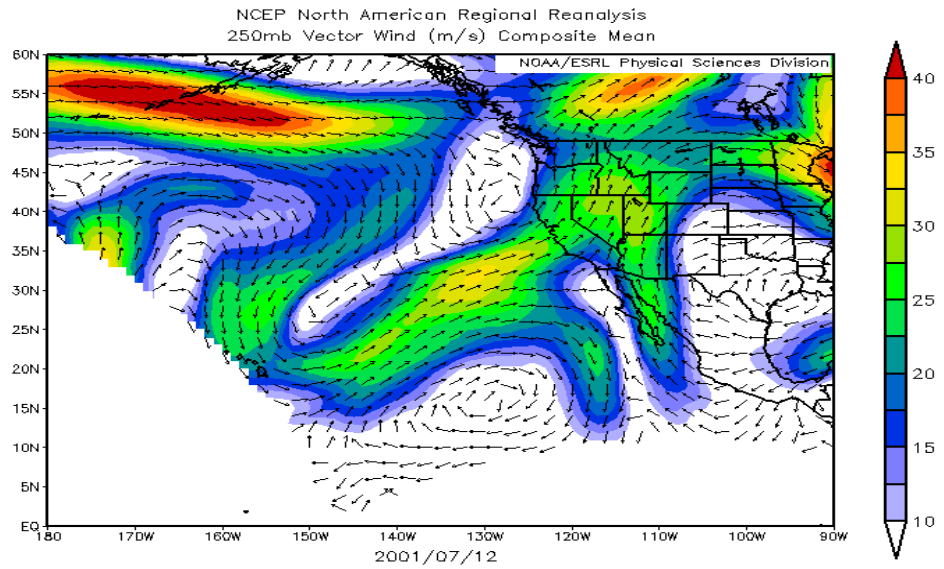
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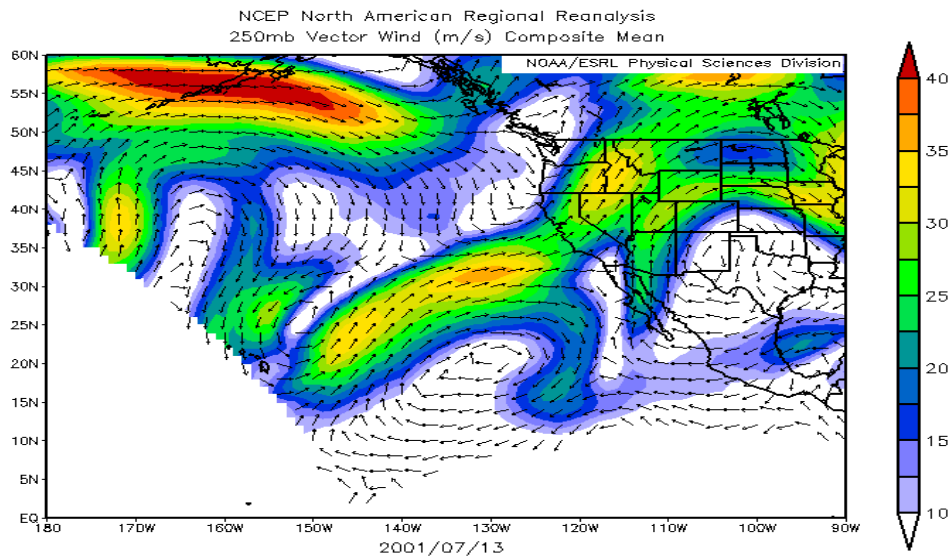
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c



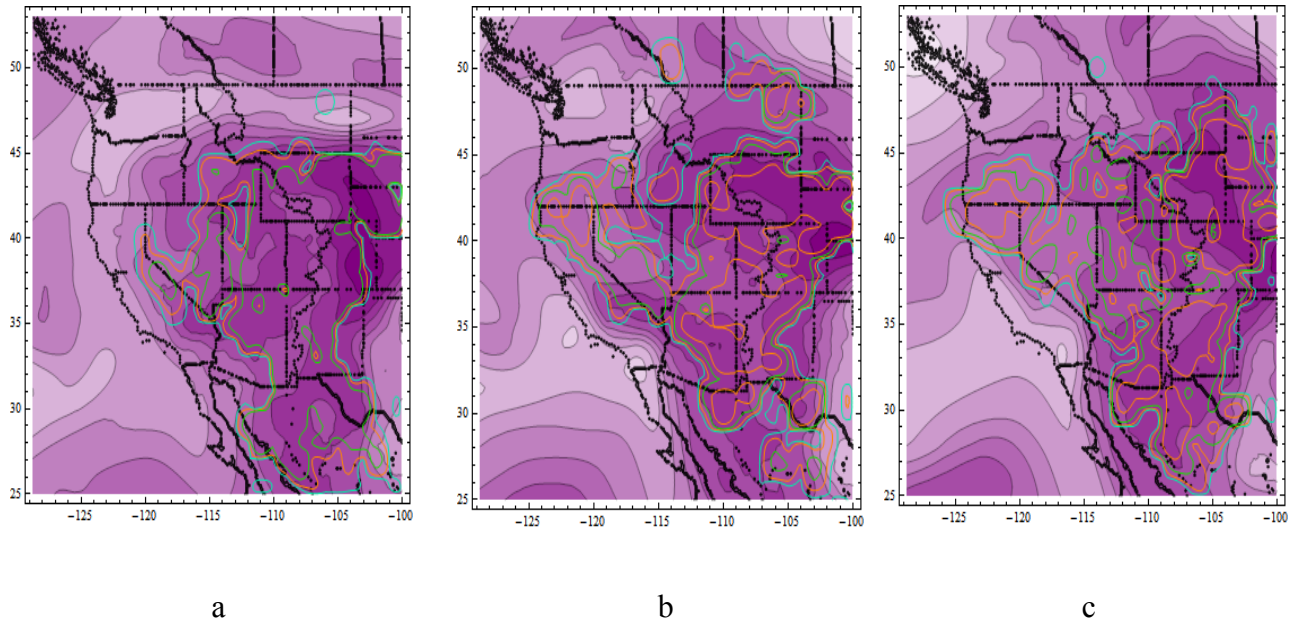
d



e

Figure B2. The 2001 case study; National Center for Environmental Prediction, North American Regional Reanalysis (NCEP NARR) daily average 250mb vector winds. Plots for (a) June 9th, (b) June 10th, (c) June 11th, (d) June 12th, (e) June 13th.

An important source of vertical instability is water vapor; however the source and level of water vapor transport for the North American Monsoon is complex (Adams and Comrie 1997; Sheppard et al 2002). As a first approximation of the water vapor density, we examined the specific humidity, q , at the 700mb level. Contour plots of the average daily lightning intensity were overlaid on daily average specific humidity contours for the 5 day period (Figures B3a-e). Comparing this sequence to the 5 day sequence of 250mb divergence reveals a clear improvement in the coincidence with lightning intensity. An additional test of the 700mb specific humidity as a measure of lightning activity is to compare it to a more commonly used measure of vertical instability. The lightning intensity for July 11th is overlaid on the best 4 layer lifted index (Galway 1959) in Figure B4. The lifted index had been selected as the most effective predictor of vertical instability in a study of lightning occurrence in Alaska (Farukh et al 2011). Comparing Figure B4 with the specific humidity in Figure B3c, both measures are in reasonable agreement with the lightning intensity, although it could be argued that the specific humidity provides a better correspondence. (For example, the lifted index fails to describe the lightning activity over the eastern Pacific near the Oregon/California border, while the specific humidity distribution does suggest this activity.) Since the primary source of water vapor is vapor flux, we next examined vapor flux and its relationship to lightning activity.



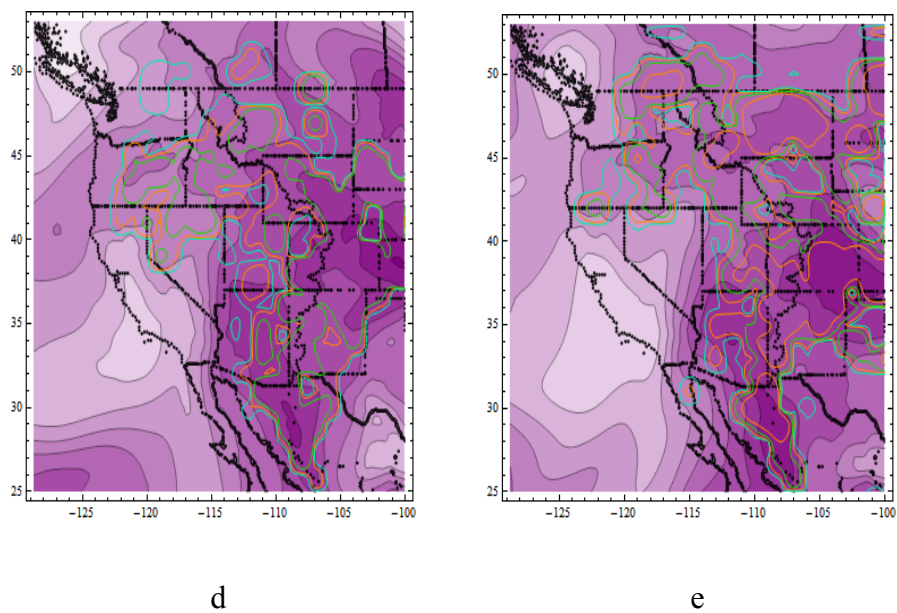
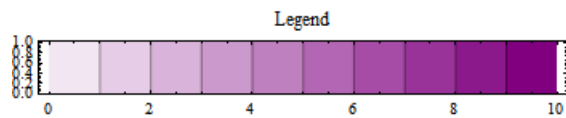


Figure B3. The 2001 case study; lightning intensity and specific humidity. The legend for Specific Humidity color shading is shown in units of g/kg (horizontal axis).



Plots for (a) June 9th, (b) June 10th, (b) June 10th, (c) June 11th, (d) June 12th, (e) June 13th.

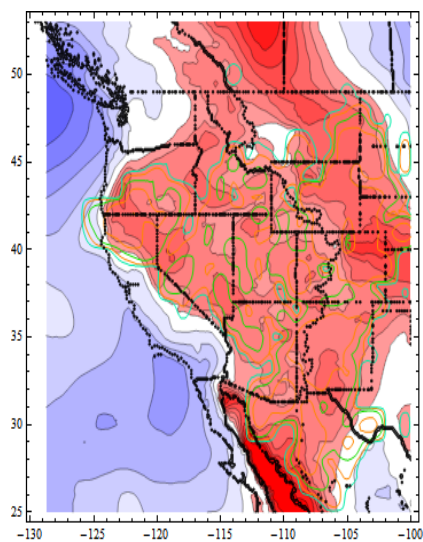
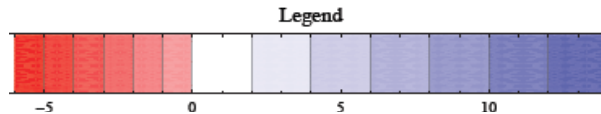


Figure B4. The 2001, July 11th lightning intensity and best 4 layer lifted index.

The legend for 4 layer lifted index color shading is shown in units of degK (horizontal axis).



The 700mb horizontal vapor flux, $\mathbf{f}$ can be well approximated by $\mathbf{f} = q\mathbf{P}\mathbf{v}/R_d T$, where, P is the pressure, $\mathbf{v}$ is the horizontal wind velocity, and T is the Temperature – all at 700mb. R_d is the dry air gas constant. The flux field for July, 11th is shown in Figure B5. The general direction of the flux field vectors (in the same direction as the wind vectors) can be estimated from the 700mb geopotential height field. In Figure B6 the wind field is superimposed on the height field. The wind field direction can be interpreted as roughly geostrophic.

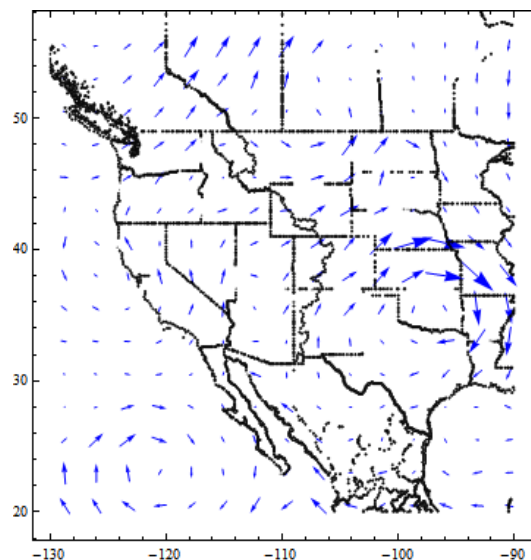
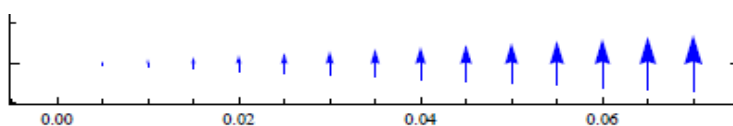


Figure B5. The 700mb 2001, July 11th vapor flux field. The legend for the vapor flux vector lengths is shown in units of kg/m²s (horizontal axis).



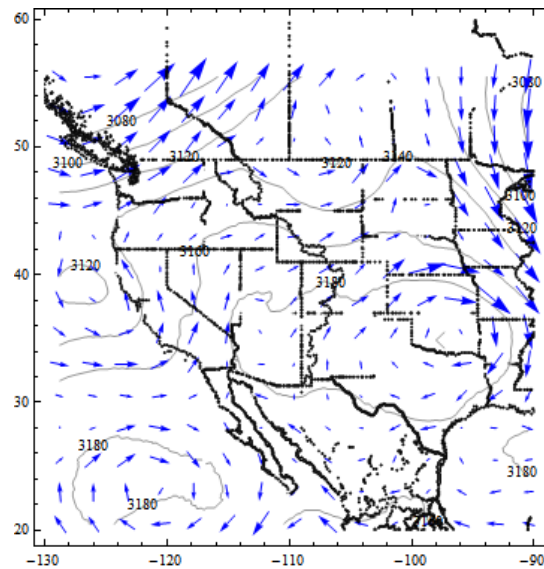


Figure B6. The 700mb 2001, July 11th wind field superimposed on the geopotential height field. The top wind speeds (eastern edge of the plot) are approximately 13m/s. The value of the geopotential height contours (in meters) are on the figure.

A more comprehensive description of the water vapor flux field can be obtained from the vertically integrated (integrated from the 1000mb to the 100mb level) vapor flux (ivf). For comparison purposes this vector field is superimposed on the 700mb vapor flux field in Figure B7 for July 11th. The two fields generally show a good correspondence and differing primarily by a scale factor whose size is consistent with the vertical integration of the vapor flux. This result is also consistent with the observation that the predominant vapor transport occurs primarily around the 700mb level. This correspondence is excellent in the vicinity of the Pacific Northwest. Directional differences do appear both over some locations in the eastern Pacific Ocean and some locations east of the Continental Divide. A more detailed analysis was done using the integrated vapor flux field, since it would be expected to yield a more complete picture of the water vapor source dynamics.

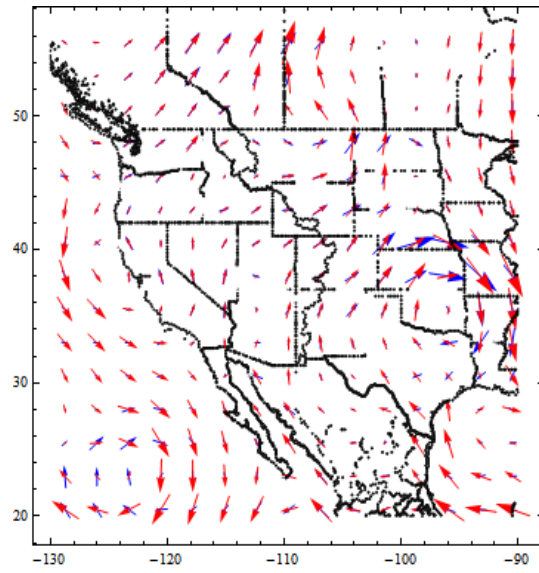
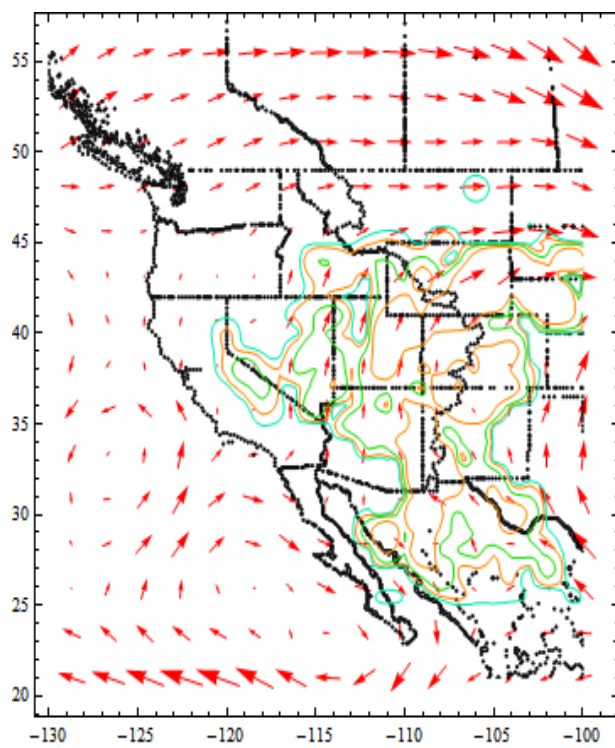
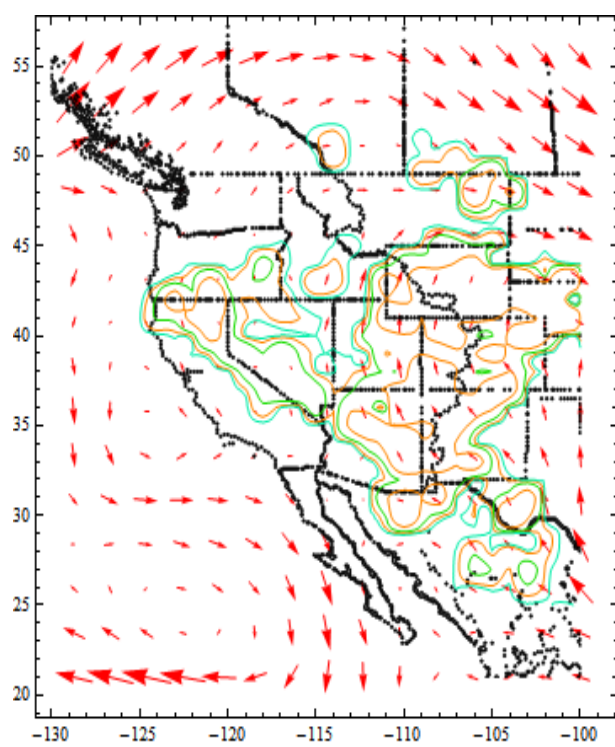


Figure B7. The 2001, July 11th integrated vapor flux field (red) superimposed on 700mb vapor flux field (blue). The legend for the integrated vapor flux vector length is shown in units of kg/ms. The maximum vector magnitude is 289 kg/ms.

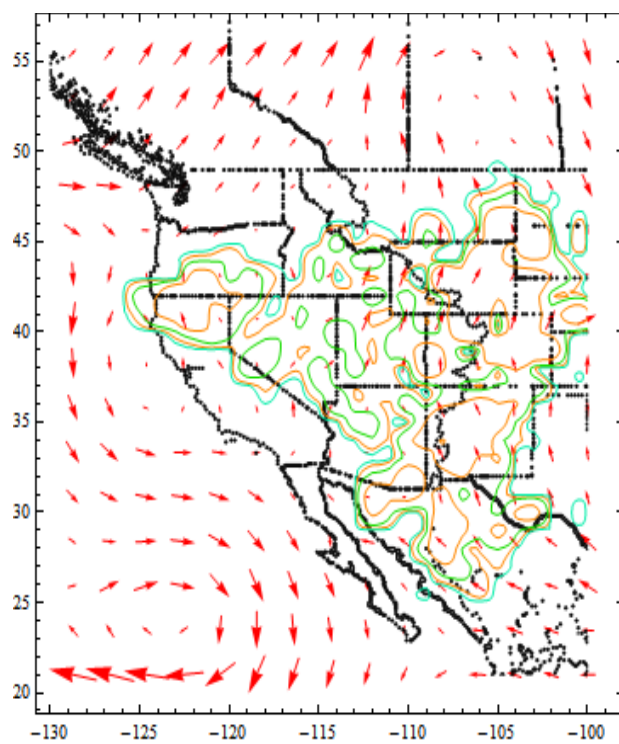
Recognizing that vapor at a particular location would have been transported by an earlier flux field incident on that location, the ivf from one day earlier was superimposed on the lightning intensity for the 5 day sequence (Figures B8a-e). Referring to a point in the lightning intensity field in Figure B21 (July 11th), as a first approximation, the vapor flux would be advected to the point in one day, along a field line from the vapor source.



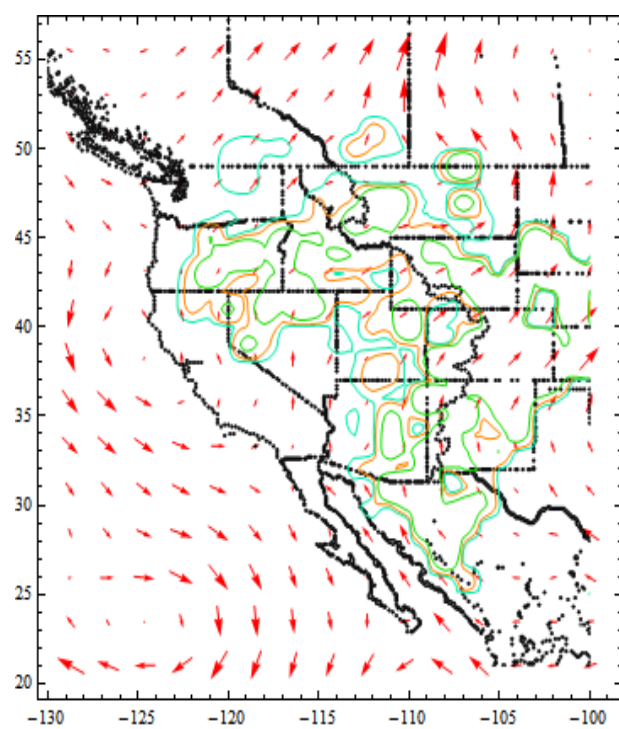
a



b



c



d

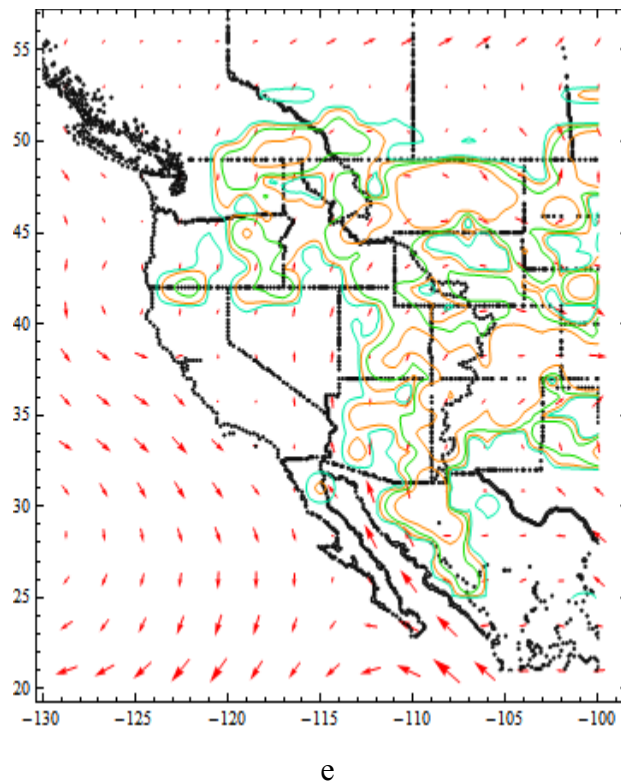
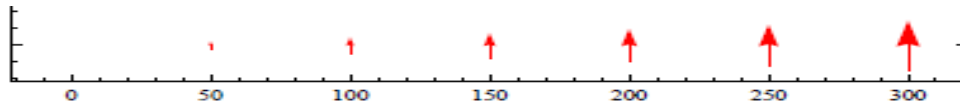


Figure B8. The 2001 case study; lightning intensity superimposed on the day earlier integrated vapor flux field. The legend for the vapor flux vector lengths is shown in units of kg/ms (horizontal axis).



Plots for (a) June 9th, (b) June 10th, (b) June 10th, (c) June 11th, (d) June 12th, (e) June 13th.

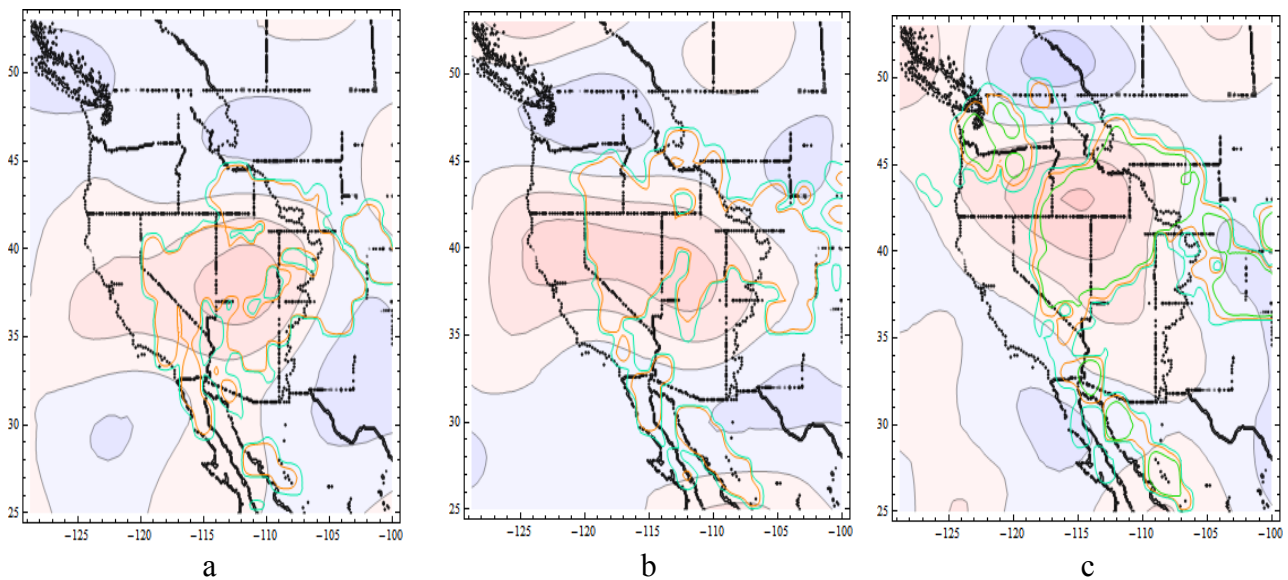
Three sources of the 700mb tropical moisture can be identified by examining the southern region of the 700mb vapor flux (Figure B5). From east to west, the first two sources can be associated with moisture from the Gulf of Mexico and the Gulf of California. The third source of moisture appears to be coming from the tropical Pacific. All of these moisture sources have been extensively examined in connection with the North American Monsoon (Adams and Comrie 1997; Sheppard et al 2002). The moisture flux from the tropical Pacific source can be interpreted as being pulled into the counter clockwise circulation (about the low pressure surface, Figure B6) centered just off the Northern

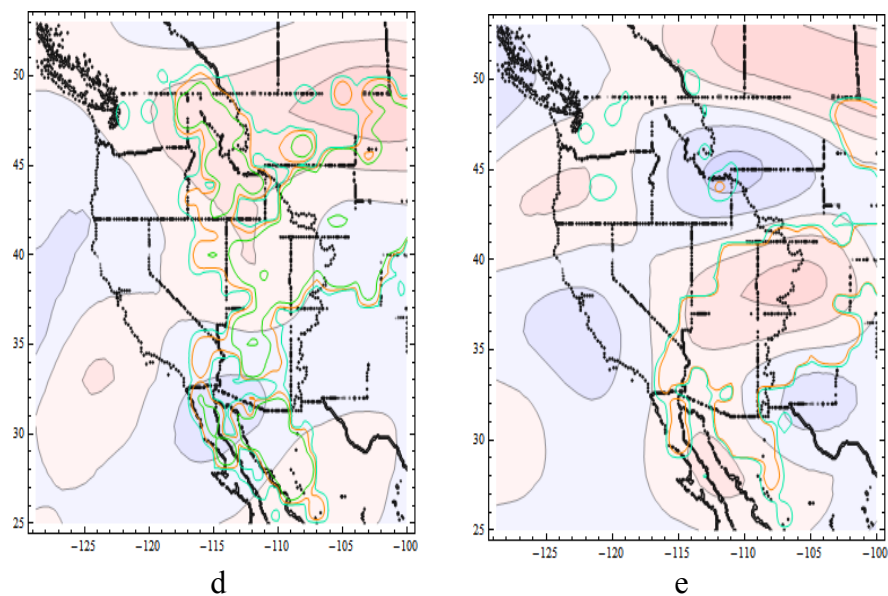
California Coast.

On the OP and the rest of Washington all are well to the north of the lowest intensity lightning contour (Figure B13). The source of water vapor is directly to the west. Not only are the temperatures cooler in this source region, directly reducing instability, but, more importantly the saturation values of the specific humidity are dramatically reduced (essentially exponentially) relative to those of the warmer tropical source regions.

Major PNW Event With Significant Activity on the OP

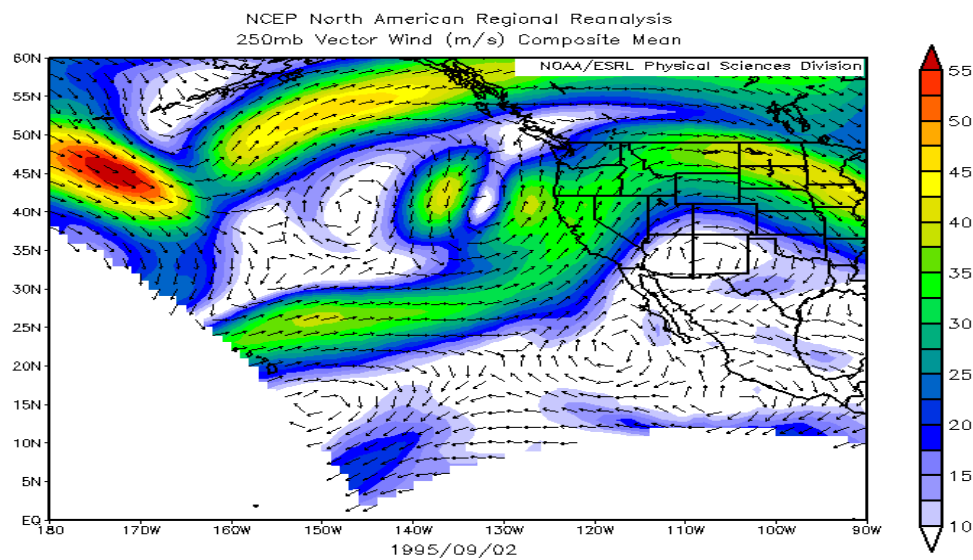
The event which had a PNW daily peak activity of 12,901 strikes on September, 4th, 1995 was chosen for this case study; it was the 4th largest of the 8 events for which the OP strike count was ≥ 100 (590 strikes on the OP). Figures B9a-e (days -2, -1, 0, 1, 2) illustrate that the 250mb wind divergence corresponds well to the lightning intensity for the 5 day period centered about this peak day. The associated 250 winds are plotted in Figures B10a-e. The jet during this event maintains a northern and southern branch -as it did in the 2001 case study. Contour plots of the average daily lightning intensity were overlaid on daily average 700mb specific humidity contours for the 5 day period in Figures B11a-e. The improvement of the coincidence of lightning with specific humidity relative to the coincidence with divergence is apparent for each day of the sequence.



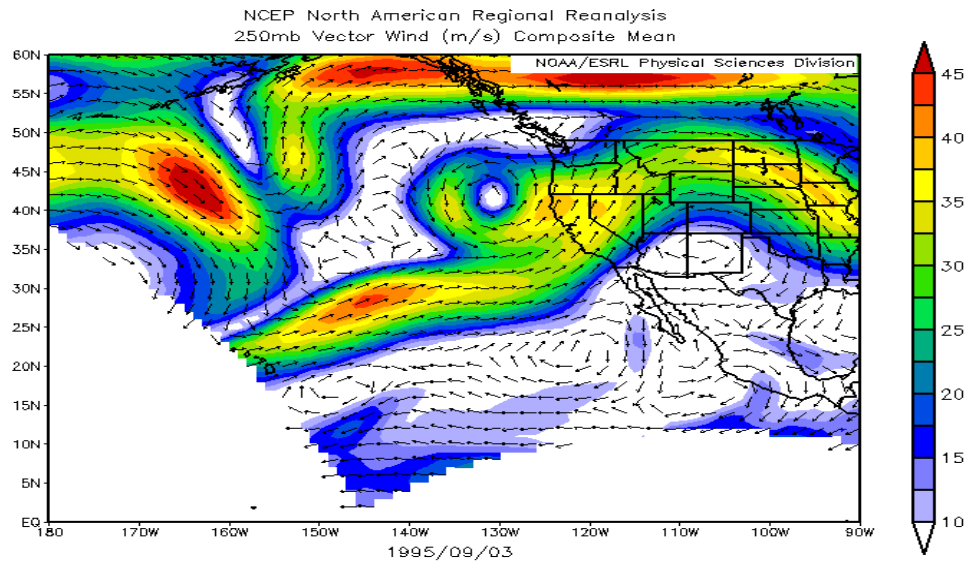


Figures B9. Same as Figures B1 for the 1995 case study.

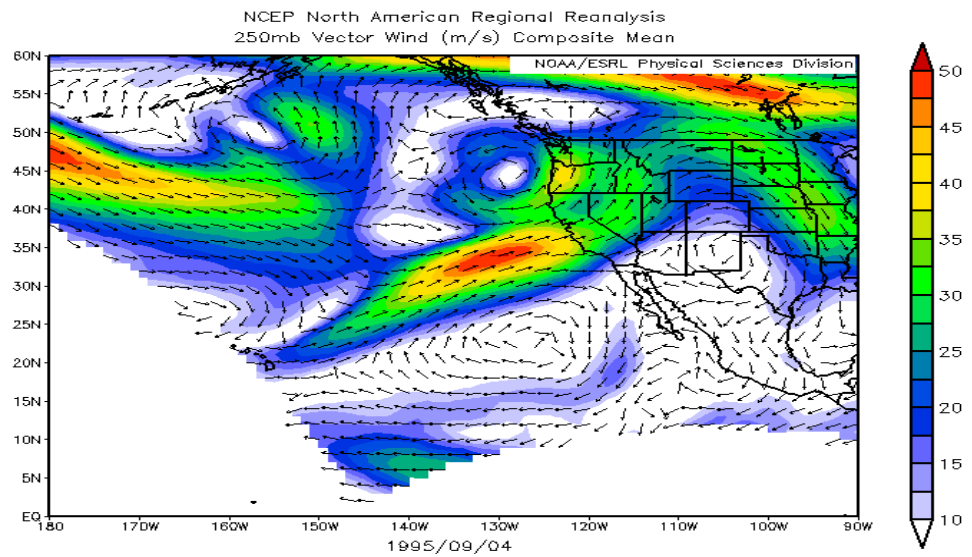
Plots for (a) September 2nd, (b) September 3rd, (c) September 4th, (d) September 5th, (e) September 6th.



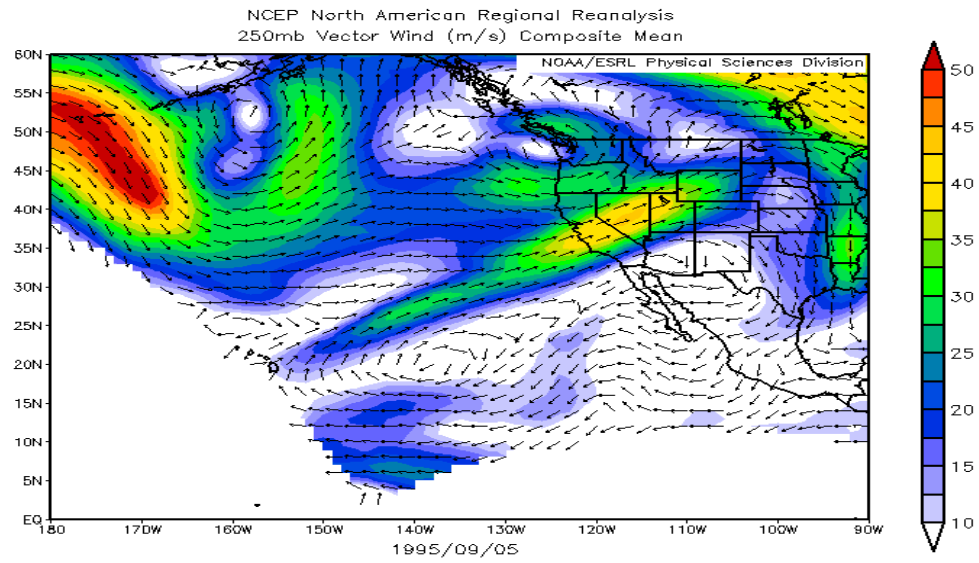
a



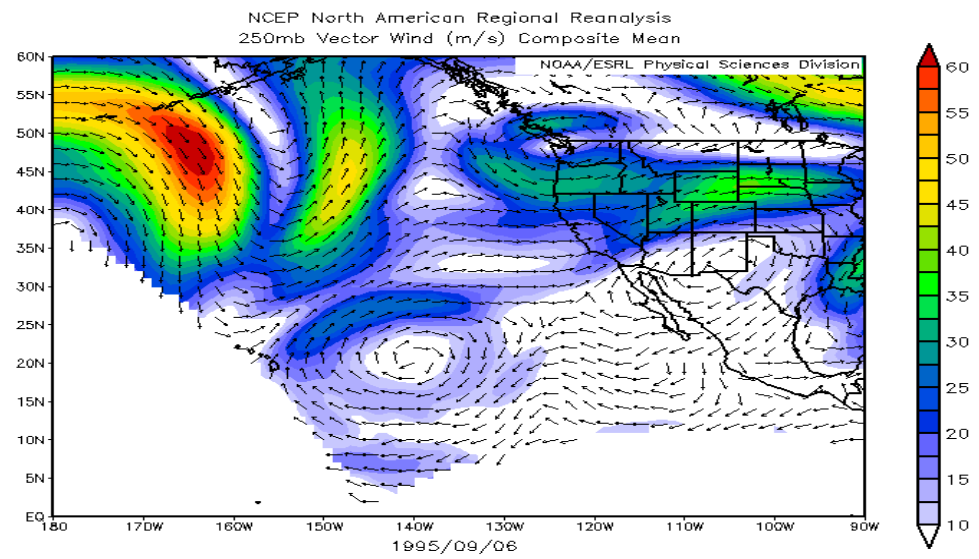
b



c



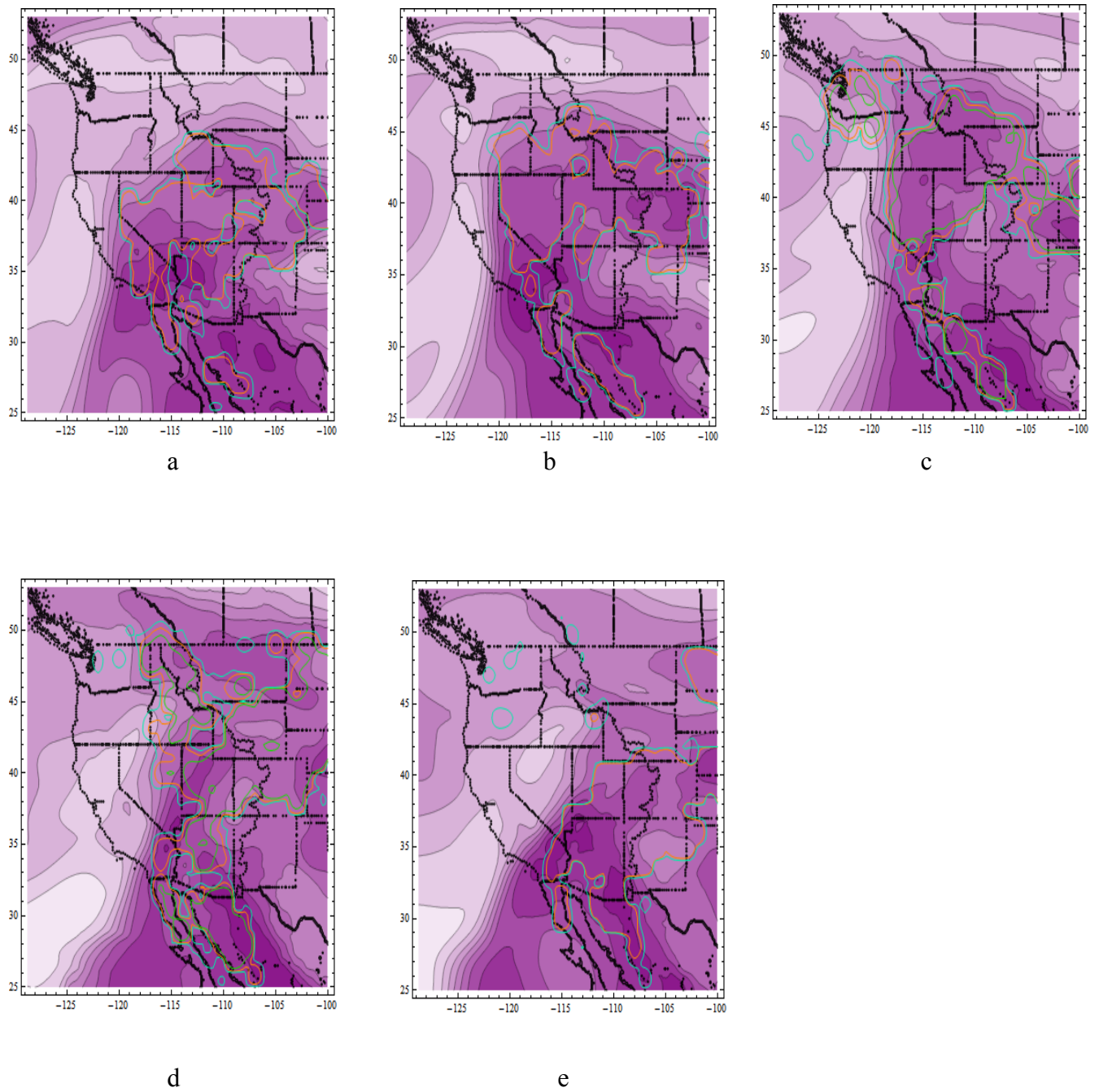
d



e

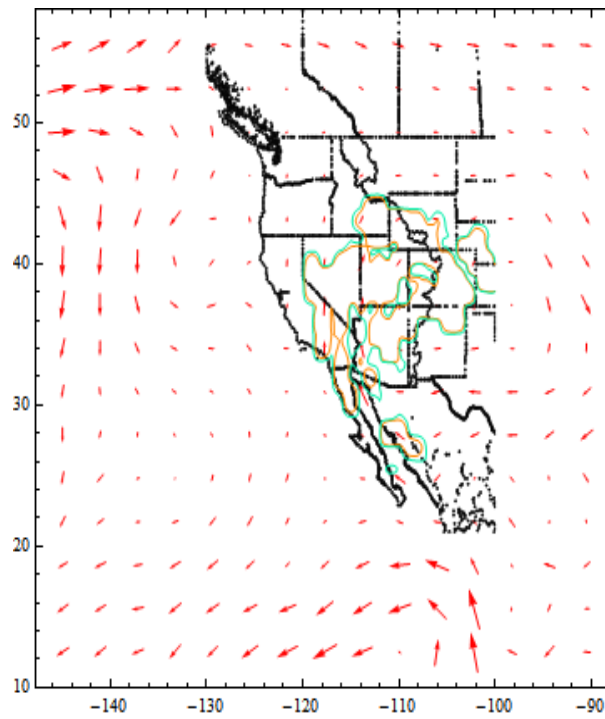
Figures B10. Same as Figures B2 for the 1995 case study.

Plots for (a) September 2nd, (b) September 3rd, (c) September 4th, (d) September 5th, (e) September 6th.

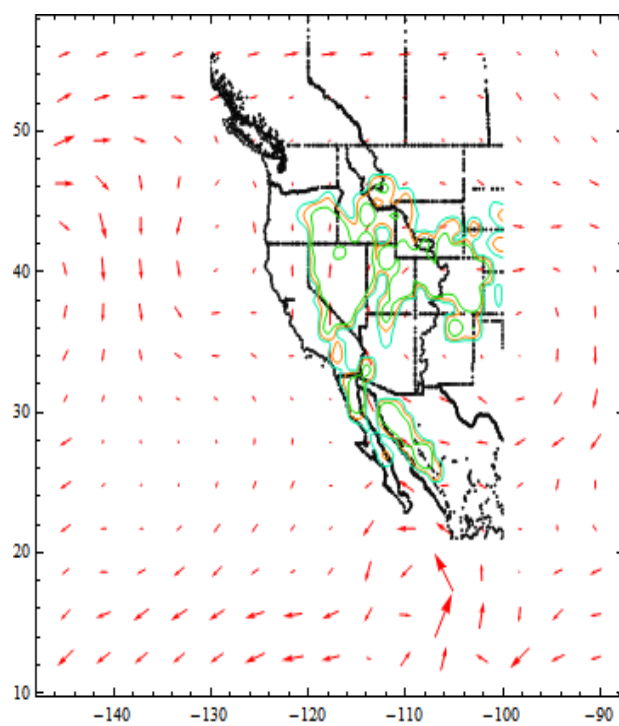


Figures B11. Same as Figures B3 for the 1995 case study. Plots for (a) September 2nd, (b) September 3rd, (c) September 4th, (d) September 5th, (e) September 6th.

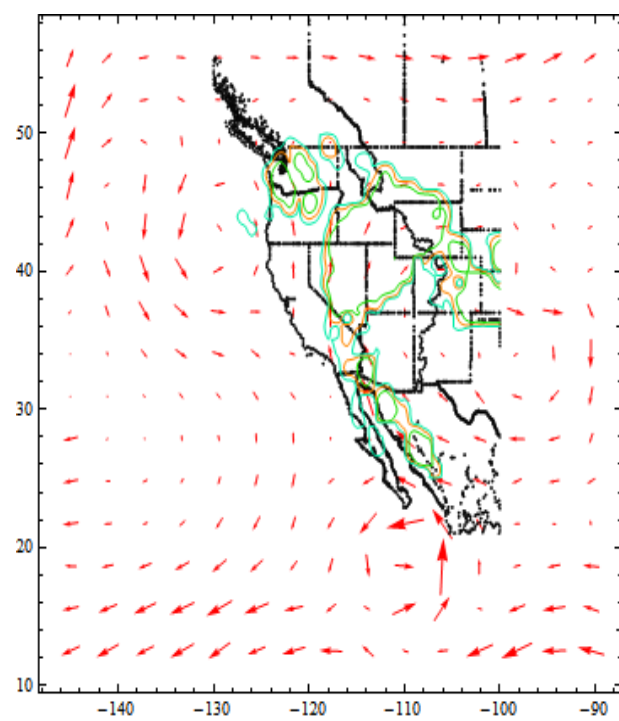
The **ivf** field, one day earlier, is superimposed on the lightning intensity in Figures B12a-e. The **ivf** field has been extended beyond the boundaries of available lightning data to enhance the interpretation of the dynamics of tropical water vapor transport. For example, on September 2nd the source of vapor fueling the instability resulting in lightning activity in the desert southwest appears to be from both the Gulf of Mexico and the Gulf of California. Looking at the tropical **ivf** field for the remainder of the sequence, it is interesting to note that a disturbance carried in an easterly tropical wave appears to be an important source of the vapor flux being transported north. By September 6th this disturbance is centered west of the southern tip of the Baja Peninsula.



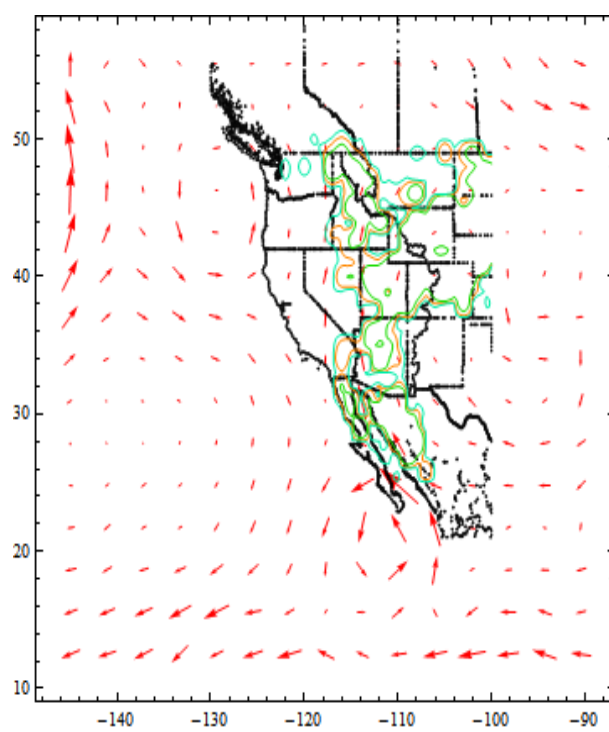
a



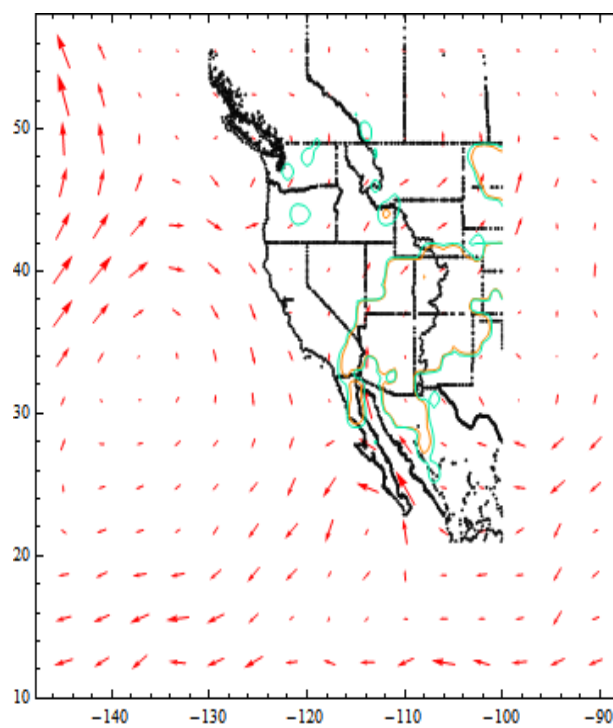
b



c



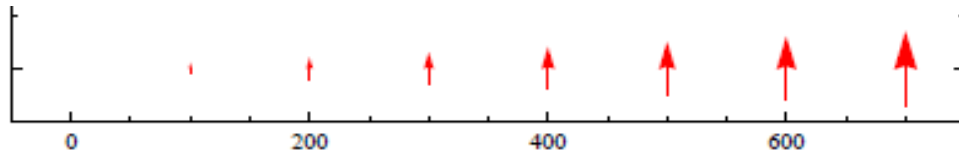
d



e

Figures B12. Same as Figures B8 for the 1995 case study.

The legend for the integrated vapor flux vector length is shown in units of kg/ms (horizontal axis).



Plots for (a) September 2nd, (b) September 3rd, (c) September 4th, (d) September 5th, (e) September 6th.

An order of magnitude estimate was made of the specific humidity advection from the day in advance wind data to illustrate the mechanism by which water vapor is transported. The basis of the estimate is that, as a first approximation, the local maxima in the specific humidity field are displaced by the wind field to a location determined by the wind vectors. The estimate was made at the 700mb level of the atmosphere where the bulk of the moisture leading to the vertical instability appears to be concentrated. We estimated the time of displacement of a parcel of the atmosphere along a trajectory determined by the wind field.

Referring to the specific humidity distribution on September 3rd (Figure B72), there is an atmospheric parcel has a value of q of about 3 g/kg at an Oregon/Nevada/California border region. This parcel will be carried north at an initial velocity of about 11m/s as can be seen from the 700mb wind field for this day (Figure B13). The parcel follows a curved trajectory taking it up to the Puget Sound area, where the wind speed has dropped to 6m/s. It is also virtually the same trajectory of the ivf (Figure B14) confirming that the flux at 700mb makes up the dominant contribution to the ivf. This trajectory is roughly 800km in length. Taking the average speed to be about 9km/s, the time required for the parcel to reach the OP is about 1 day. Looking at the specific humidity distribution 1 day later (Figure B73), the specific humidity on the OP has risen to about 3g/kg and lightning has increased to its peak intensity for this event.

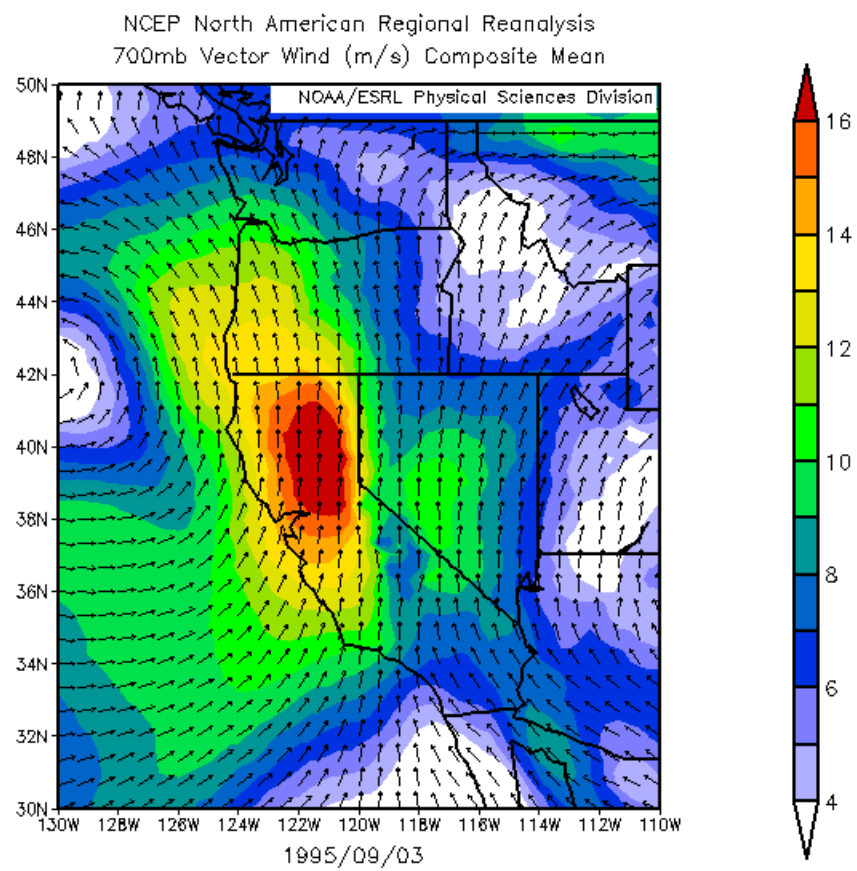


Figure B13. September 3, 1995; NCEP NARR daily average 700mb vector winds.

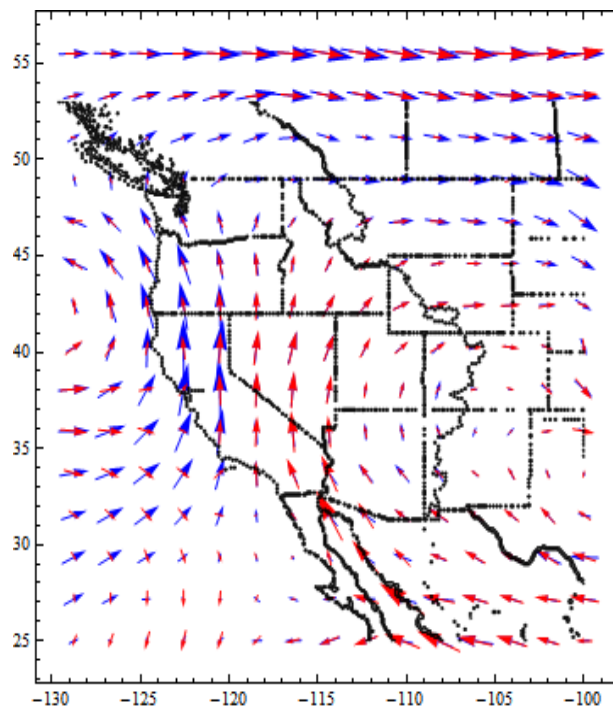


Figure B14. September 3, 1995; integrated vapor flux field (Red) overlaid on the 700mb wind field (Blue).

The model upon which this estimate is based is certainly an oversimplification. A full description would require an accounting of all of the hydrological inputs at all elevations. Overlaying the same day's *ivf* field on the lightning intensity would provide some prediction of the location of the following days activity.

A feature which appears in all 5 days of the *ivf* sequence is the counter-clockwise circulation of the *ivf* field over the eastern Pacific (Figures B12a-e). On day -2 it is weak, but centered of the coast near 129W, and 41N. By day 0 it has strengthened. The vapor flux on shore from Northern California to Washington – inland to about 119W conforms to this rotation. Tropical moisture appears pulled into this circulation appears to have been responsible for the instability resulting in lightning strikes in this region, north of roughly 44N.

Returning to the *ivf* field sequence for the case study with insignificant activity on the OP

(Figures B8a-e), a similar circulation feature appears in this sequence. On day -2 the center is near 126W, and 32N. By day 0 it has moved north to about 38N and is influencing on shore circulation most of California, and Southern Oregon and Western Nevada. Tropical moisture resulting in lightning strikes, initially appears to have been pulled into the Sierra Nevada Mountains and, by July 11th into Northern California, Western Nevada, and Southern Oregon.

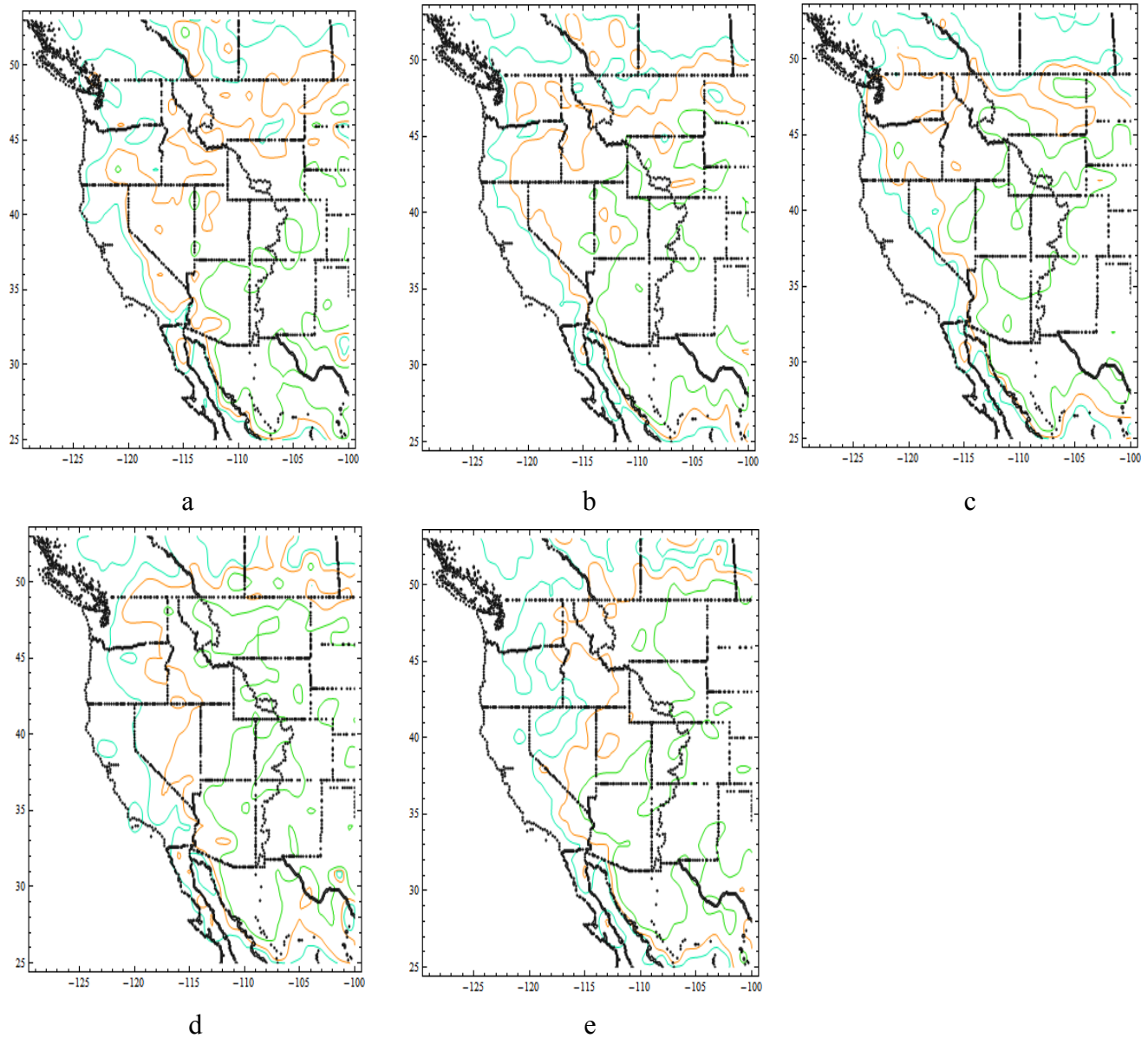
Composite Analysis

In order to characterize conditions that would distinguish PNW lightning events that occur on the OP from those that do not, we chose two separate groups of events representing these two conditions. Focusing on measures of atmospheric conditions discussed in the previous case studies, we looked for significant differences in the composites of these conditions that would distinguish one group from the other. There were several criteria in the selection of the members of either of the two groups.

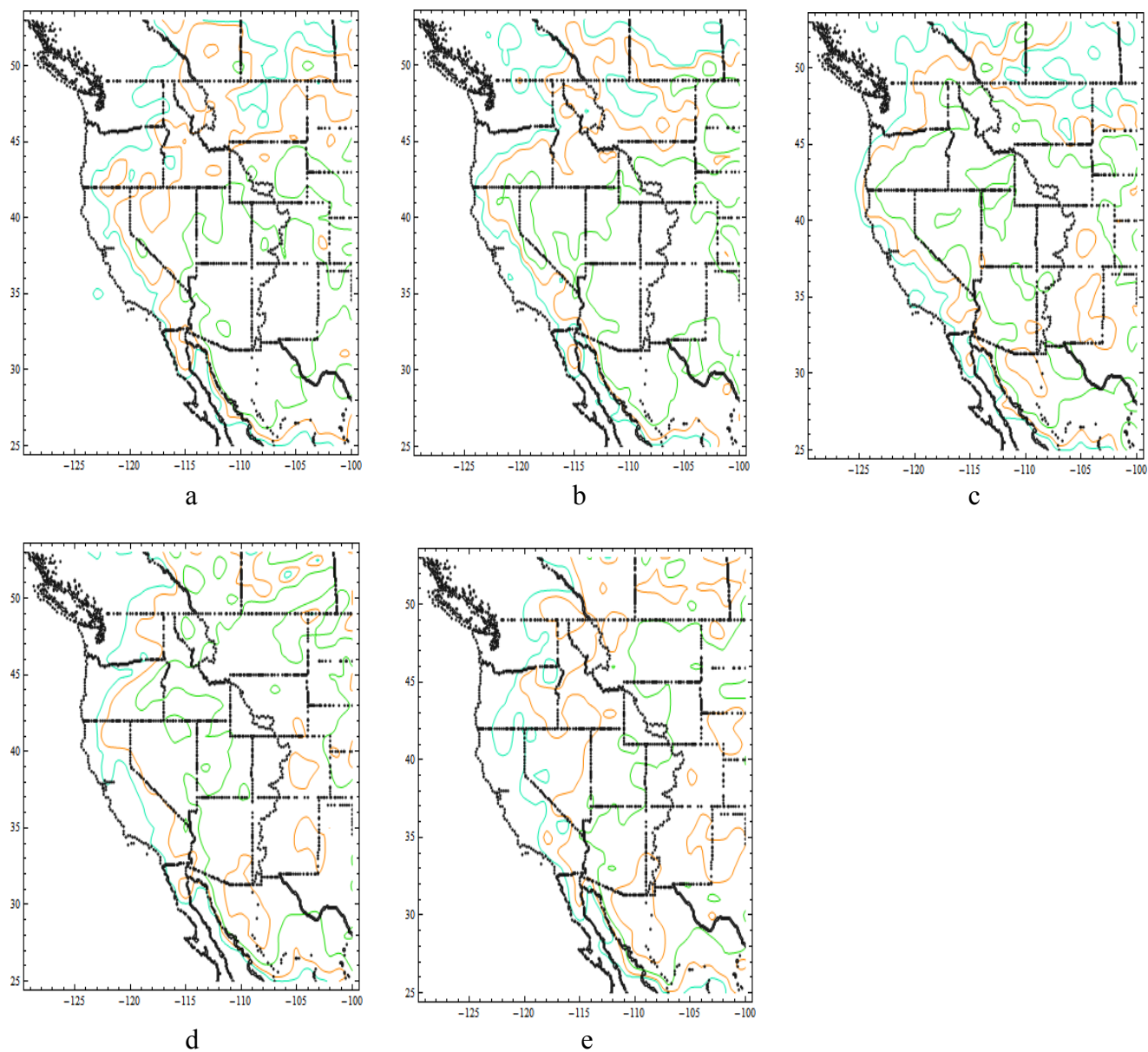
The primary criteria was that 10 or more strikes occurred on the peak day of an OP event for the first group and 1 or less strikes occurred on the OP for the peak day of a PNW event for the second group. Additional criteria for membership in groups 1 or 2 are presented in **Appendix B1**.

The 5 day composite series for group 1 lightning is displayed in Figures B15a-e (days -2, -1,0,1,2), and in Figures B16a-e for group 2. The important distinction for these composites is that some of the lightning strikes reach the Olympic Peninsula for group 1, but, they do not (in significant number) for group 2. Of course, the groups were constructed to satisfy this criteria, but in order to examine the distinction between the two series for the rest of the Western United States we computed the difference between the group 1 and group 2 intensity series. We then computed the regions where this difference was significant at the 95% confidence level. While some significant differences are apparent in most days of the series, the areas of greatest significance appear on the day of peak intensity in the PNW (day 0); this result is displayed in figure B17. The area of significantly greater activity extends through most of western Washington as expected from the day 0 composites

themselves (Figures B26 and B31). The area of significantly less activity, especially in the southern Oregon, northern California, western Nevada is not so apparent from the composites. The reasons for this difference is explored below.



Figures B15. The 5 day composite intensity fields for lightning. Group 1 Averages – 28 events for which the peak lightning counts on the OP was ≥ 10 (group 1). The sequence is centered about day 0, the day of peak activity (Figure B15c). Composites for days (a) -2, (b) -1, (c) 0, (d) 1, (e) 2.



Figures B16. Lightning intensity composite sequence; events for which the peak activity on the OP was ≤ 1 (group 2). Composites for days (a) -2, (b) -1, (c) 0, (d) 1, (e) 2.

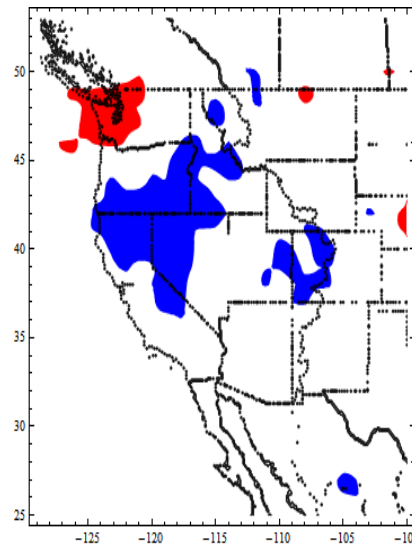
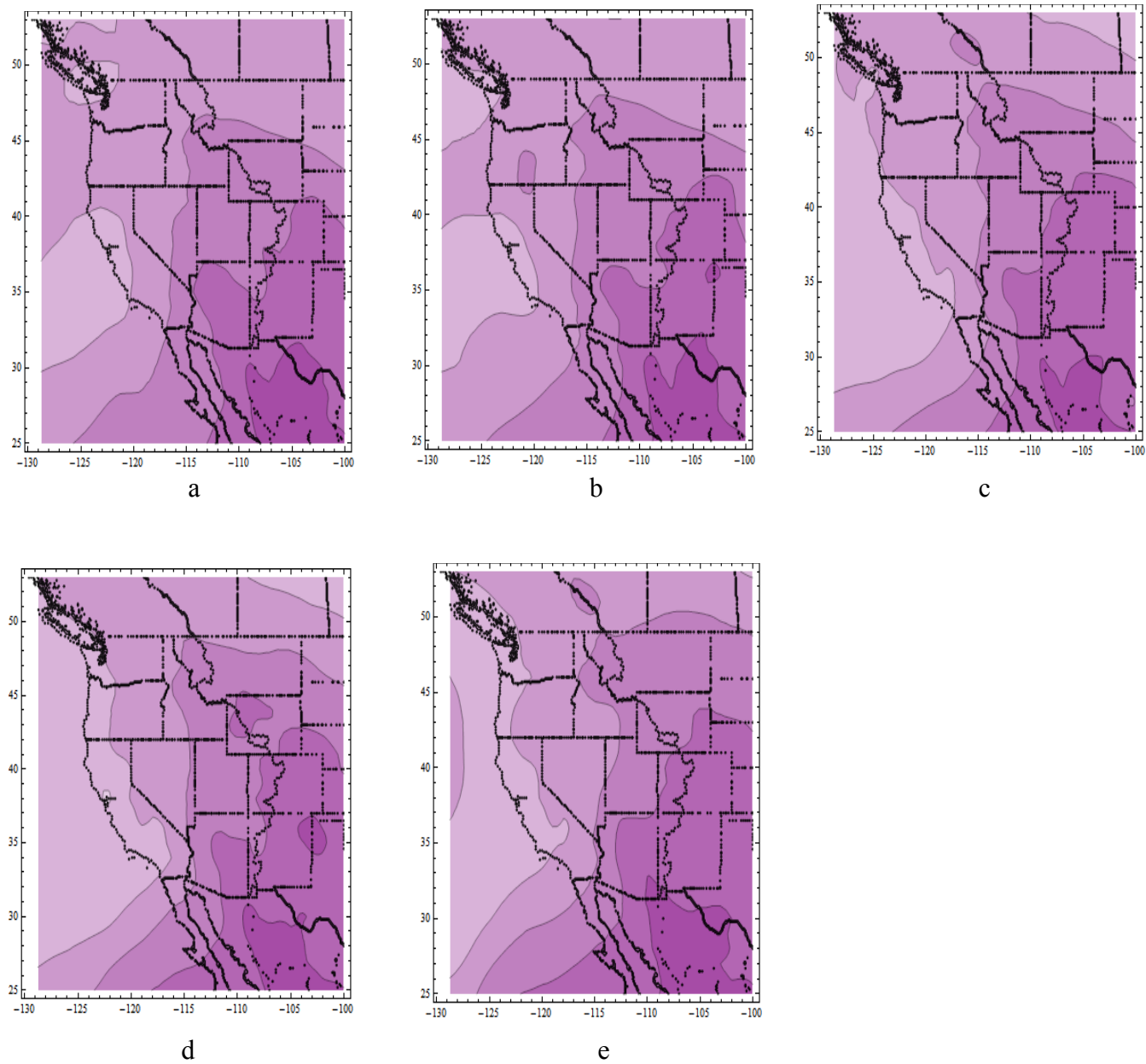
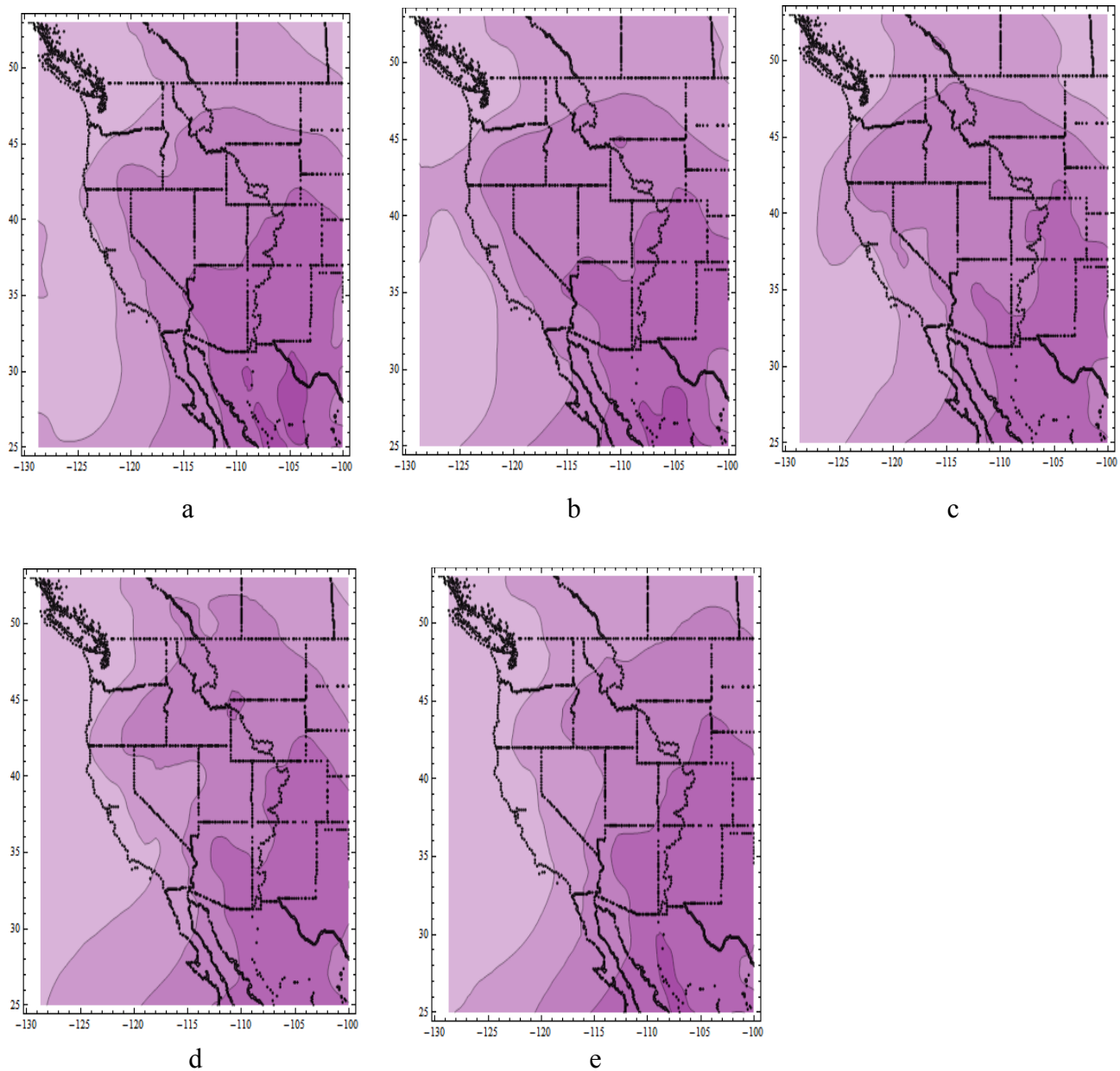


Figure B17. Regions of significant ($\geq 95\%$ confidence level) difference between the group 1 lightning intensity field and that of group 2 (for day 0). Red represents a positive difference; blue represents a negative difference.

Since the 700mb specific humidity corresponds so closely to the lightning activity in the 2001 case study, a similar composite behavior would also be expected. These results for group 1 are displayed in Figures B18a-e; the series for group 2 are displayed in Figures B19a-e. The day 0 areas of significant difference in specific humidity are displayed in Figure B20. Keeping in mind that lightning data is not available from the NLDN for latitudes above 49 degrees, the areas of significant difference in Figures B17 and B20 are in general agreement, although the regions of significant specific humidity difference are not as extensive as they are for the lightning intensity. The case studies suggest that these similarities and differences can best be understood by examining the composites of the moisture source – the *ivf*. (As discussed in the case studies, because of the *ivf* causal relationship to the lightning, each day in the 5 day series precedes the lightning day by one day (days -3,-2,-1,0,+1).)



Figures B18. The 5 day group 1 composite specific humidity fields at 700mb. Composites for days (a) -2, (b) -1, (c) 0, (d) 1, (e) 2.



Figures B19. The 5 day group 2 composite specific humidity fields at 700mb. Composites for days (a) -2, (b) -1, (c) 0, (d) 1, (e) 2.

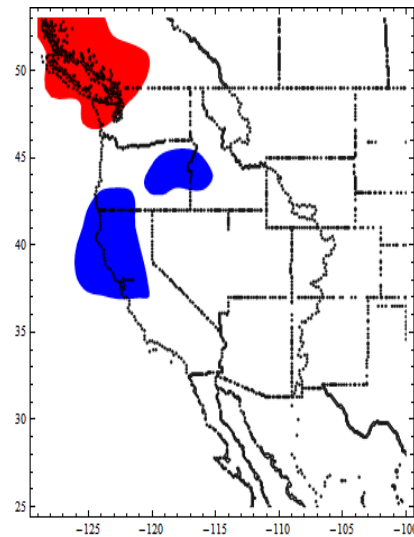
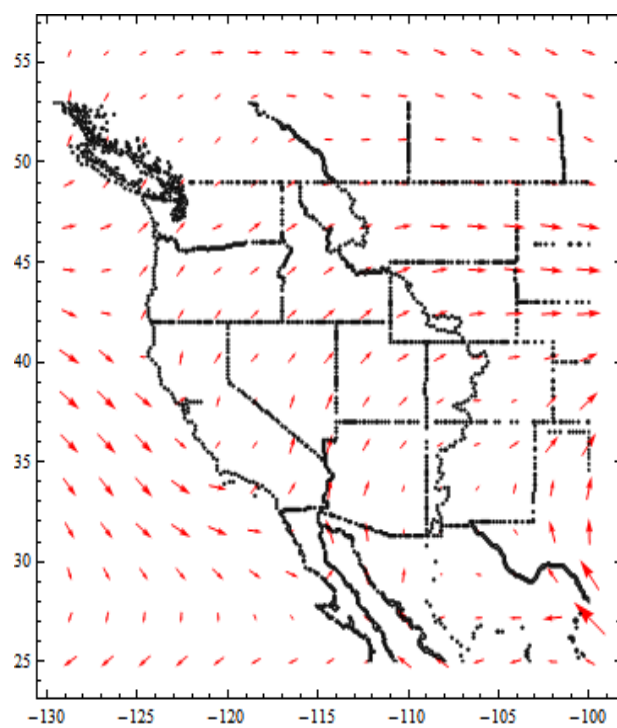
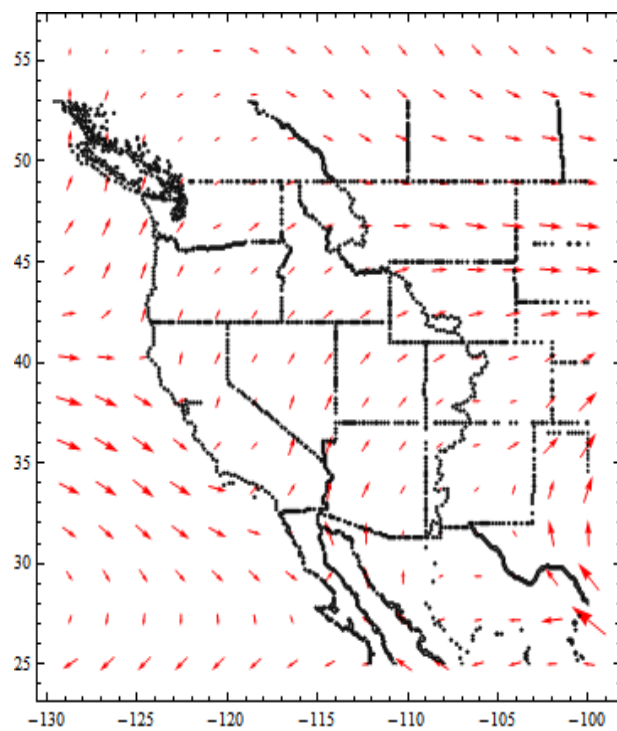


Figure B20. Same as Figure B17 for the group 1 and group 2 specific humidity fields on the day of peak lightning activity.

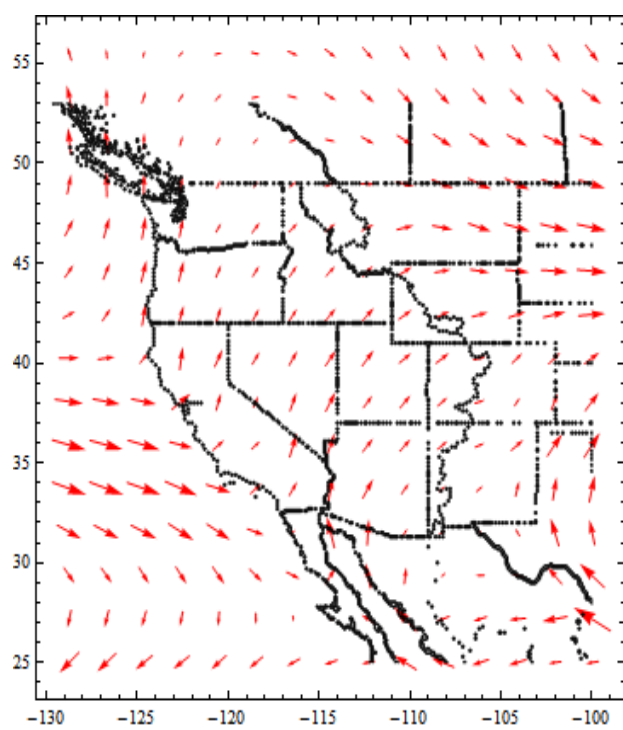
The 5 day ivf composite fields for group 1 are shown in figures B21a-e; for group 2, they are shown in figures B22a-e. A day by day comparison between the two groups show subtle but important distinctions between them. Perhaps the most important distinction occurs on the peak lightning day - day -1 of this series. Over the OP, the group 1 flux direction is nearly from the south, and the group 2 flow is nearly from the southwest. Other important distinctions are revealed by examining the areas of significant difference between the two groups. These are most distinct in the zonal component of the field (figures B23a-e). (The meridional differences are less distinct and non-existent in the PNW and are not shown). In all 5 days of the series there is a large area of significantly negative difference in zonal flux - especially to the north of the Canadian border region. This area generally progresses westward and finally, northwestward out into the Pacific. Looking at the group 1 and group 2 composite series, this negative difference results from the dominant positive zonal flux of the group 2 events. It generally strengthens in the Pacific during the sequence while the group 1 zonal flux actually becomes slightly negative in the last 3 days of the sequence.



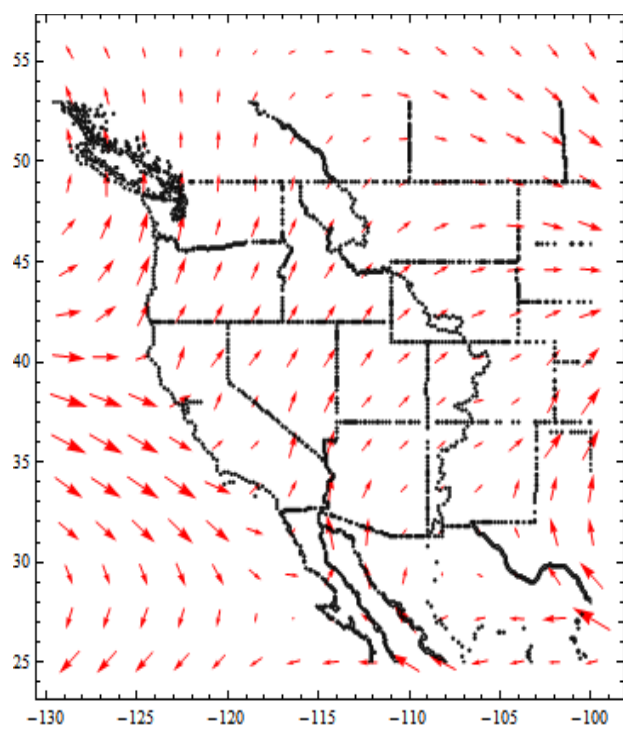
a



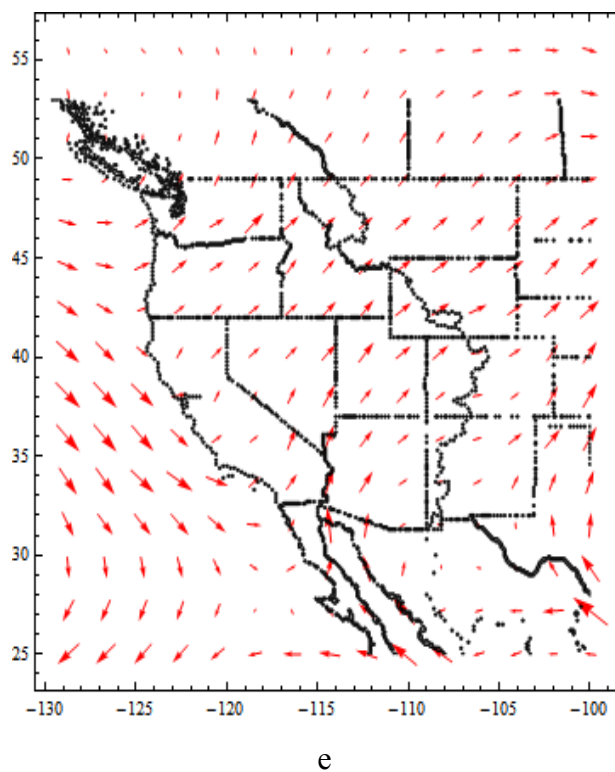
b



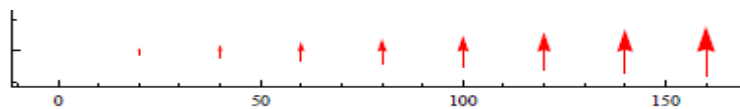
c



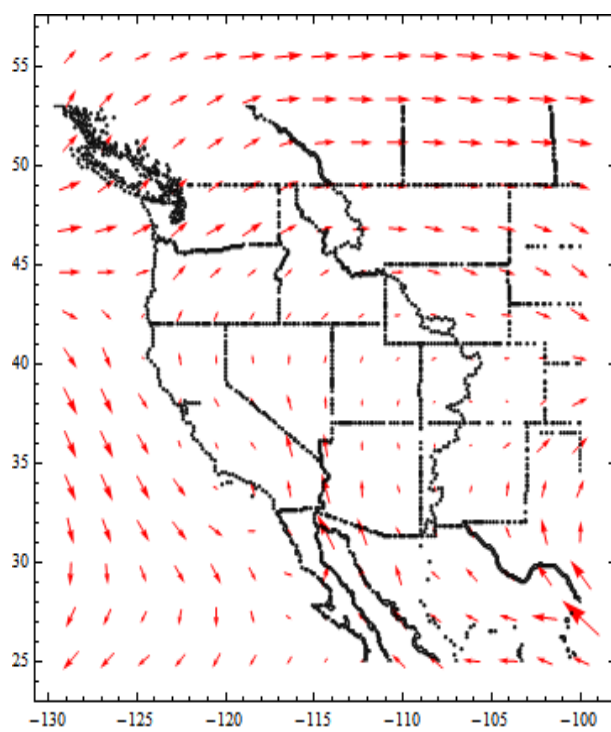
d



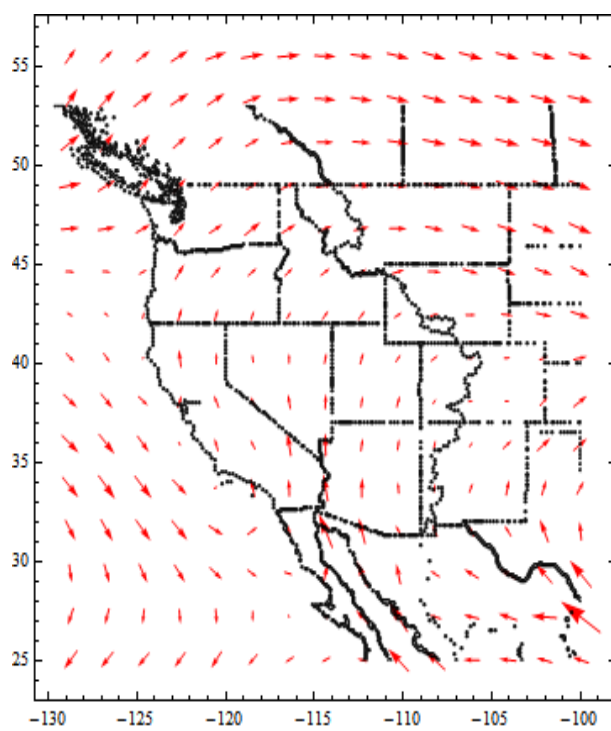
Figures B21. The 5 day group 1 composite integrated vapor flux fields. The legend for the composite integrated vapor flux vector length is shown in units of kg/ms (horizontal axis).



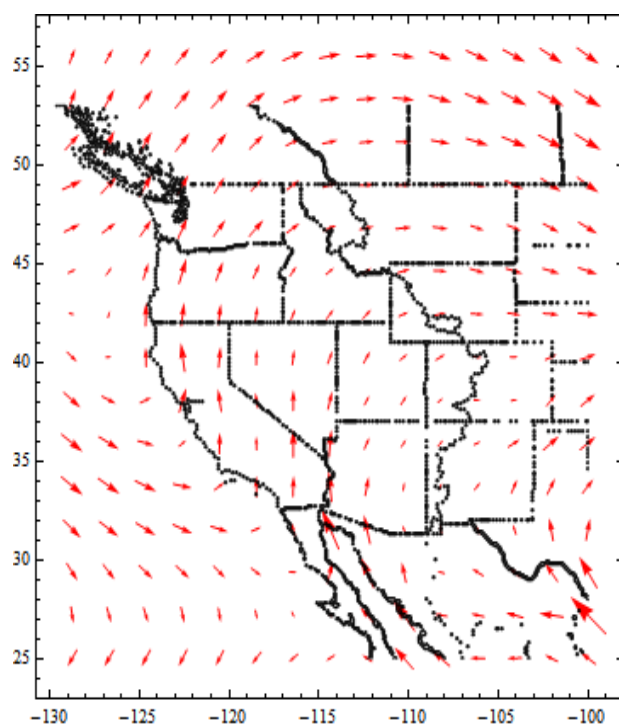
Composites for days (a) -2, (b) -1, (c) 0, (d) 1, (e) 2.



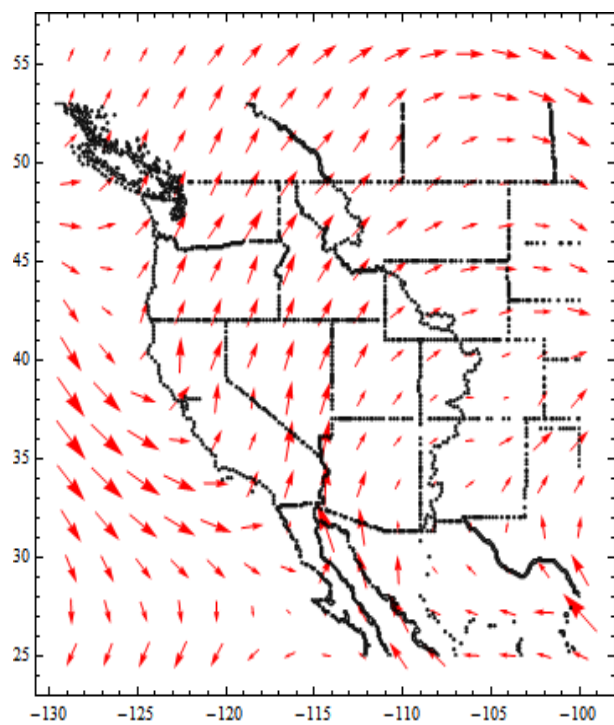
a



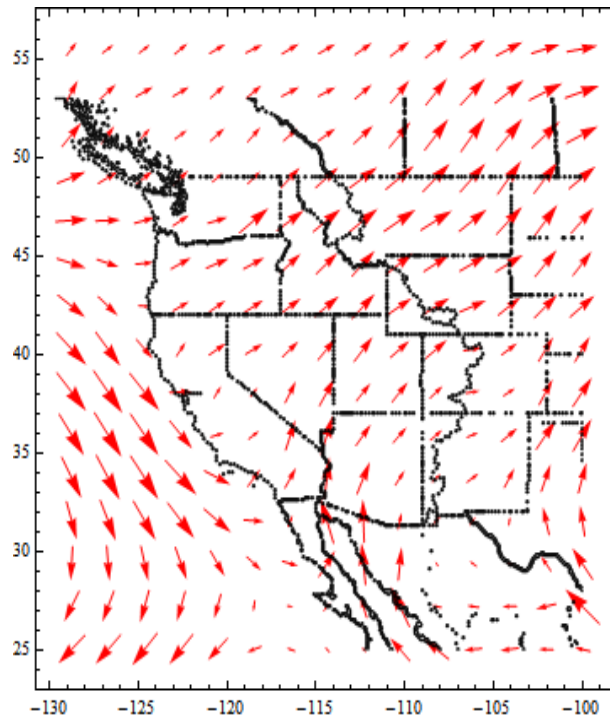
b



c

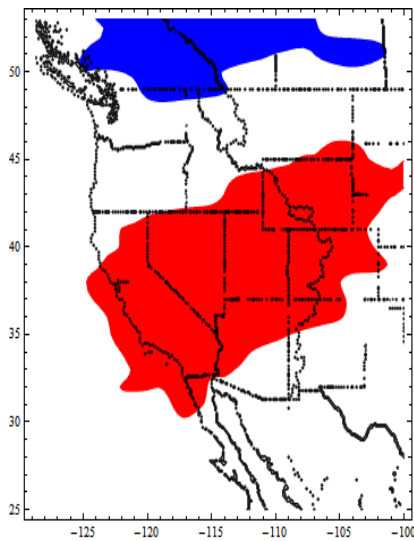


d

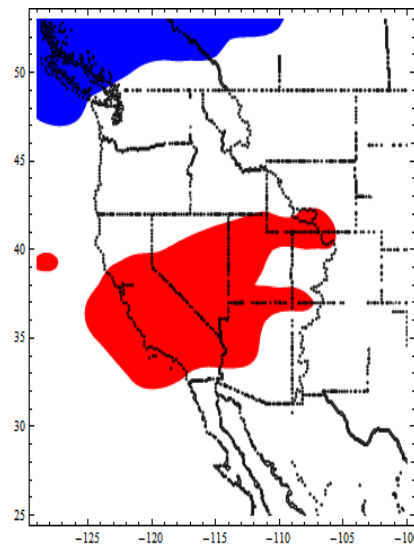


e

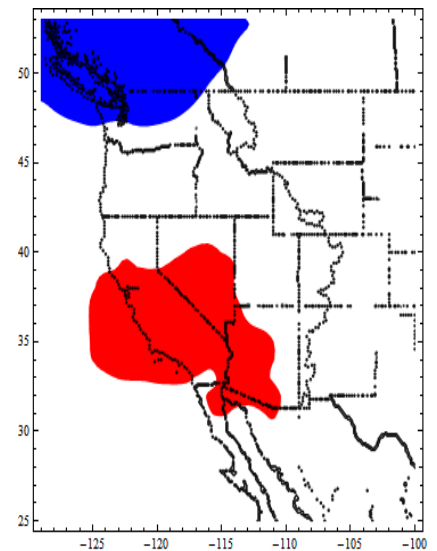
Figures B22. The 5 day group 2 composite integrated vapor flux fields. Composites for days (a) -2, (b) -1, (c) 0, (d) 1, (e) 2.



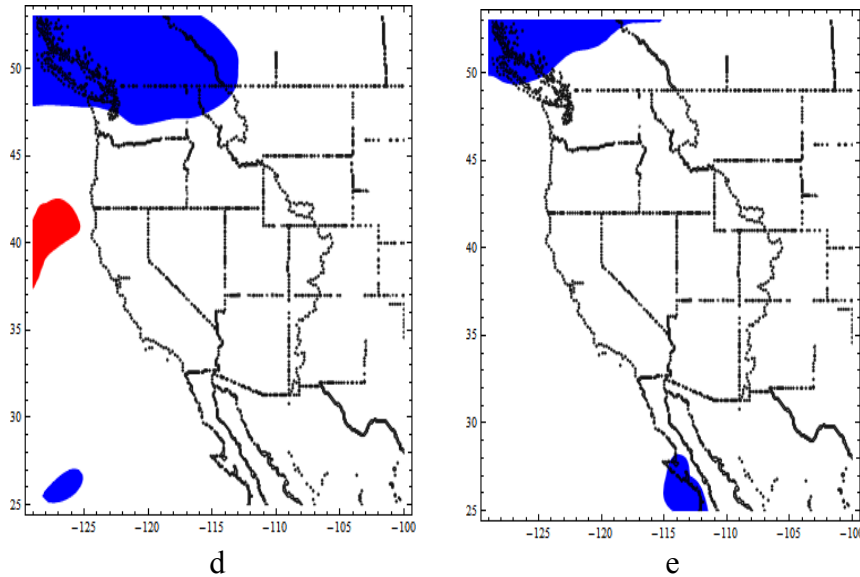
a



b



c



Figures B23. Same as Figure B17 for the group 1 and group 2 zonal component of the integrated vapor flux fields. Composites for days (a) -3, (b) -2, (c) -1, (d) 0, (e) 1.

In the southwestern states region, the situation is similar - but reversed. During the first 4 days of the sequence there is significantly more group 1 positive zonal flux. This pattern generally progresses westward into California and then northwest out into the Pacific. In this situation the dominant zonal flux is from the group 1 events. It generally strengthens in the Pacific during the sequence while the group 2 zonal flux is actually negative the first 3 days of the sequence (over land). The difference between these two regions can be unified into a single causal explanation.

Discussion

The apparent latitudinal reversal in the significant zonal flux difference between the group 1 and group 2 composites (Figures B23a-e), can now be interpreted as due to a single characteristic pattern of the ivf field in the vicinity of lightning events for both the group 1 and group 2 events. It is primarily characterized by a counter-clockwise circulation off the California coast for group 2 events, but, shifted north off the PNW coast for group 1 events. The group 1 case study illustrates this situation when a lightning event occurs in the vicinity of the OP (Figures B12a-e). There is a counter-clockwise circulation off of the PNW coast, resulting in a negative component of the zonal flux in the northern half of this circulation. The group 2 case study illustrates the field when the lightning event occurs in the PNW, but misses the OP (Figures B8a-e). The counter-clockwise is off the California coast, resulting in a negative zonal flux in the northern half of this circulation. Referring once again to Figure B17, this event illustrates why significantly more lightning in group 2 than group 1 would be expected in land near this latitude. This is the area in blue in Figure B17 where the difference in the lightning intensity between group 1 and that of group 2 is significantly negative.

We examined the 5 day ivf field sequence for all of the 8 largest PNW lightning events for which the peak strike number on the OP was ≥ 100 (largest group 1 events). This characteristic counter-clockwise circulation feature appeared in each of the central portions of the 5 day sequences with the center of the circulation off the coast ranging from west of the Oregon/California border to west of Vancouver Island (not shown). We also examined the largest 8 PNW events for which the OP activity was ≤ 1 (largest group 2 events). Again this counter-clockwise feature was in all or part of each 5 day sequence. The location of the center of these circulations ranged from west of northern Baja California to west of Washington (not shown). This circulation pattern characterizes the extreme warm season events examined in the 1995-2005 period – with the latitude of the center of the counter-clockwise circulation feature related to the latitude of the lightning events. The differences in the position of the cyclonic circulation explains the significant differences in the zonal component of the vapor flux field for the composite fields derived from all 56 events from groups 1 and 2. This suggests that this circulation pattern is at least a common feature of many the PNW lightning events -serving as a signature distinguishing events that are likely to occur on the OP from PNW events that do not. While it is not surprising that the central portion of the circulation feature is obliterated in the group 1

and group 2 composites because of the range of its locations, some evidence of it can be seen in both composites (Figures B21a-e and Figures B22a-e). For group 2 the reversal of the flux field in the first 2 days of the composite sequence (Figures B22a&b) between just off shore and inland along the California coast suggests that this represents the average of the counter-clockwise circulation flux or field at various locations near the coast. The counter-clockwise circulation on day 0 of the group 1 composite sequence can actually be seen by extending the longitudinal range of the composite west to 147W. This is shown in Figure B24 with the center of circulation of the northern tip of Vancouver Island at about 135W.

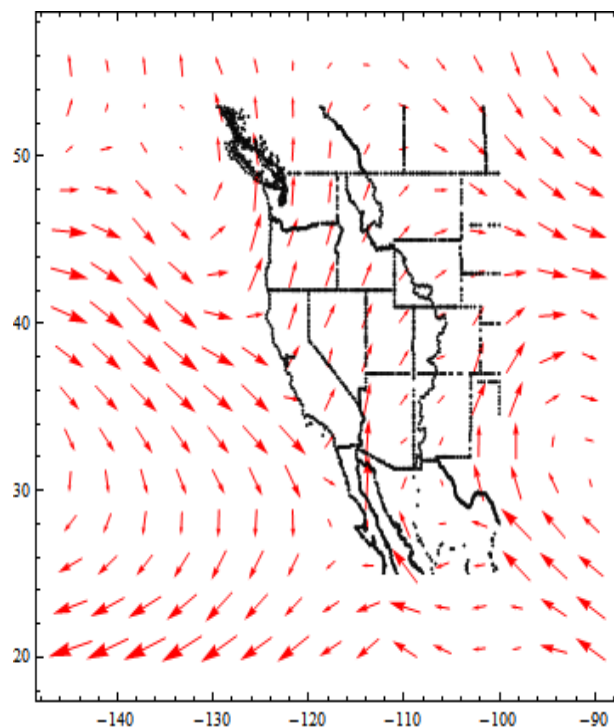


Figure B24. The group 1 extended composite integrated vapor flux field on the peak lightning day (day 0). The legend for the extended composite integrated vapor flux vector length is shown in units of kg/ms (horizontal axis).

We also examined the 250mb wind field sequence for all of these 16 Group 1 and Group 2 major events (for example see Figures B10a-e and Figures B2a-e for the Group1&2 case studies). In every case the 700mb vortex was positioned between two branches of the jet stream; it was closer to

the southern branch. A reasonable hypothesis for future research is that the 700mb vortex is created and driven by this upper troposphere pattern. A clear distinction between the pattern for the 8 events corresponding to an OP lightning event and the 8 events with almost no activity on the OP is that the latitude of the northern branch of the jet is roughly 67N in the former case and 52N in the later case (not shown). This position is consistent with the average latitudes of the 700mb vortices in the two cases.

While no statistical analysis of these 16 largest group one and group two events was attempted, they would be expected to dominate the 56 composites for which confidence levels were computed. Consequently we interpret the intraseasonal composite analysis as a predictor whether large lightning events would be expected on the OP.

C. Storm Motion

Observation of the variability of the evolution of lightning strikes on the OP suggests that an explanation of the dynamics responsible for this variability is complex. Rather than attempt a statistical analysis of these observations we present a number of case studies illustrating a variety of storm motion characteristics. A comparison of these case studies does suggest the possibility of a number of common causes of these behaviors. The choice of cases to investigate was largely motivated by the time and space distributions of lightning presented in detail in previous sections. Specifically, we chose cases representing distinct warm season, wet season, and diurnal behaviors. As might be expected the most distinctive behaviors were associated with the largest events in these categories. Multiple day events were first ranked by the largest one day total OP strikes (Pacific Standard Time (PST)) during the event (Table A2). Choices of case study events from each of the above categories are described in more detail in the separate sections for that category.

The analysis of the intraseasonal behavior during the warm season suggests that, much of the lightning activity can be attributed to the distribution of water vapor at the 700mb elevation of the atmosphere. The evolution of this distribution can largely be explained by advection of the moisture by the 700mb synoptic scale circulation. In order to understand the evolution of lightning on the OP we used the 700mb specific humidity and wind data over a period of 5 days centered about the day of peak activity – with the exception of the largest event. (GMT times are used, since several time zones are incorporated in this data.) (Additional data was added over the eastern Pacific beyond the range of the land based lightning sensors to give a more complete representation of the 700mb data.) The August 4, 1999 event was so exceptionally large that this data was plotted over a period of 10 days to capture the evolution of the event. On a grid scale of 1 degree latitude by 1 degree longitude, daily averages of lightning intensity were computed over an area from 24°N through 55°N and 144°W through 100°W.

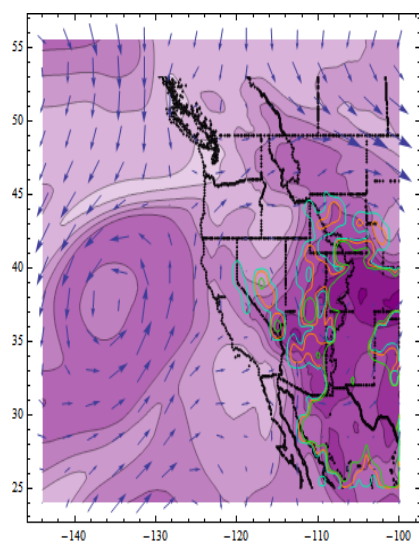
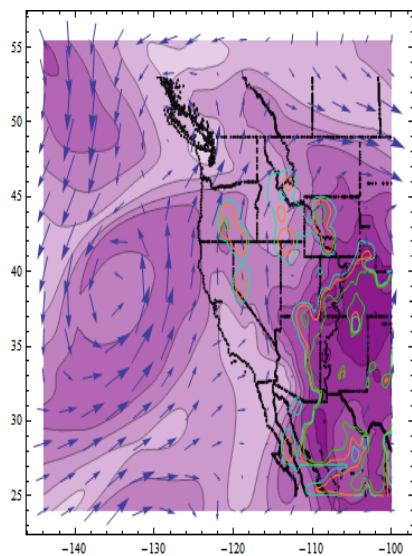
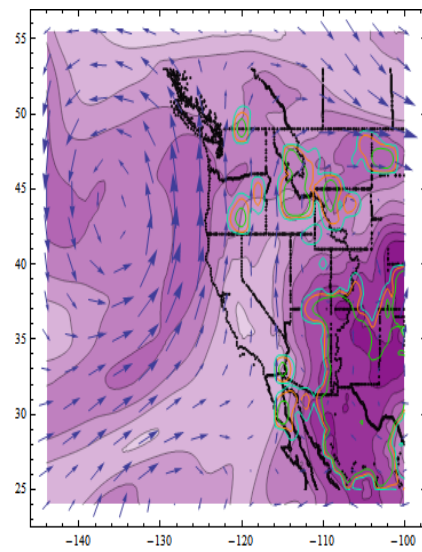
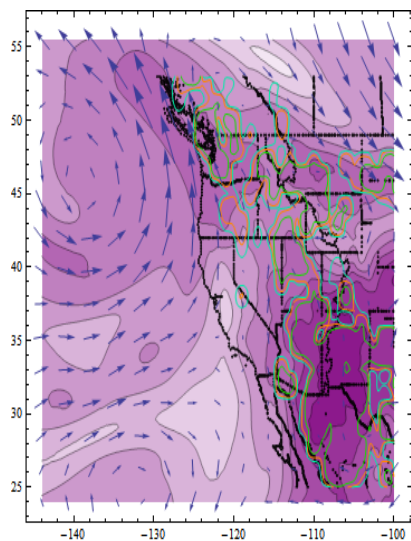
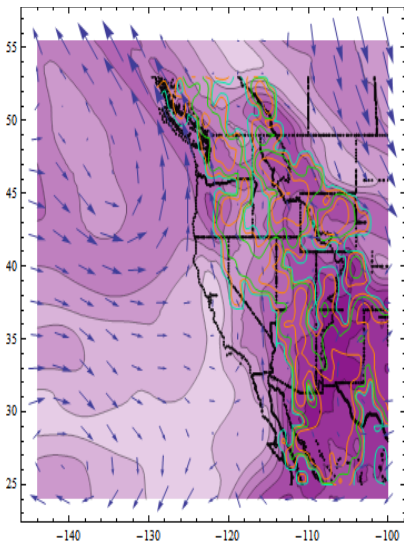
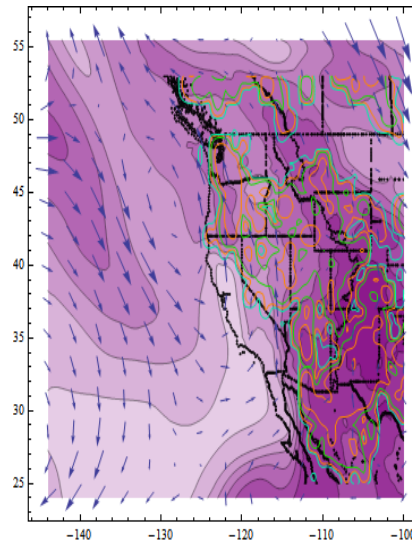
In order to investigate local influences, such as orography, on the evolution of strike activity, measured strike locations and times were plotted over a time interval encompassing the major activity of the OP event (Times for this local data are PST). Consequently, only data from 1994 through 2009 was analyzed since a significant portion earlier lightning strikes were not detected because of the lower collection efficiency of the sensors. This data was overlaid on topographical and selected local 700mb wind data. We suggest in the Elevation Distribution subsection of the **Distributions** section that cloud

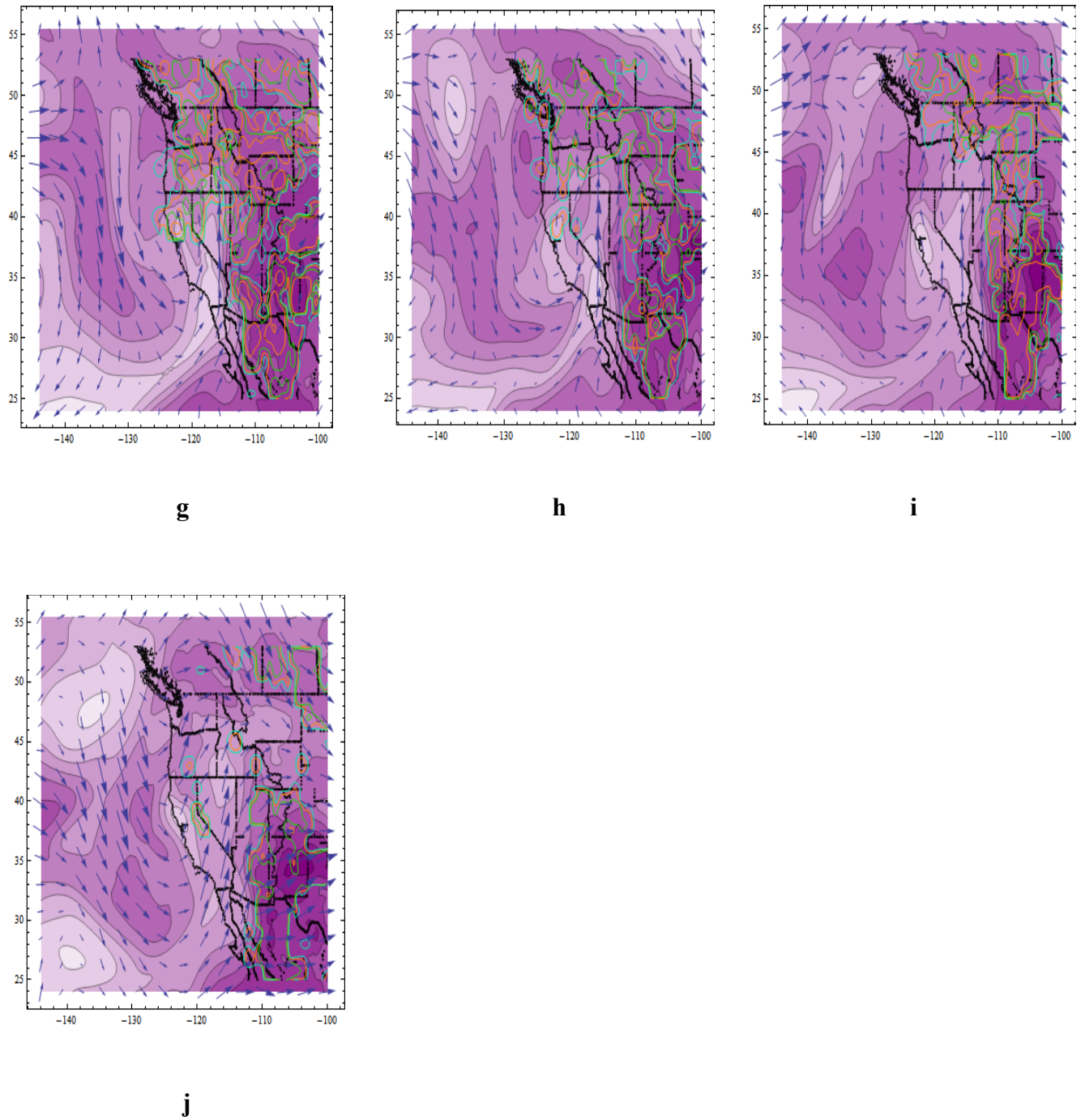
base height might also be an important determinant of storm direction; this data was analyzed for several of the case studies. For some events for which individual strike data was available, additional insight was gained by plotting individual strikes in an enlarged area extending beyond the boundaries of the OP.

Warm Season

August 4, 1999

This event was not only the largest event to occur on the OP during this 25 year study, but it was the largest event that occurred in the PNW during this period. While it peaked on the OP on August 4th, it impacted much of Western North America (WNA). We investigated a 10 day period from July 31st, through August 9th – both because of the size of the event and in order to provide a detailed description of the event since it contains many of the common elements of the other case studies. A sequence of 10 figures (Figures C1a-j), starting with July 31st illustrates the daily averaged (over GMT days) lightning intensity, and 700mb estimates of the specific humidity and winds from the NARR. The evolution of this event follows much of the behavior articulated in the section: **Intraseasonal Behavior During the Warm Season**. However, in this section we plot the 700mb wind for the same day as the lightning intensity (not the previous day) in order to use the wind direction as a predictor of the future evolution of the advected specific humidity. From the perspective of storm direction on the OP, the 700mb specific humidity and wind direction prior to the initiation of activity on the OP can be analyzed to determine the arrival direction and evolution of the event on the OP.

**a****b****c****d****e****f**



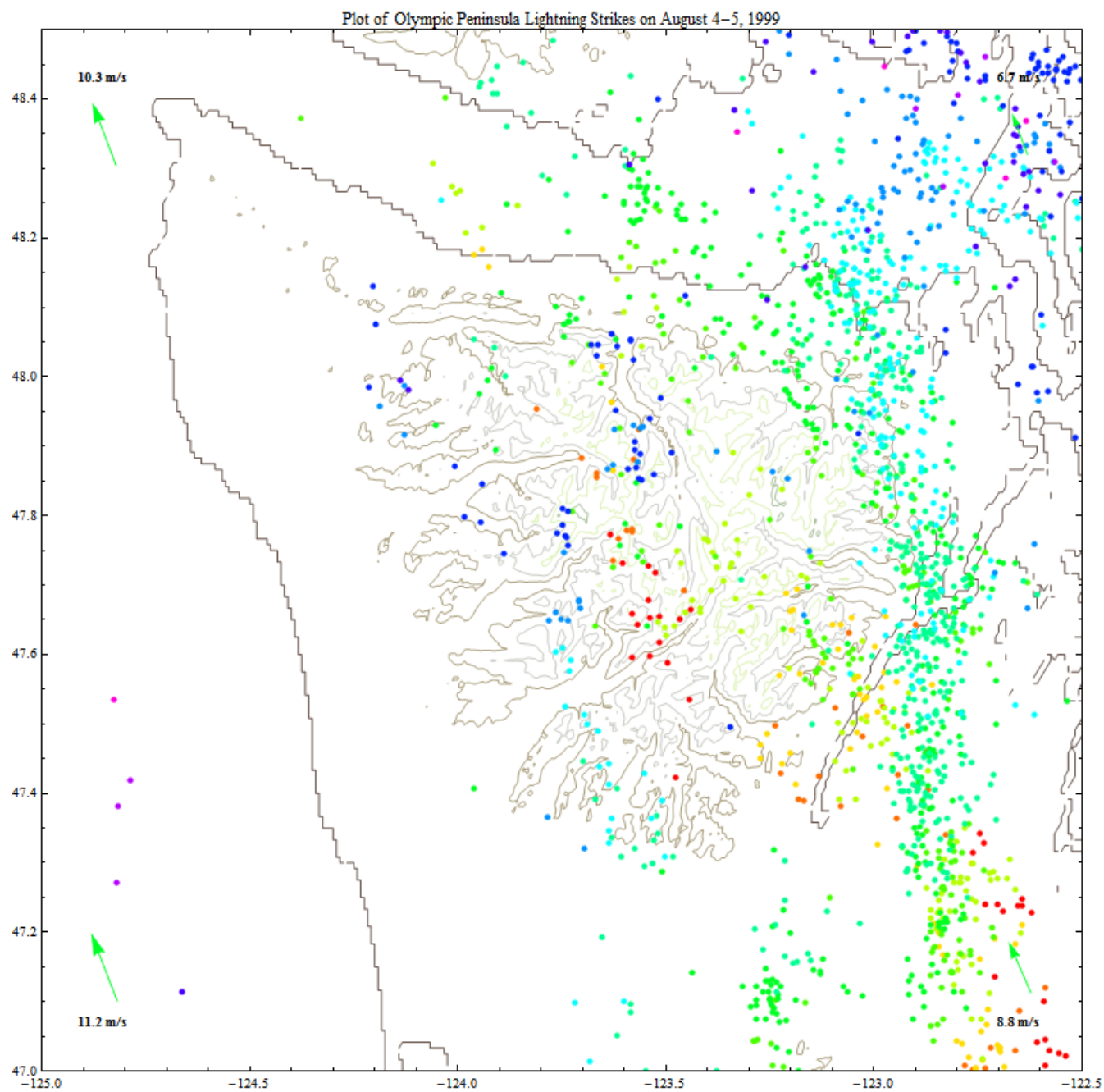
Figures C1. Ten day sequence of lightning intensity for WNA overlaid on the 700mb specific humidity for the August 4, 1999 case study starting July 31st, 1999. Lightning intensity units and contour levels are shown in Figure Caption B1. Specific humidity units and contour levels are shown in Figure Captions B3. Plots are for (a) July 31st, (b) August 1st, (c) August 2nd, (d) August 3rd, (e) August 4th, (f) August 5th, (g) August 6th, (h) August 7th, (i) August 8th, (j) August 9th).

Referring first to Figure C1a, the area of lightning activity over WNA is restricted to the region of highest specific humidity in the desert Southwest. Looking further south and east at the NARR representation of the 700mb specific humidity and wind field (not shown here), the regions of highest moisture can reasonably be inferred to come from the Gulf of Mexico. The cyclonic vortex off northern California appears to be influencing the western most tongue of this moisture and itself providing an additional source of moisture from the tropical eastern Pacific. In Figure C1b, this moisture and associated lightning activity has moved north into south central Oregon and the vortex has moved in the direction of the Oregon-California border. In Figure C1c the moisture associated with the vortex has moved north with the vortex center off of the Oregon coast and the highest specific humidity bordering the Oregon-Washington coast. In Figure C1d this region of highest specific humidity is now centered over Vancouver Island and associated with winds directed toward the north northwest. The area of lightning activity is centered along the inland side of this moisture tongue including the initiation of activity on the OP. The center of the vortex has moved northwest and associated winds along the coast have increased. In Figure C1e the vortex has become elongated along the direction of the coastline with lightning activity continuing over the OP. In Figure C1f the vortex has moved back to the southeast closer to the Oregon-Washington coast. The inland area of peak specific humidity associated with the vortex is now over the OP extending south southeast over the Oregon cascades. This is the day (August 4th PST) of highest activity on the OP. In Figure C1g the center of the vortex has moved further south to just off the northern California coast and much of the coastal lightning activity has moved south. In figure C1h the vortex has moved again north to off the northern Oregon coast and the remaining coastal activity lies to the north and south of the vortex center including activity on the OP. In Figure C1i the vortex has weakened and has become elongated with its center stretching along the coast from the Canadian boarder to central California. There is a tongue of high specific humidity over western Oregon, but the winds are weakly onshore along the Oregon coastline. In Figure C1j the vortex has dissolved with remnants of lightning activity in southern Oregon and northern California. The winds on the Washington coast are from the northwest.

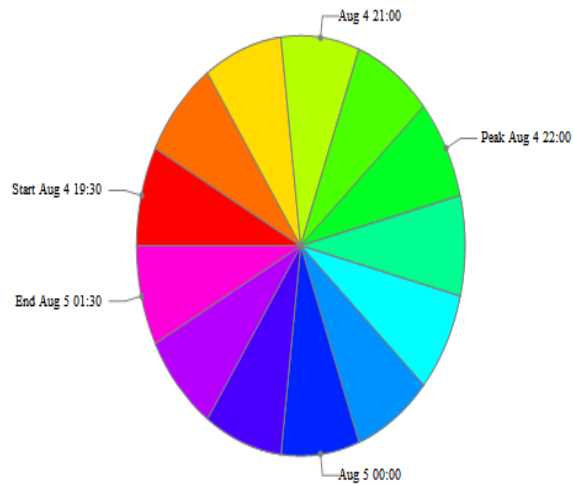
In summary, the lightning activity associated with tropical moisture was strongly affected by the motion of the 700mb cyclonic vortex lying off of the west coast. Lightning activity approaches the OP as the vortex moves up the coast, declines as it moves to the south, increases again as the vortex moves back north and disappears when the vortex dissipates and is overwhelmed by the northwest winds off

the coast.

Individual strike locations on the OP are plotted in Figure C2 for a period surrounding the time greatest activity for this event (19:30, August 4th through 1:30, August 5th (PST)). These strike locations are color coded to indicate the time of each strike in 30 minute intervals. The interval of peak activity is from 22:00 to 22:30. These strike locations are superimposed on a background of 500m contour elevation intervals. The 700mb wind velocities are also plotted at the time of peak activity, at the 4 corner locations indicated, along with the individual strikes. (In most of the following case studies the positions of the calculated wind vectors remains the same; in situations where individual strikes are plotted on an enlarged area beyond the boundaries of the OP, additional positions and times of wind vector calculations are added to illustrate the strike data illustrated.) The most notable feature on the strike progression is that they are aligned streaks along lines roughly oriented in the NNW direction.



Lightning Strike Colors in Half-Hour Increments

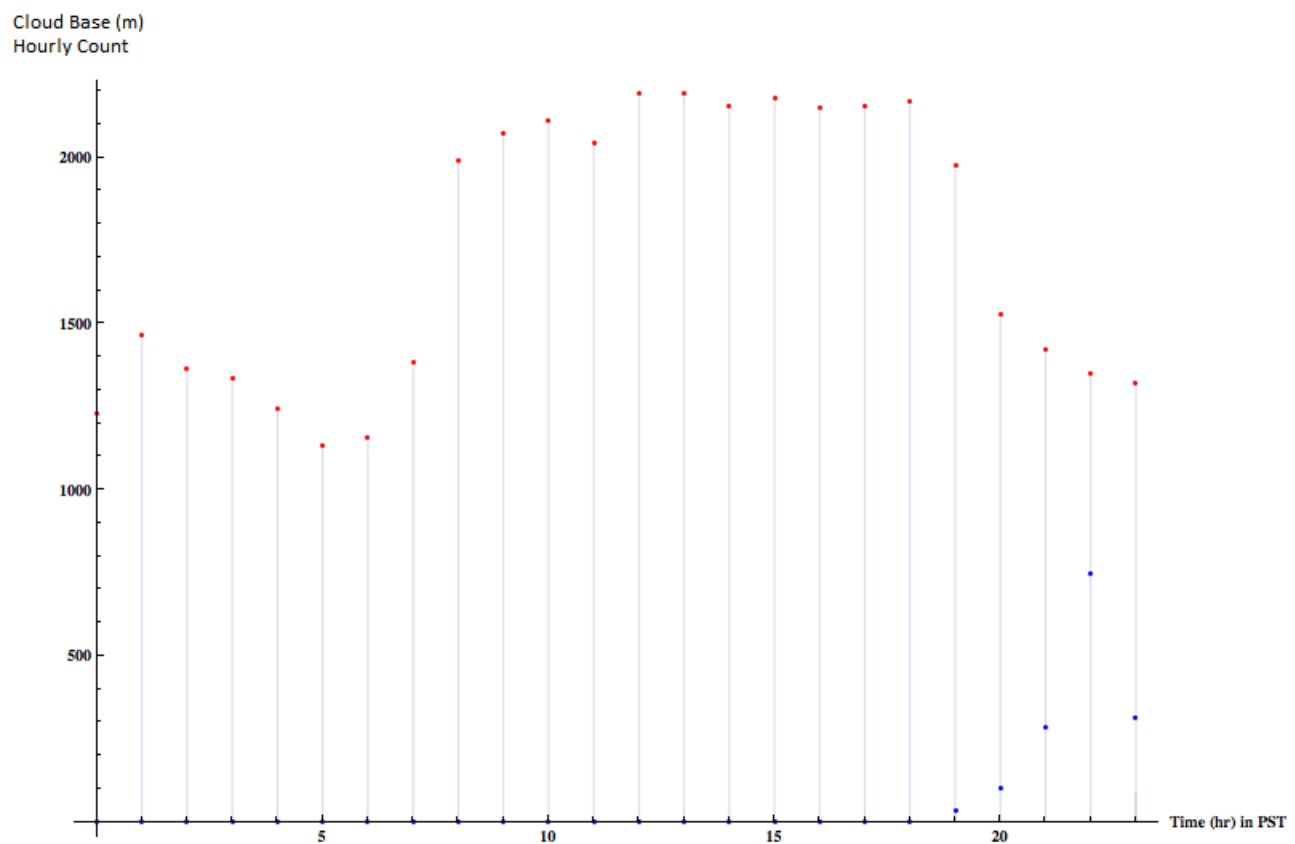


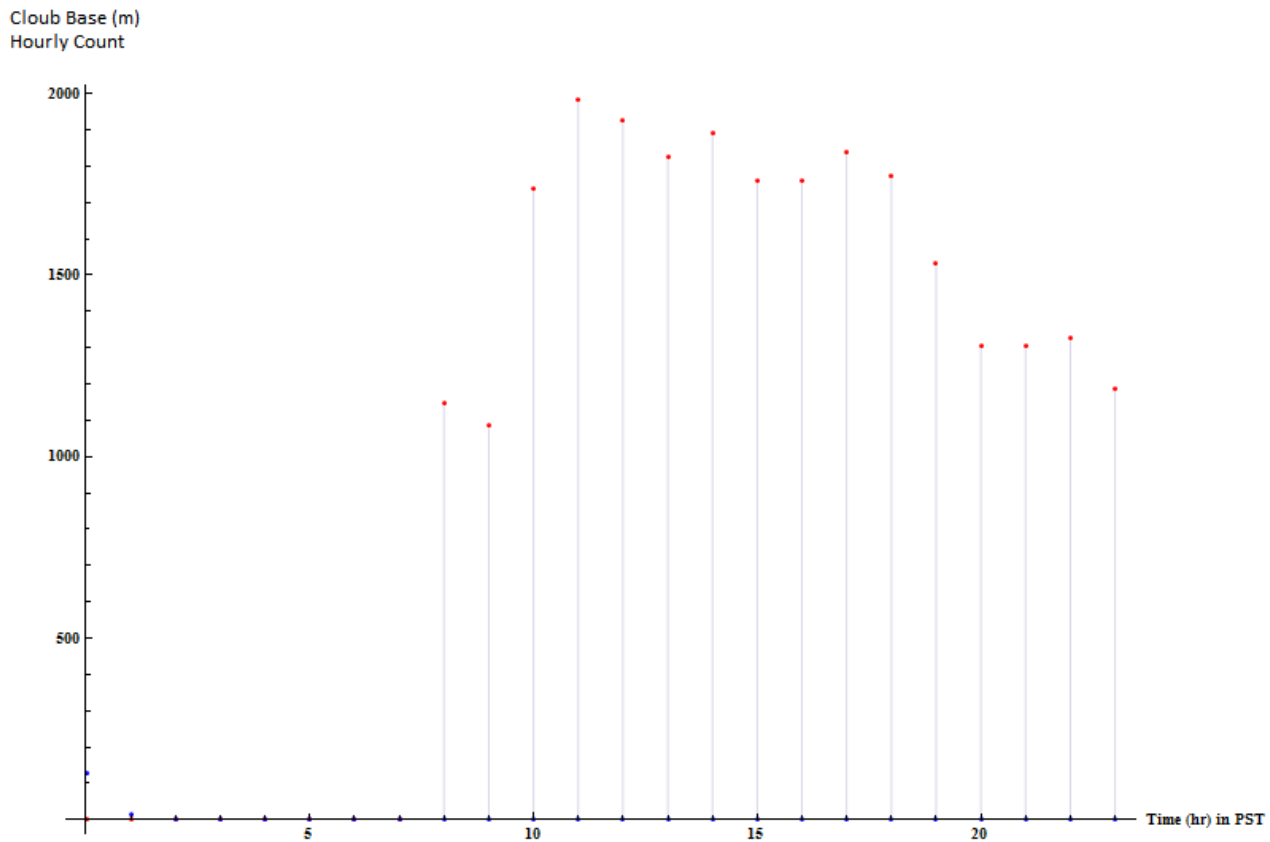
Figures C2. August 4, 1999 case study. (a) Strike locations on the OP during a period surrounding the time of peak activity. 700mb wind vectors are also displayed at the locations shown during the 30 minute interval of highest lightning activity. Elevation contours at every 500m are also shown. (b) Wind vectors and strike locations are color coded for 30 minute time increments. For example, the “Peak Aug 4 22:00” color interval begins at 22:00 and ends at 22:30. The times of the initial, final, and peak increments are also indicated on the “color wheel”.

We estimate in **Appendix C1** that the individual strike foot print of the streak, associated with the peak time interval, moves in the same direction and speed as the 700mb wind. A similar result was found by Marshall (1980) from the analysis of rainfall data for storms in England. It seems reasonable to interpret streaks as being associated with thunderstorm cells. Another characteristic of the streaks is suggested from the cloud base data.

The total hourly strike count for the OP is plotted along with cloud base height as a function of

time in Figures C3a-b. Cloud base heights are calculated exclusively from Cougar Mountain data (**Appendix A1**). As Figure C3a indicates, lightning activity is initiated about the time that the typical evening decline in cloud base occurs. Since, the vast majority of strikes are recorded below the cloud base (see the Diurnal – Elevation Distribution section), strikes occur at successively lower and lower elevations as time progresses beyond the time of initial strike activity (Figure C2). By the time of peak activity, almost all strikes are “channeled” through the Hood Canal – Puget Sound region and some activity appears to be shunted west around the higher elevation areas of the Olympic Mountains. Thus it appears that measured lightning activity direction is partially influenced by the cloud base ceiling. This phenomena is illustrated in some of the other case studies as well.





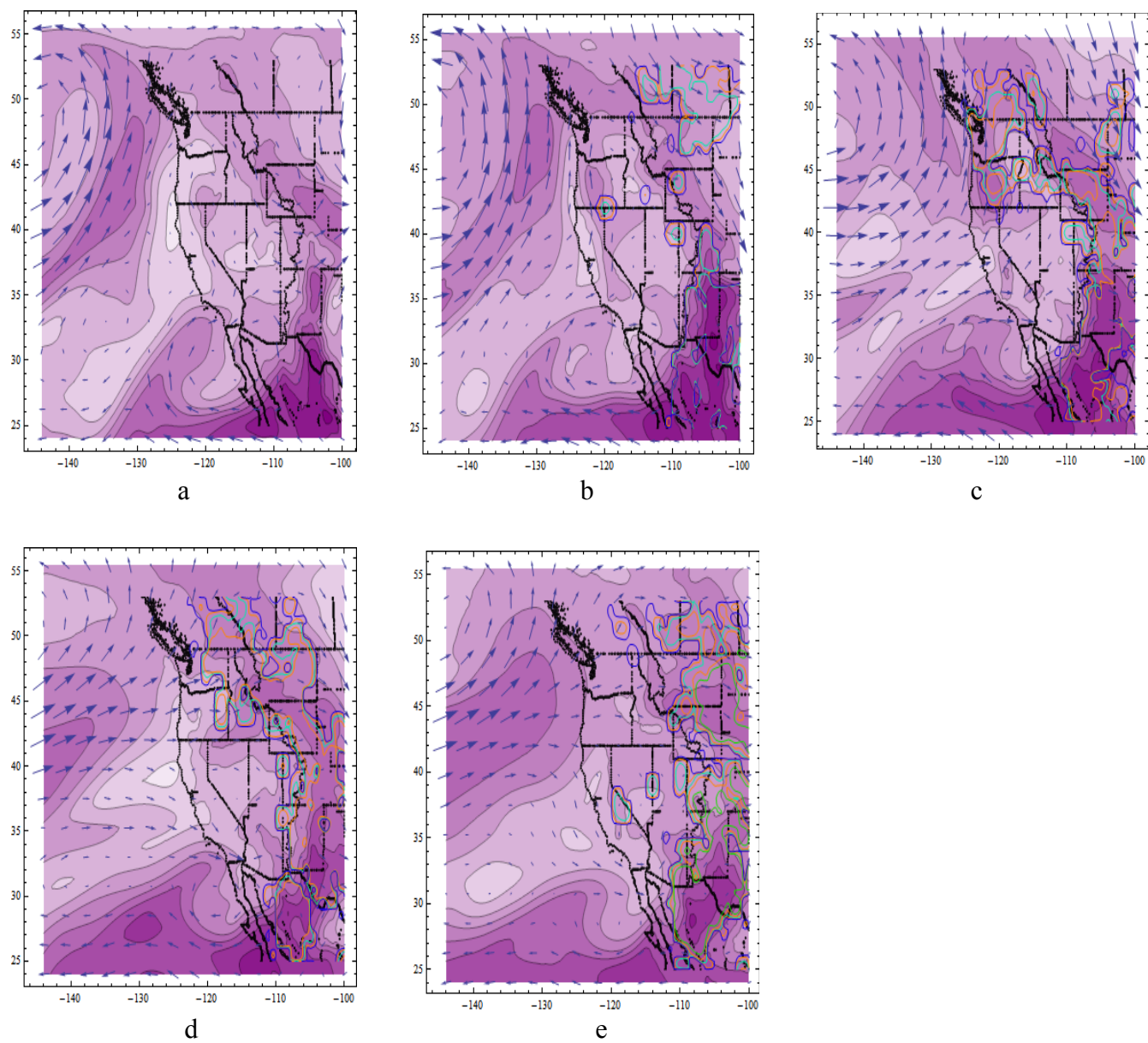
Figures C3. Hourly cloud base height estimates from the Cougar Mountain surface weather data (red dots). (For this and the following storm direction case studies, cloud base heights below the elevation of Cougar Mountain could not be estimated; in the cloud base height plots, the height values were set to 0 in at times when this situation arose). Hourly lightning strike totals near the event peak hour are also shown (blue dots – numerical OP strike count totals are on the same scale as the numerical elevation scale values). Plots for (a) August 4th, 1999, (b) August 5th, 1999.

While there are exceptions, a general northeastward displacement of the streaks is also apparent. The sequence of the 3 day evolution of the 700mb circulation pattern and specific humidity distribution

(Figures C1e, C1f, C1g) surrounding the period of peak lightning activity suggests that this displacement is associated with the details of the eastward drift of the pattern – especially the vortex off the coast to the west of the OP. This suggests that the direction of thunderstorm activity can be interpreted as the superposition of the motion of a larger storm complex - primarily influenced by the eastward circulation of the mid latitude upper tropospheric circulation - and the local motion of individual thunderstorm cells relative to the storm complex (Bluestein and Jain 1985, Marwitz 1972).

July 5, 1997

This was the second largest event to occur on the OP. A sequence of 5 figures (Figures C4a-e), starting with July 3rd illustrates the daily averaged (over GMT days) lightning intensity, and 700mb estimates of the specific humidity and winds from the NARR. It is distinguished from the prior case study, because the source of moisture resulting in the lightning activity on the OP appears to come from the tropical eastern pacific – while activity in the desert southwest appears to have originated from moisture from the Gulf of Mexico (July 3rd & 4th - Figures C4a&C4b. The sequence of these two figures illustrates the influence of the propagation of Tropical Easterly Waves on the transport of this moisture to the subtropics and temperate latitudes (Fuller and Stensrud 2000). On July 3rd peaks in these easterly waves appear to be located at 104°, 128°, and 145°W longitude (Figure C4a&C5). On July 4th, moisture from the 128° peak results in lightning strikes in southeastern Oregon. By July 5th this moisture advects over the OP along with lightning activity. This appears to be largely the result of the increased influence of a large cyclonic vortex centered to the west of the OP at approximately 145W longitude (Figure C4c). As this vortex moves east and north southwesterly winds sweep the moisture and lightning activity rapidly to the east (Figures C4c-C4e).



Figures C4. Same as Figure C1 except for the five day sequence surrounding July 5th.

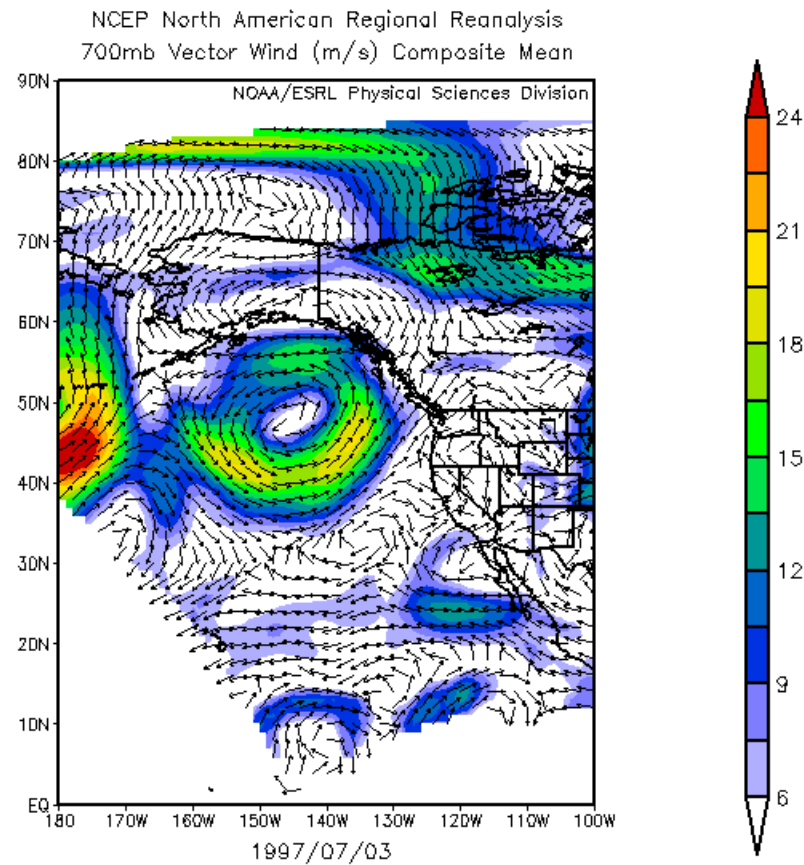
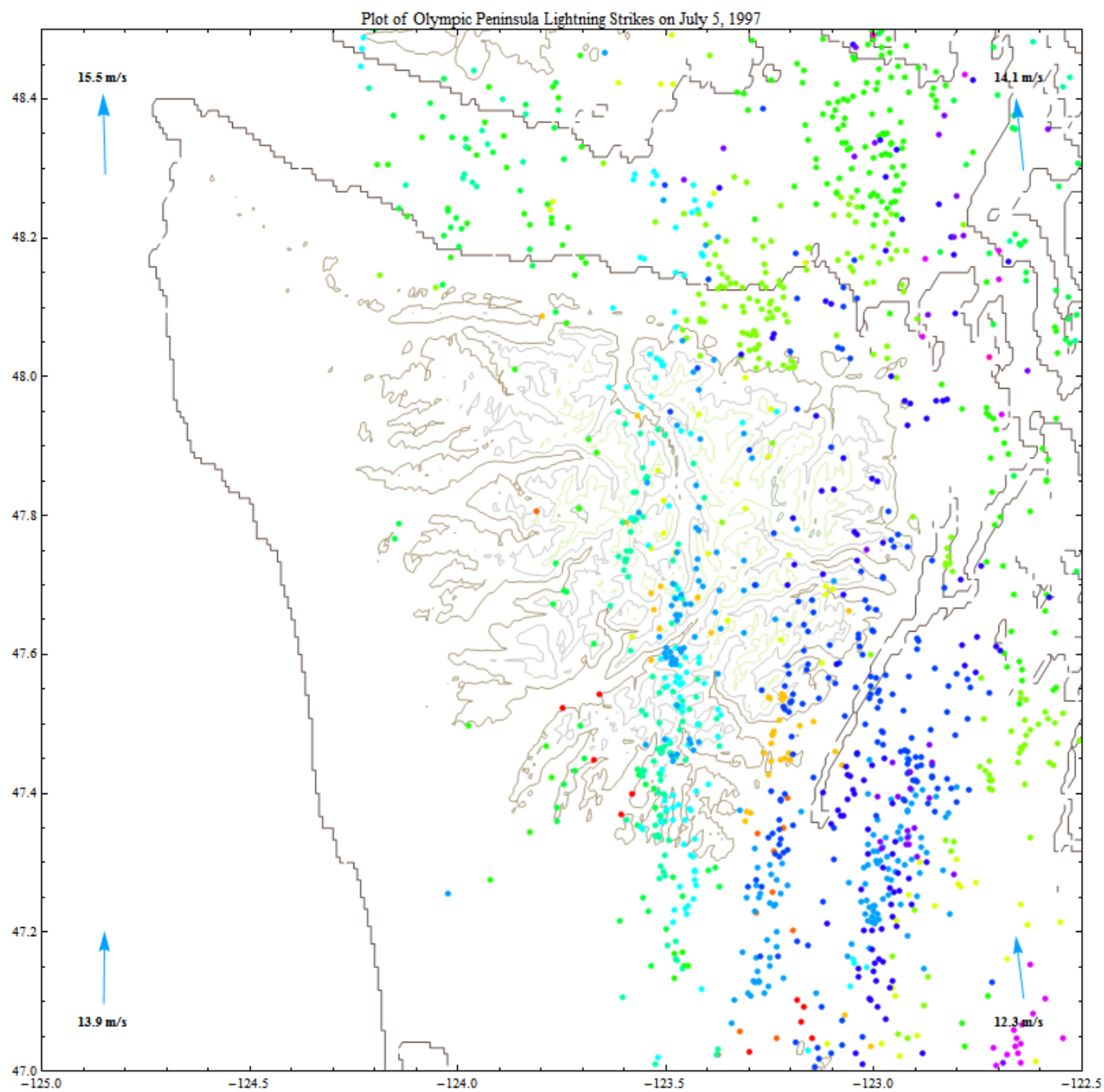


Figure C5. The 700mb NARR wind field for July 3rd, 1997.

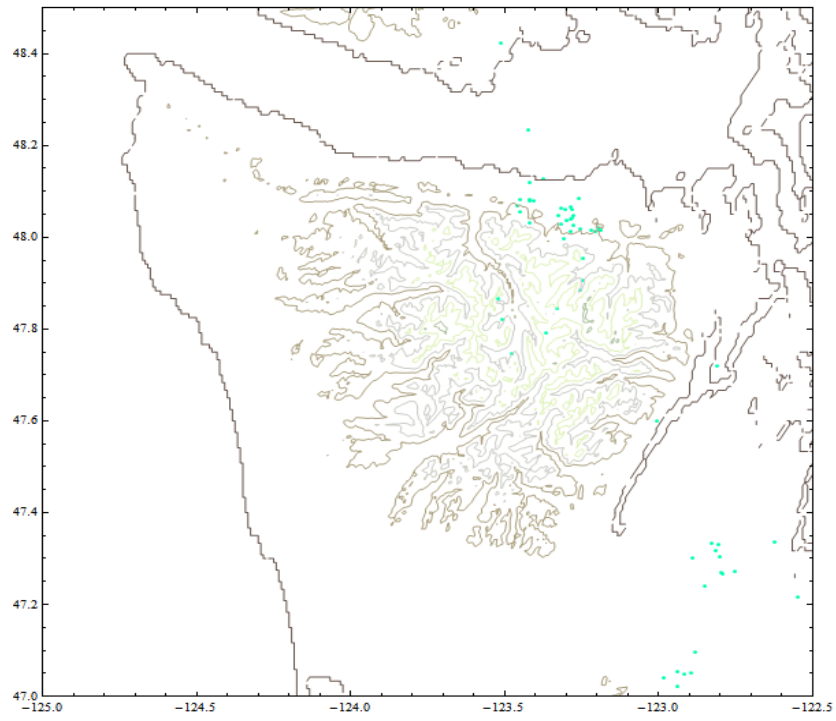
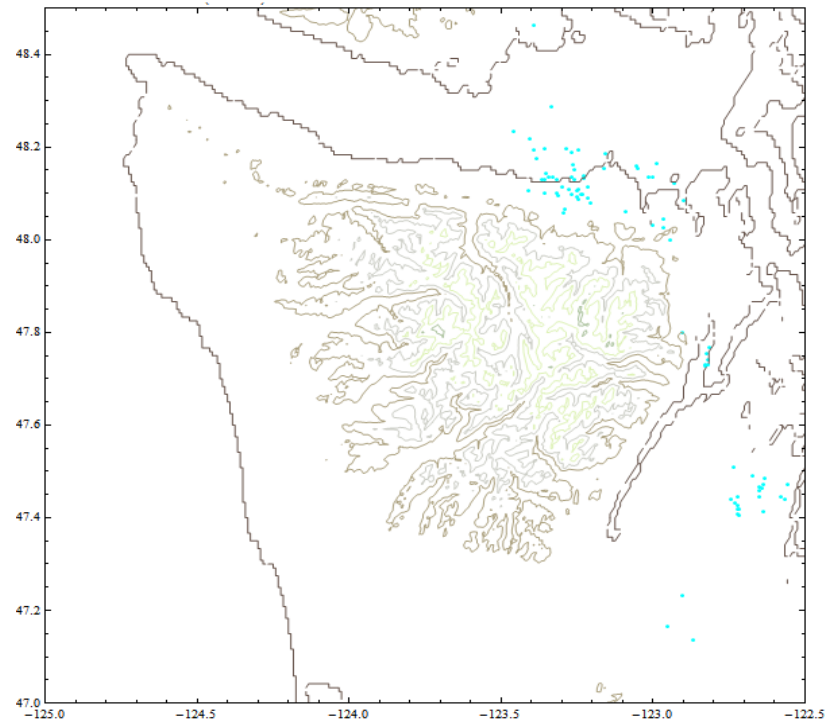
The difference in motion of this lightning event from that of the first, August 4th, 1999 case can be attributed to the difference in location motion of the 700mb cyclonic vortex for these two cases (Figures C1a-j & Figures C4a-e). In the first case, as described in more detail above, over the 10 day period, the center of the vortex, initially at approximately 136° West, 38° North, moves NNE for the first 4 days. Then it moves SE to near the coastline for the next 4 days and finally inland before dispersing on the last day of the 10 day sequence. In contrast the vortex in this second case starts on the 1st day at 144°, West, 46° (Figure C5) moves only slightly to the NNE during the study period has strengthened considerably during the peak OP lightning day as it moves north finally sweeping moisture and instability rapidly to the east by the last day of the 5 day sequence.

Referring to Figures C6 the individual strike locations are plotted for a period around the time of greatest activity, from 4:30 through 11:30 PST. The lightning streaks are again oriented along the direction of the 700mb wind which is moving almost directly to the north. A perplexing feature that can be seen in Figure C6, but, is better illustrated by plotting two 15 minute time intervals starting at 6:30 PST (Figures C7a&C7b). Contrary to the expectation that lightning strikes should occur on the less stable up slope side of the mountains (Bourscheidt et al, 2009, Fosdick and Watson 1995, Lopez et al 1997), a concentration of strikes are initiated in the 6:30 – 6:45 period on the down slope side of the Olympic mountains between Sequim and Port Angeles, Washington. Once this activity is initiated, presumably in an active thunderstorm cell, it continues as the cell moves to the north northeast (Figure C7b and plots for later time intervals (not shown)).





Figures C6. Same as Figure C2 for the July 5th, 1997 case study.

**a****b**

Figures C7a&C7b. Strike locations on the OP in two successive 15 minute time intervals near the time of peak activity. a) 6:30 – 6:45 interval. b) 6:45- 7:00 interval.

One possible explanation is that the cloud base drops rather abruptly at 7:00 (Figure C8) resulting in an effective ceiling for the elevation of detected strikes – as introduced in the previous case study. However, in this case study an additional constraint is apparently needed to explain why substantial number of strikes prior to 7:00 (including the down slope strikes shown in Figures C7a&C7b) are also generally restricted to lower elevations (C6). A more detailed examination of the 700mb specific humidity suggests that moisture is the more fundamental constraint and cloud base height is secondary importance. The daily average specific humidity plot (Figure C4c) does not indicate any difference in moisture concentration over the OP. However, the NARR data provides estimates of the 3 hour averaged specific humidity with a resolution of .3 degrees latitude and longitude. Figures C9a-c are plots of this data for the periods 4-6, 7-9, and 10-12 (PST) respectively. Figure C9a suggests that the strike distribution is primarily constrained by moisture concentration to the southeastern OP and the Hood Canal region at the time before 7:00, when the cloud base is high. In the next time period (Figure C9b) the specific humidity moves northwestward over the higher elevations of the OP, but the lower cloud base height constraint is now limiting strikes, secondarily, to the lower elevations including both the up slope and down slope sides of the OP. Finally, in Figure C9c, the strike locations are once again restricted to the southeastern corner of the OP primarily by the moisture distribution. This double constraint mechanism appears to be consistent with some of the following case studies as well. We also observed that down slope concentrations of strikes did occur fairly commonly (relative to the number of up slope concentrations) in the other of these cases.

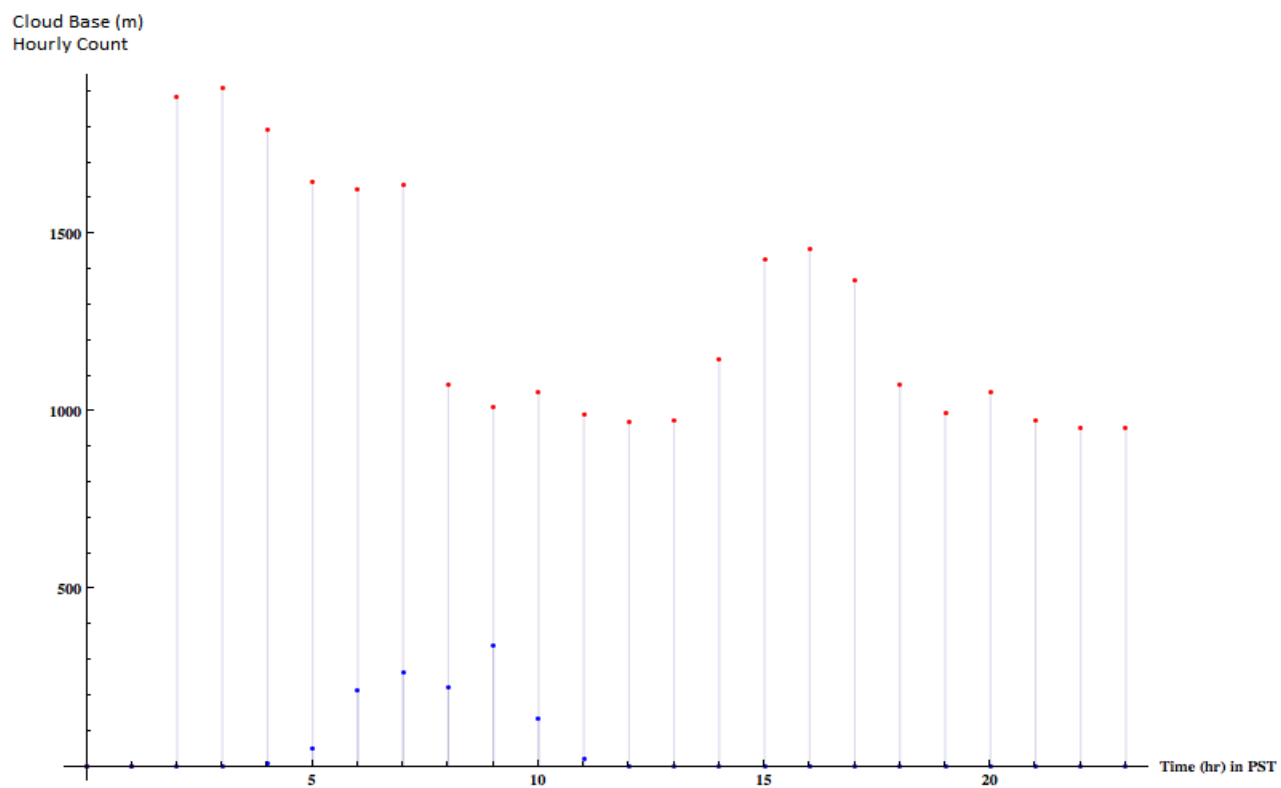
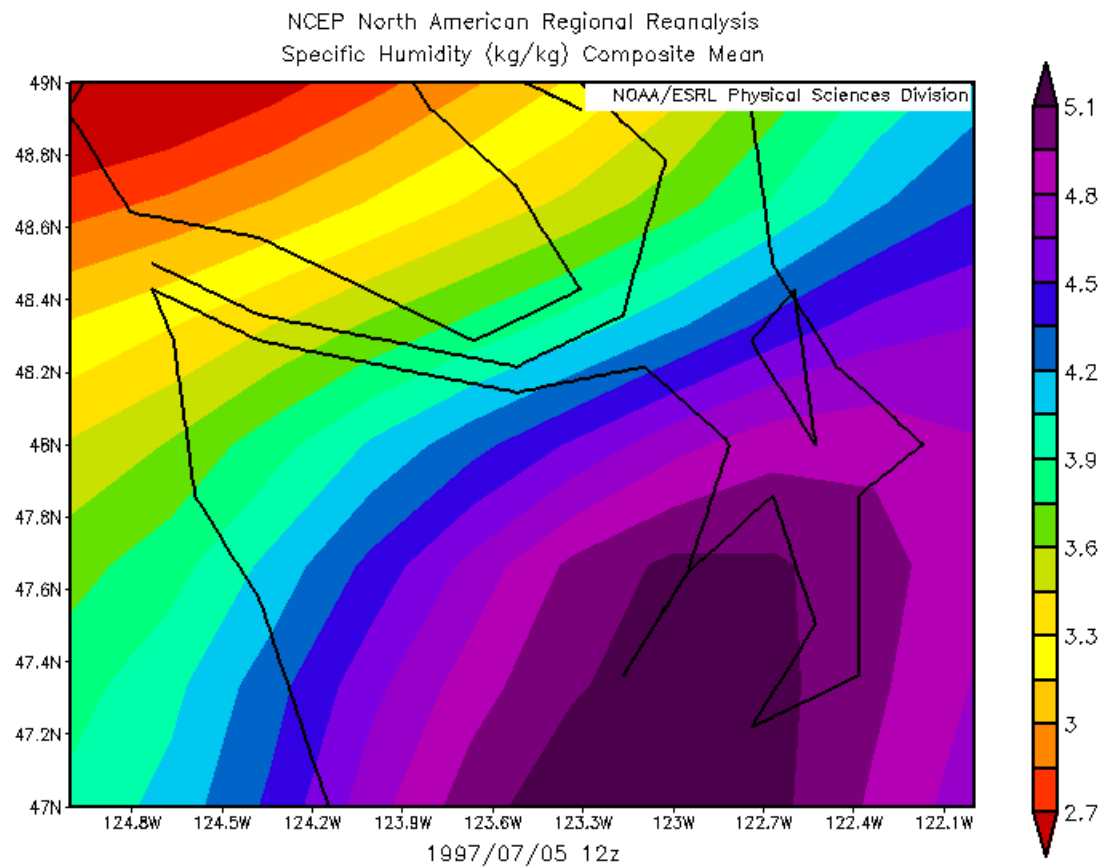
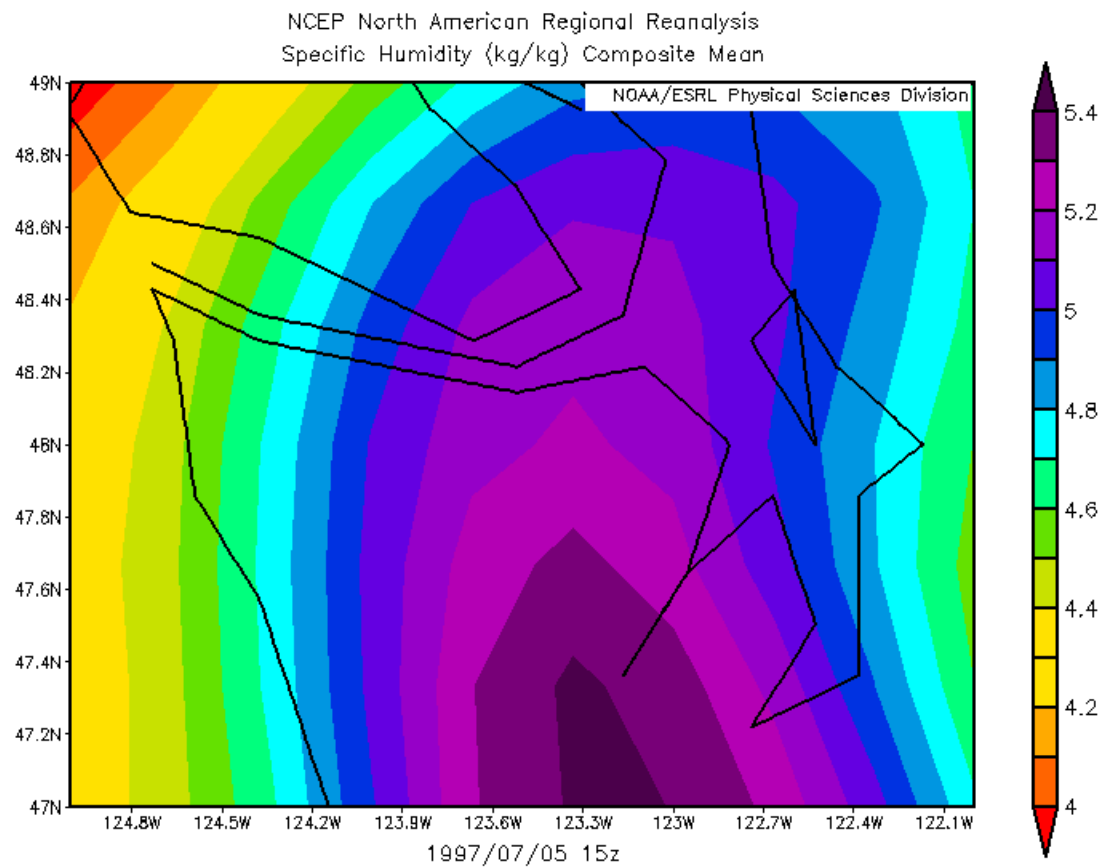
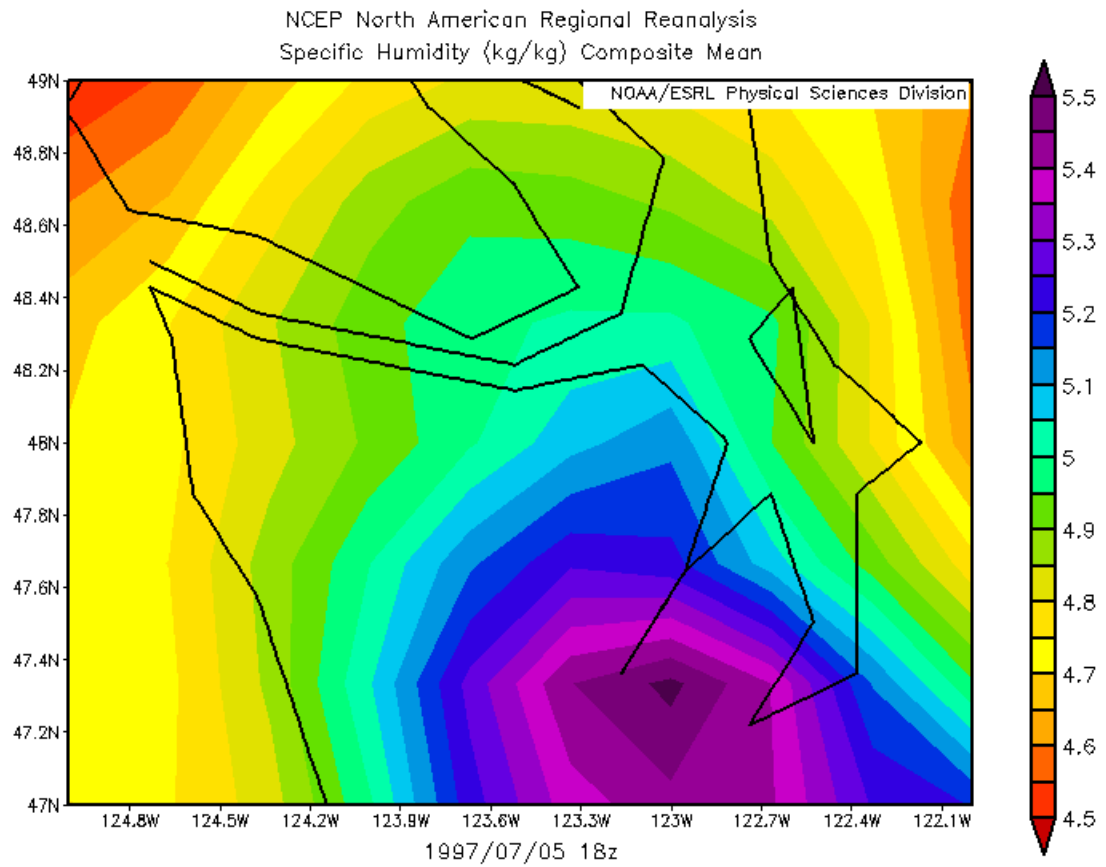


Figure C8. Same as Figure C3 for July 5th, 1997.

**a**



b

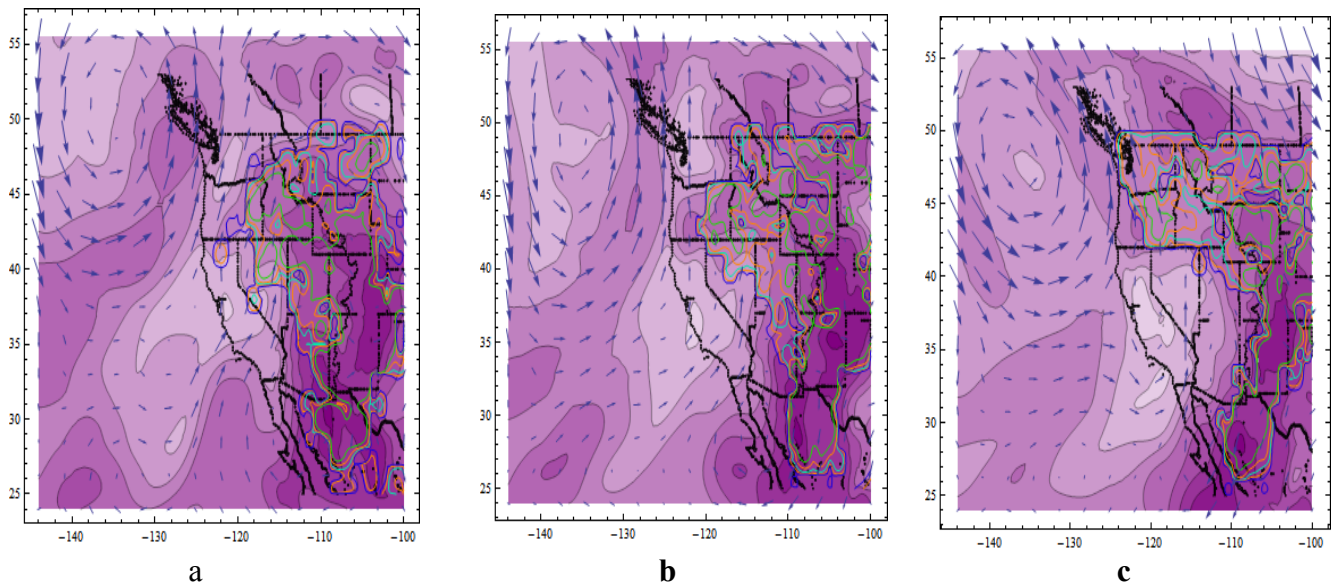


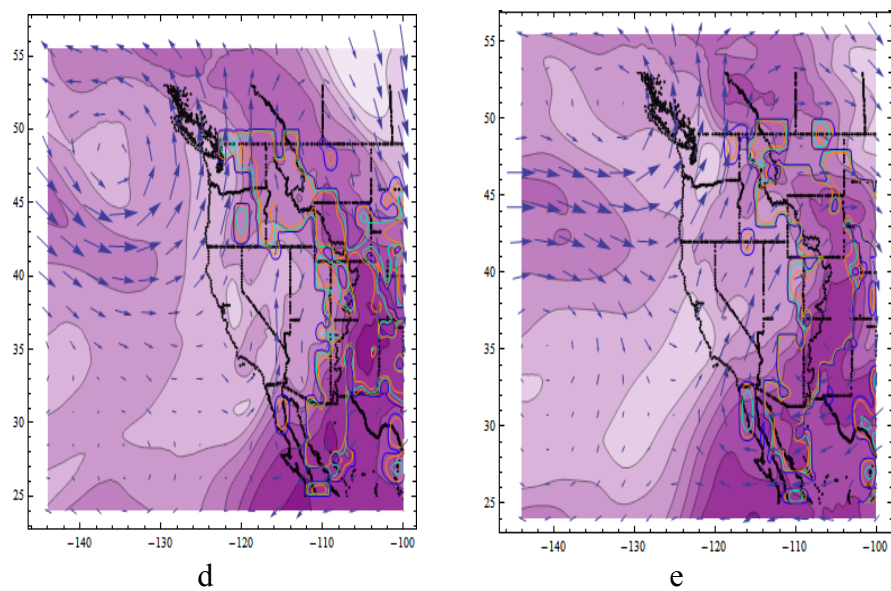
c

Figure C9. The 700mb NARR 3hr averaged specific humidity plotted with .3 degree latitude and longitude resolution for July 5th, 1997. Plots for times (a) 12-14Z, (b) 15-17Z, (c) 18-20Z.

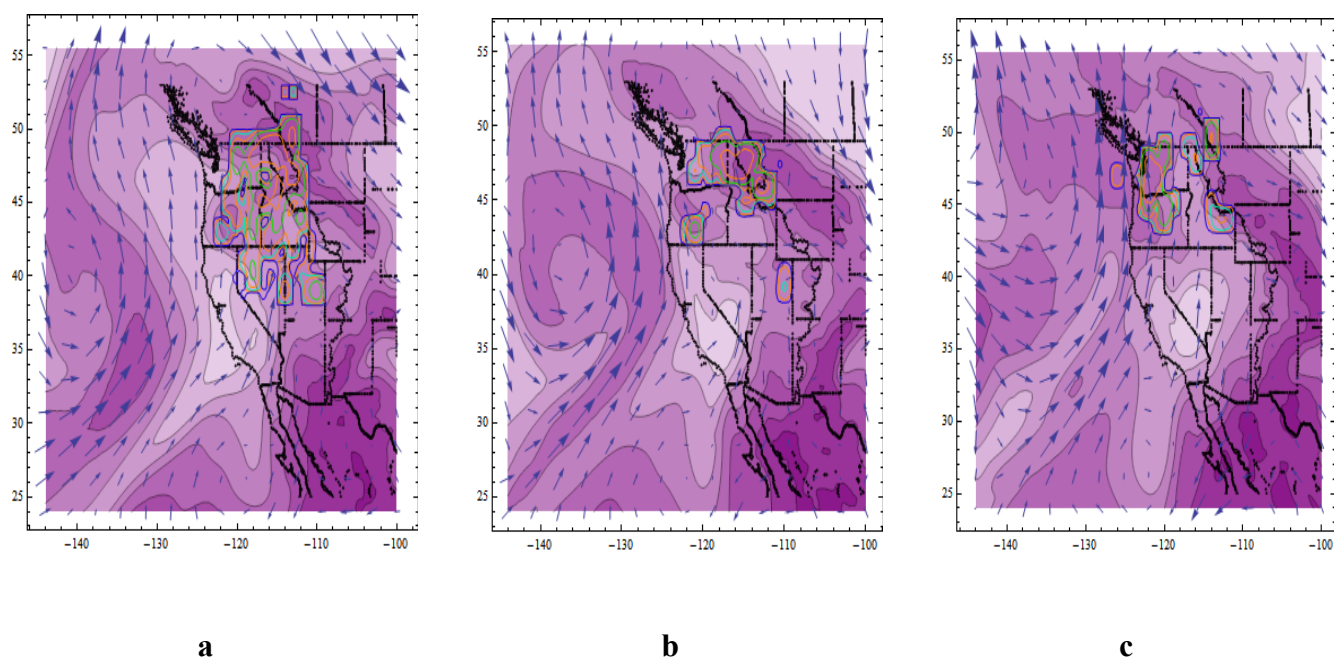
August 3, 1994 and July 2, 2008

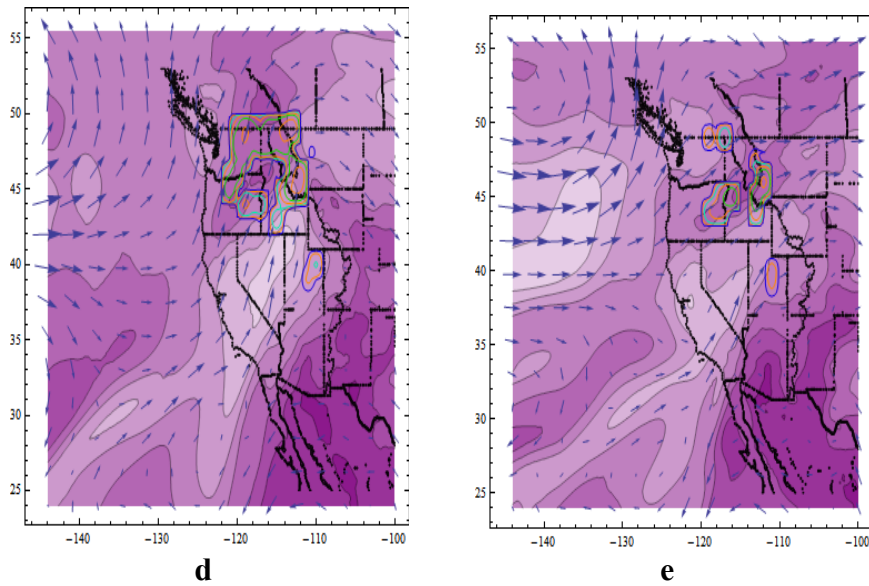
These two events share the similarity that the strikes are constrained to lower elevations, but the location and direction of the events are different. The daily average evolution of the August 3rd event is illustrated in Figures C10a-e, and Figures C11a-e for the July 2nd event. Figures C10a & C11a indicate a quite similar initial structure in so far as the moisture and lightning activity which reaches the OP are concerned. Both indicate moisture and instability in eastern Oregon which is generally advecting to the north. However, the important factor which differentiates the two is the position and strength of the 700mb cyclonic eastern Pacific vortices. The vortex in Figure C10a is stronger and centered off of the coast near the United States Canada Border. The vortex in Figure C11a is weaker – lying off the northern California coast. The following day the first vortex moves slightly south and the second moves closer to the coast and slightly north. On the third day (the day of maximum lightning activity on the OP), the first vortex has moved south off the Washington coast and the second vortex has moved northwest (at least beyond 150°W (not shown)) - although a northerly flow over the OP persists. After the peak day, both circulations result in a northeasterly flow in the vicinity of the OP and the moisture and lightning activity is swept in this direction.





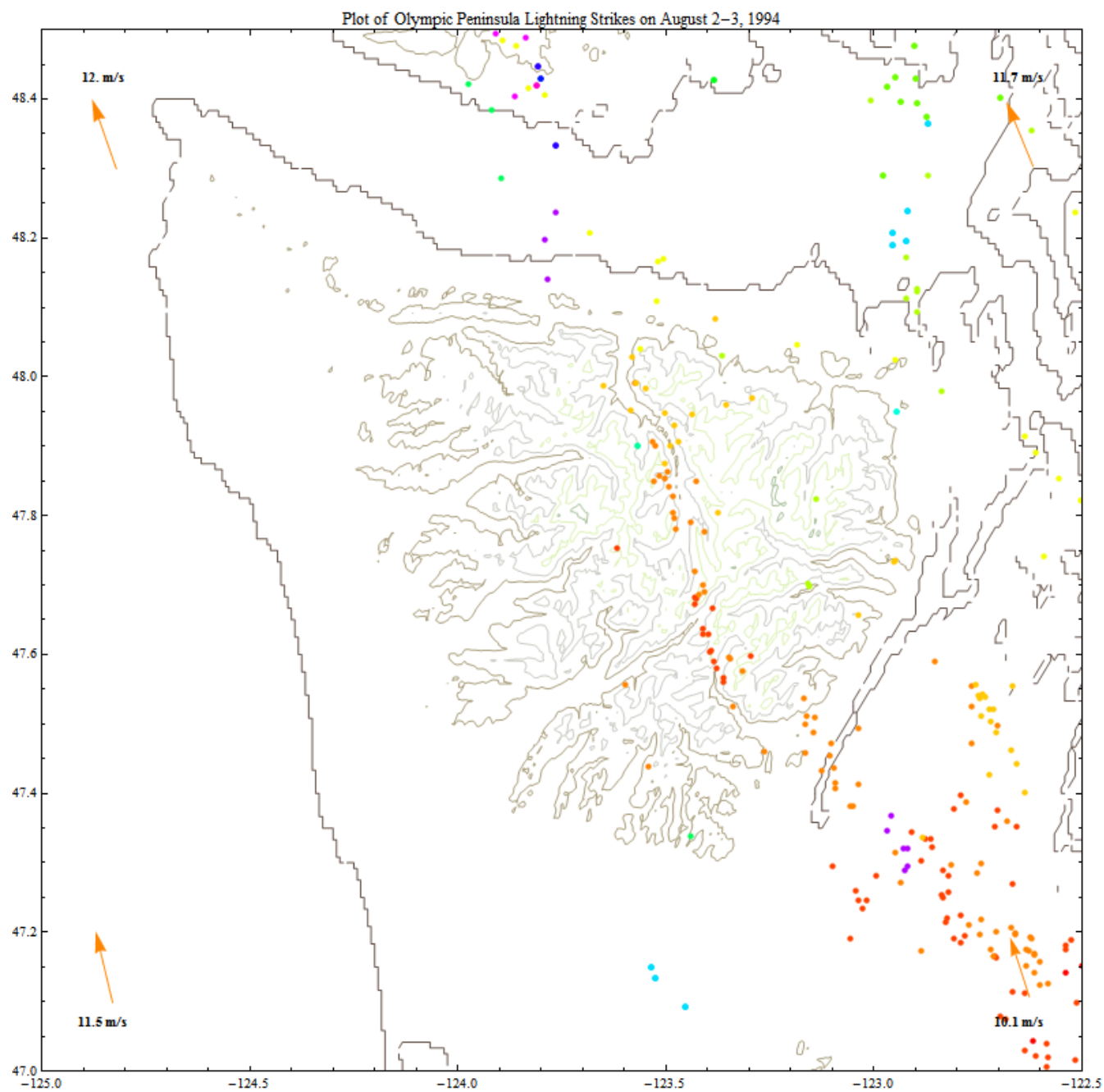
Figures C10. Same as Figure C1 except for the five day sequence surrounding the August 3rd, 1994 case study.

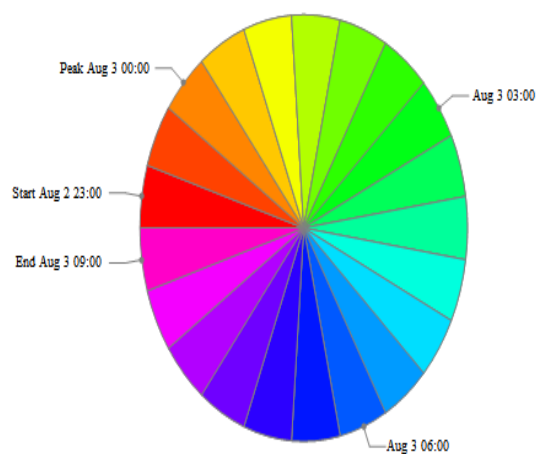




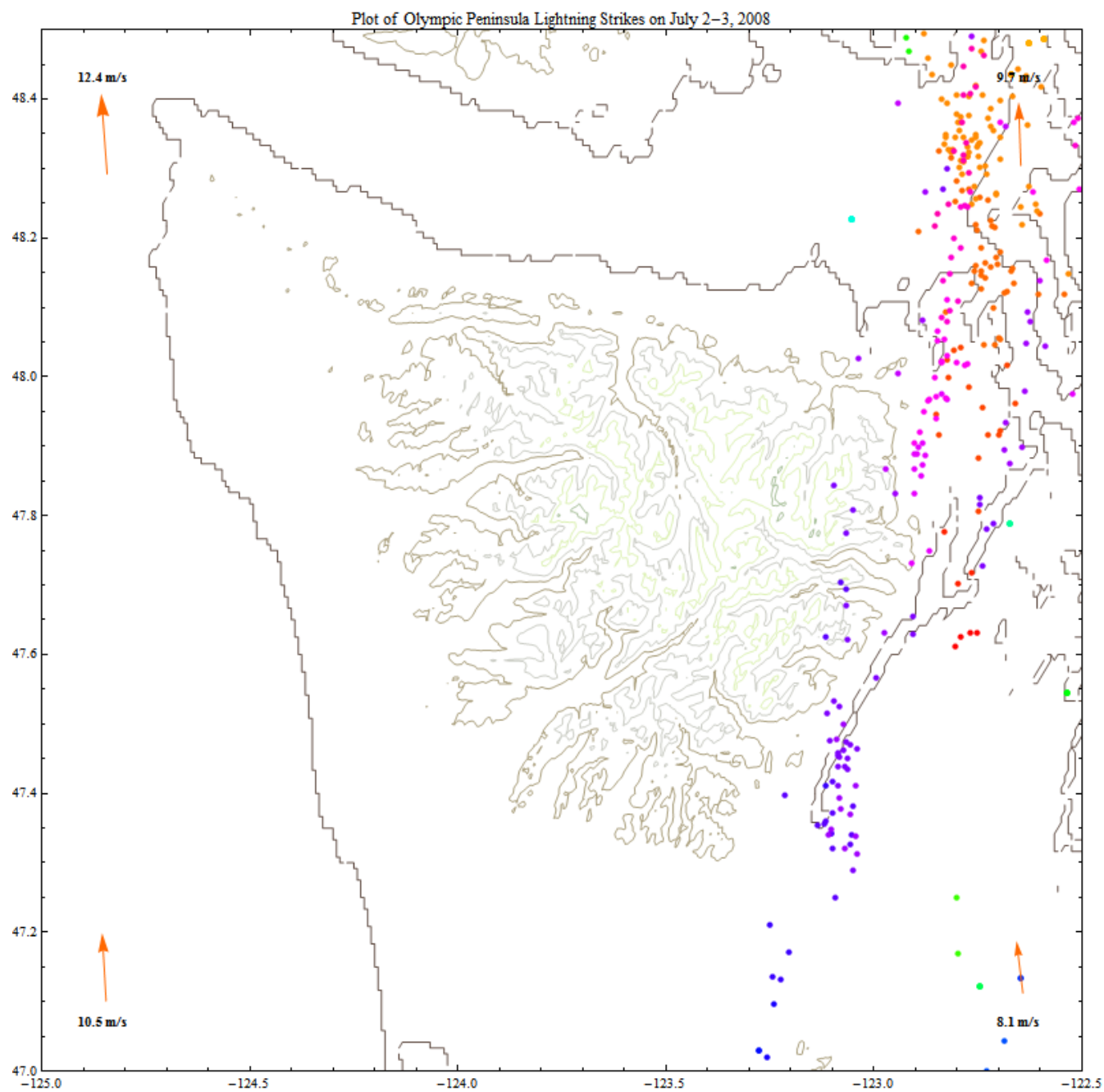
Figures C11. Same as Figure C1 except for the five day sequence surrounding the July 2nd, 2008 case study.

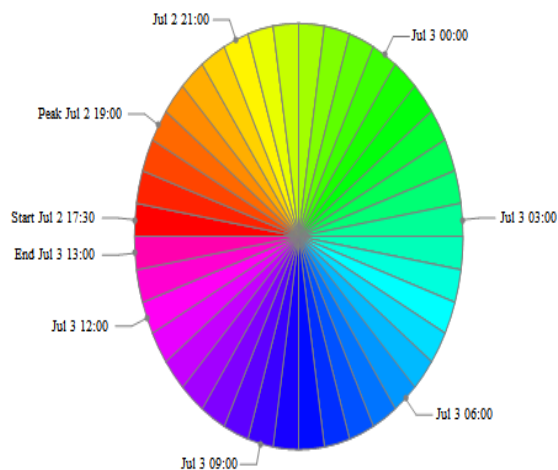
Comparing the detailed peak strike activity for the two events on the OP (Figures C12 and Figures C13), the slight difference in the 700mb wind direction resulting from the difference in the circulation pattern (Figures C10c and C11c) appears to be important in differentiating the two thunderstorms evolutions. The wind direction at the peak activity time for the August 3rd event appears to be consistent lightning strike streaks directly across the middle of the Olympic Mountains, through the Skokomish drainage on the upslope side and through the Elwha drainage on the downslope side. At later times some of the activity is confined to the Hood Canal region. The wind at the peak time for the July 2nd event appears to be consistent with the direction of the streaks confined to the Hood Canal region. (The activity indicated in C11c off the OP coast is too far west to show up in the OP plot).





Figures C12. Same as Figure C2 for the August 3rd, 1994 case study.

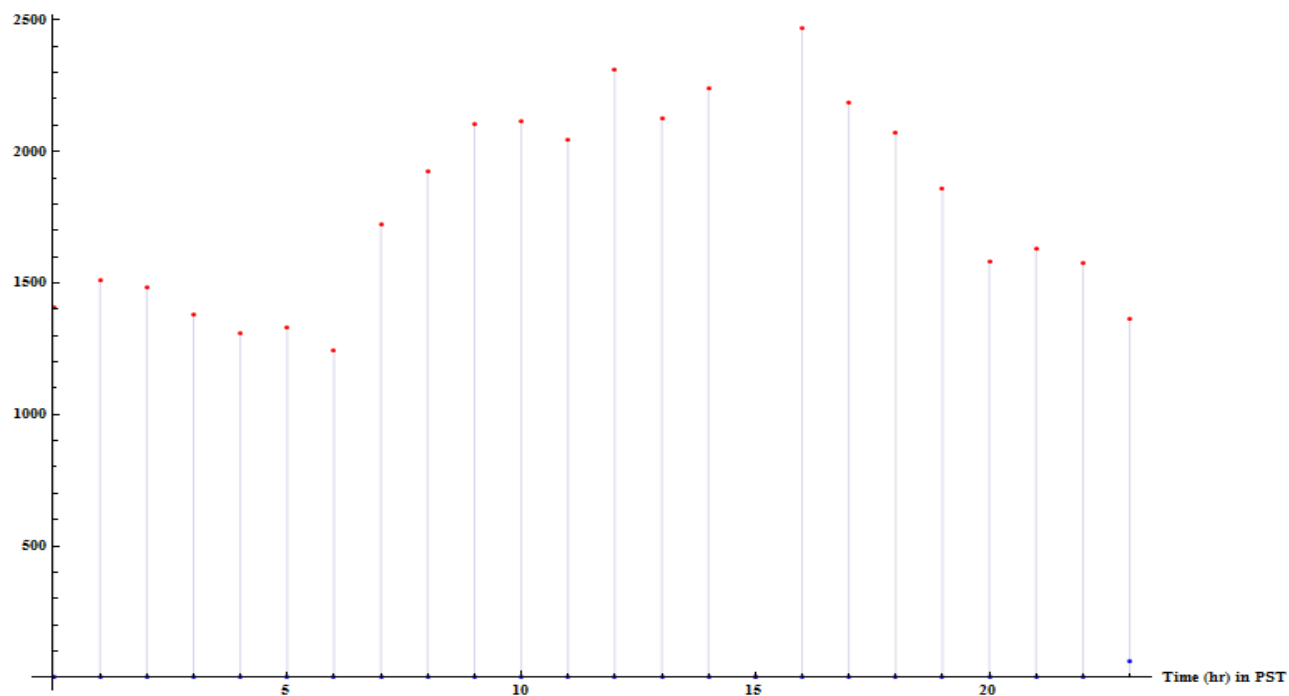




Figures C13. Same as Figure C2 for the July 2nd, 2008 case study.

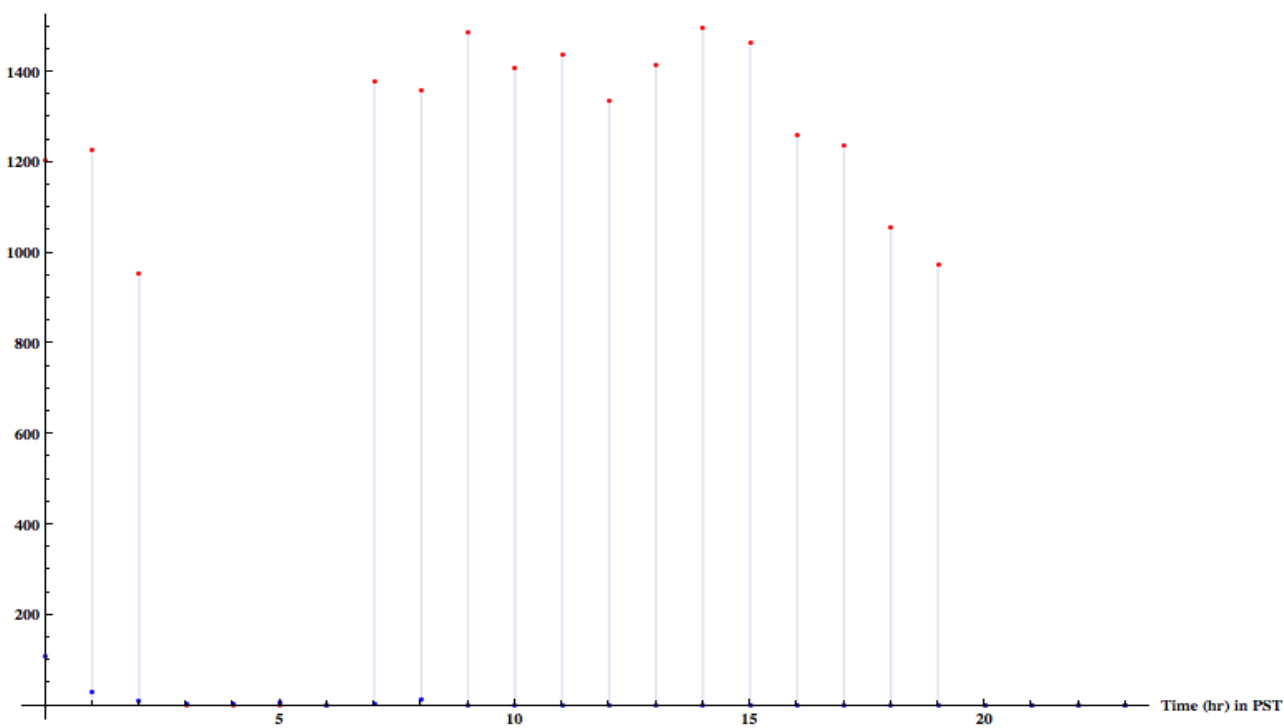
A detailed examination of the elevation contours of both plots indicates that strike activity is almost exclusively confined to values below 1500m with most strikes below 1000m (Figures C14a&b and Figures C15a&b). This additional constraint appears to result from the cloud base height ceiling introduced in the August 4th, 1999 case study. The only times that the cloud base is above 1500m is the early hours of activity on July 2nd (Figure C15a). All elevations are below 1000m in the vicinity of the strike streaks for this case study. It is unusual for the strikes to be confined to the major river drainages for the August 3rd case (Figure C14a). It would appear that the low nighttime cloud base is responsible for this strike path progression.

Cloud Base (m)
Hourly Count



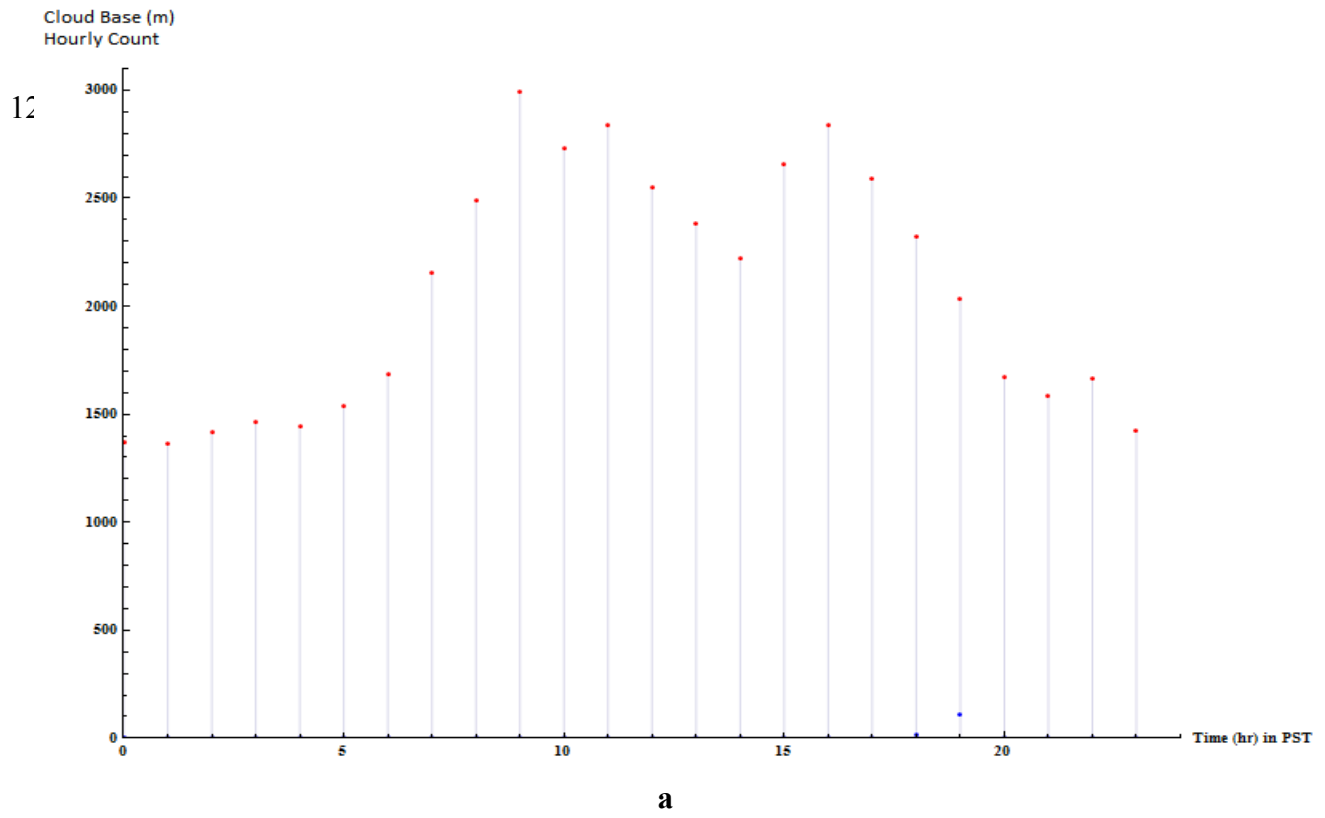
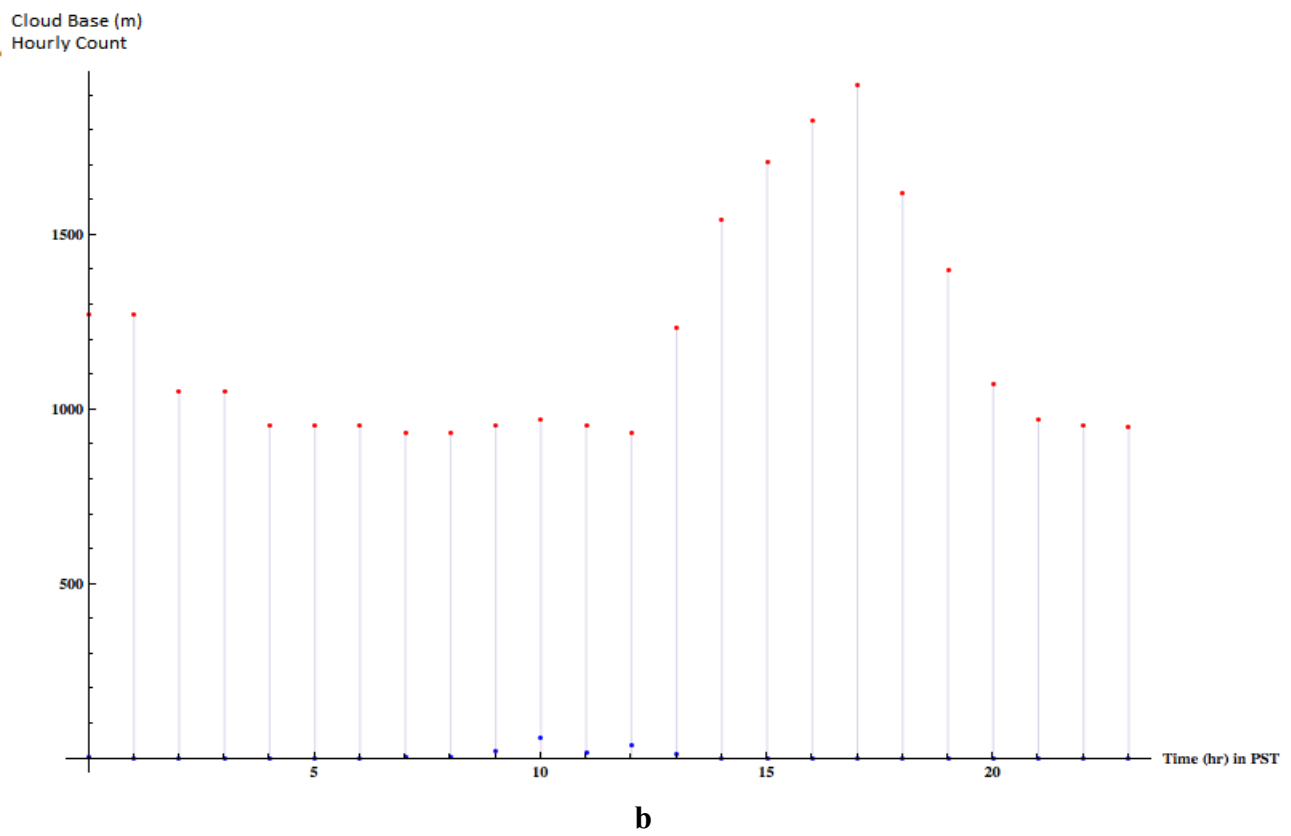
a

Cloud Base (m)
Hourly Count



b

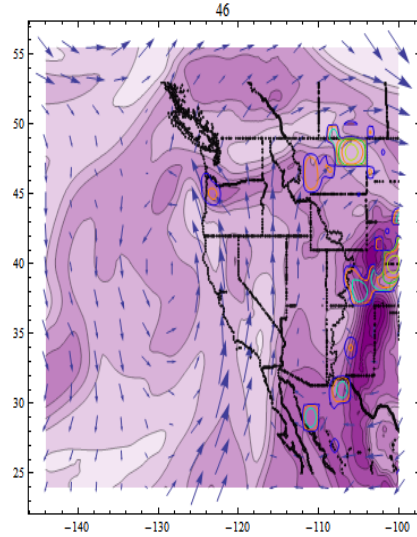
Figures C14. Same as Figures C3 for (a) August 2nd, 1994 and (b) August 3rd, 1994.



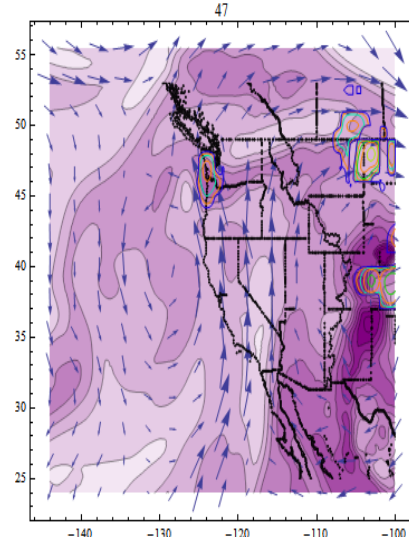
Figures C15. Same as Figures C3 for (a) July 2nd, 2008 and (b) July 3rd, 2008.

June 21, 2005

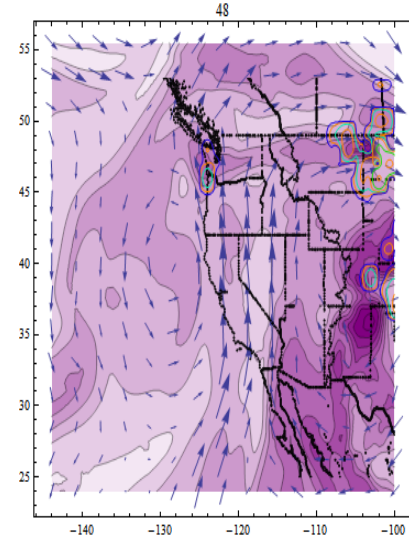
This event was chosen as the final major event case study because individual strike data was available for western North America during this time period. The data was first aggregated in 3hr intervals coinciding to the finest time scale of the NARR 700mb wind and specific humidity data. Ten consecutive 3hr time intervals are plotted, using the same units as the previous case studies, in Figures C16a-j starting at June 20th 20:00 and ending June 21st 23:00. Times for these plots are computed for local PST in order to focus on the local diurnal cycle for the OP. Referring to Figure C16a, moisture from the tropical eastern pacific appears to be entrapped in a rather stable 700mb cyclonic vortex just of the Oregon California border. This vortex extends vertically to the 250mb level and is located between two branches of the jet stream for 5 consecutive days surrounding the June 20th 20:00 through June 21st 23:00 time period (Figures C17a-e). This vortex remains remarkably stable as is often the case when such a vortex extends through the depth of the troposphere. Images from the GOES10 satellite suggest that this moisture originated from the central Pacific Inter Tropical Convergence Zone (Figure C18). An area of lightning activity in NW Oregon in a local region of high specific humidity would be expected to move in the northwest direction resulting from advection due to the 700mb winds (Figure C16a). The 700mb circulation pattern appears to be largely determined from the cyclonic vortex. Notice also that the 700mb winds just to the north of the OP are moving to the north east. Three hours later the region of strike activity has intensified and moved into the southwestern OP (Figure C16b). In the next 3 hours the intensity has declined as the region of high specific humidity moves further to the northwest (Figure C16c). Three hours after that, at 5:00, June 21st, activity has dramatically declined as the area of highest specific humidity moves offshore (Figure C16d). By 14:00 June 21st activity has once again resumed on the southwestern OP (Figure C16g). Probably the initial decline in activity and this second wave of activity, continuing through 17:00 (Figure C16h) can be attributed to the vertical instability driven by the diurnal cycle. By 23:00 the vortex has evolved into a trough just offshore and the OP wind direction is from the southwest. The remaining lightning activity has moved east into the Rocky Mountains (Figure C16j).



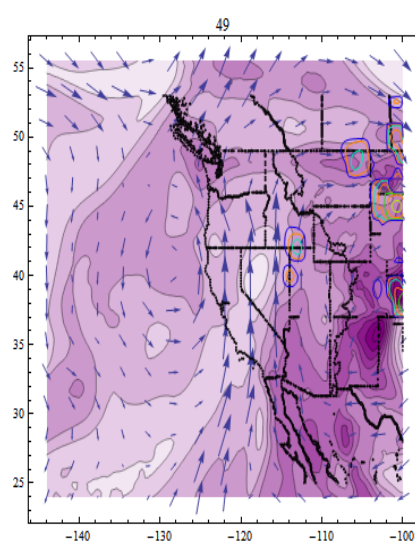
a



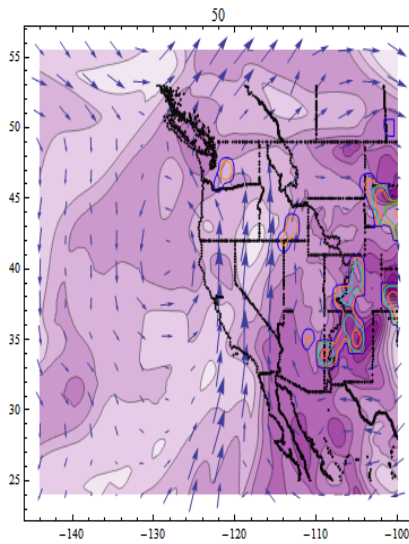
b



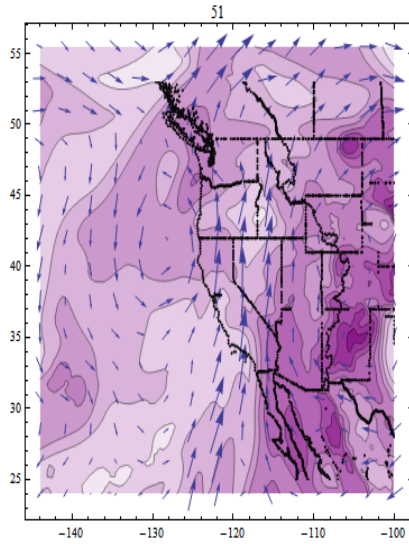
c



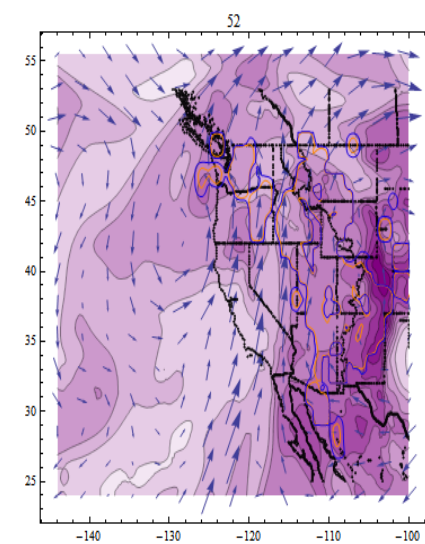
d



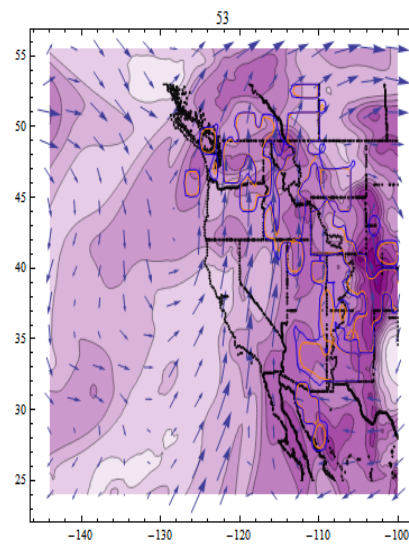
e



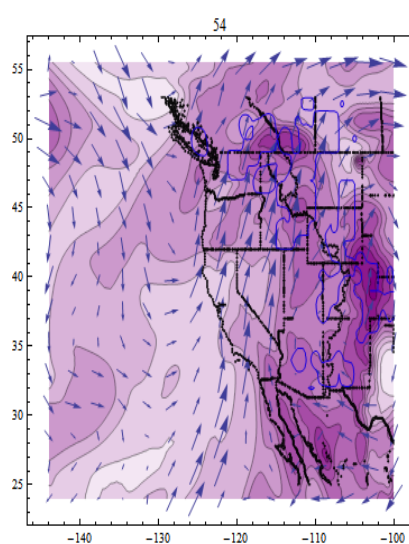
f



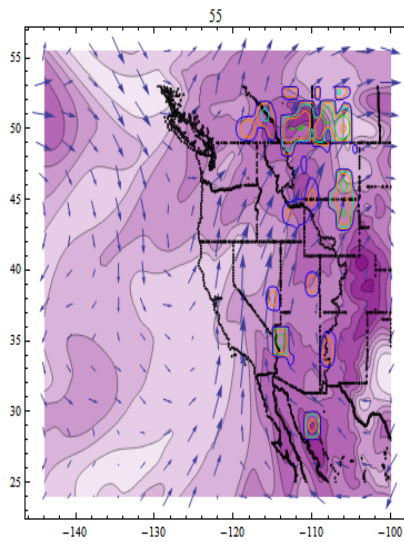
g



h

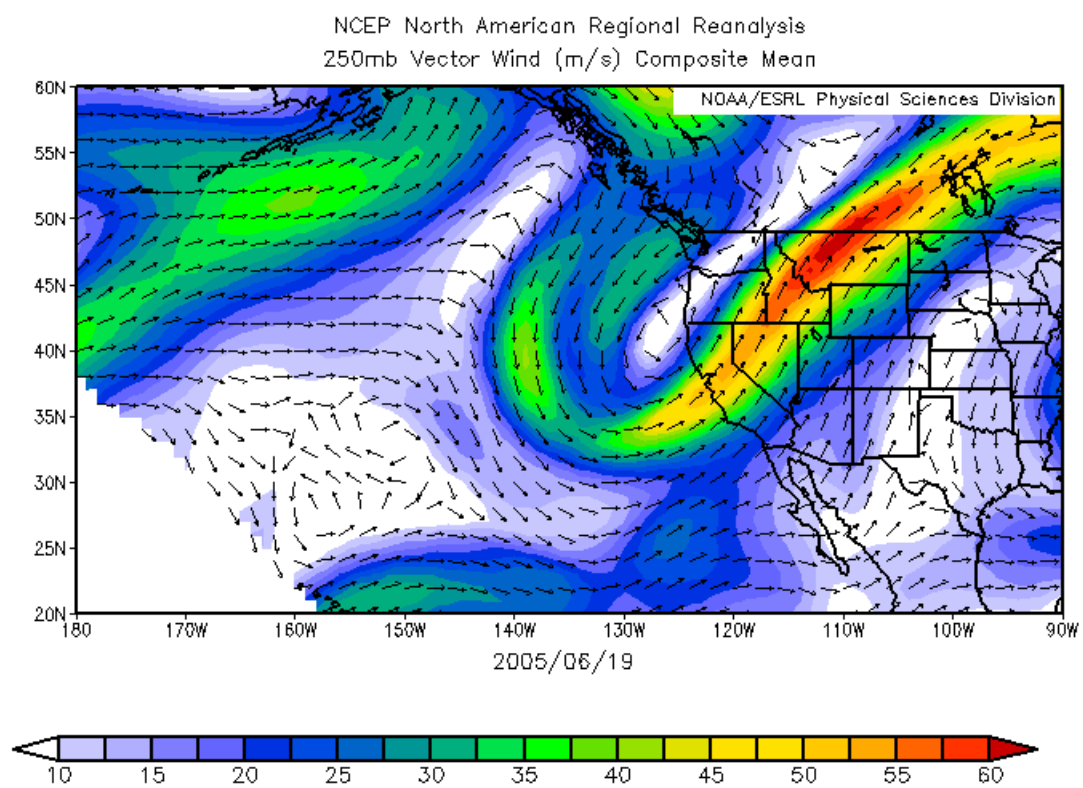


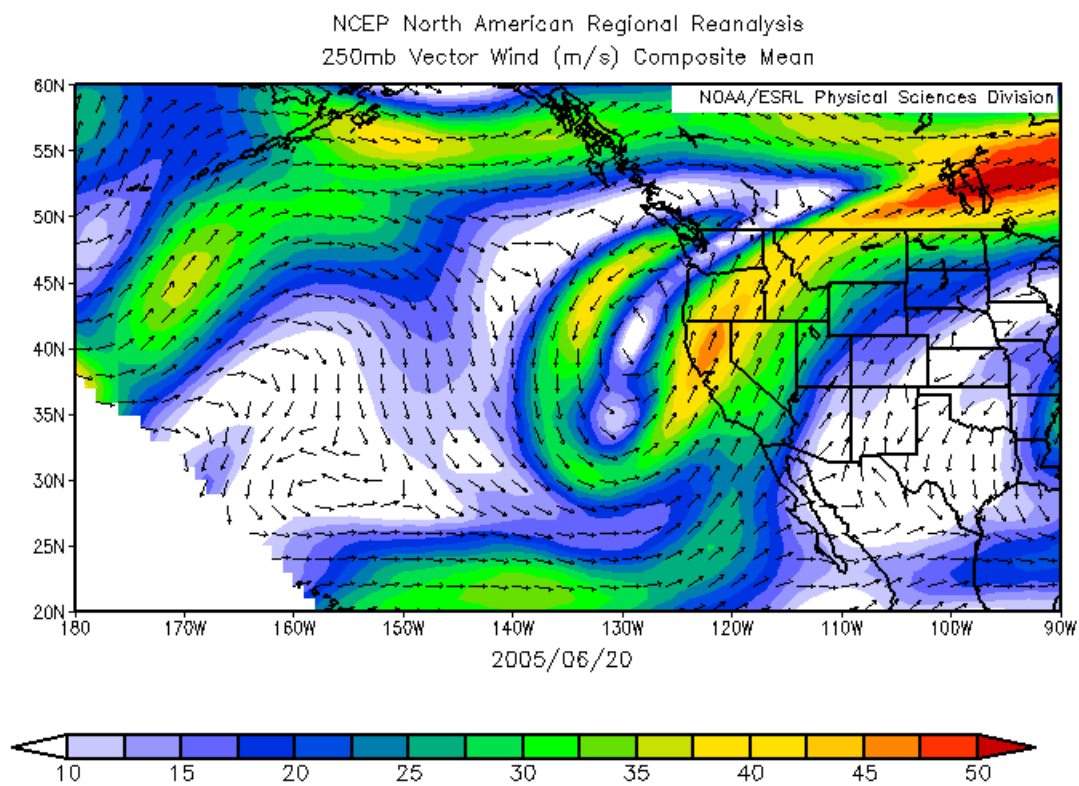
i

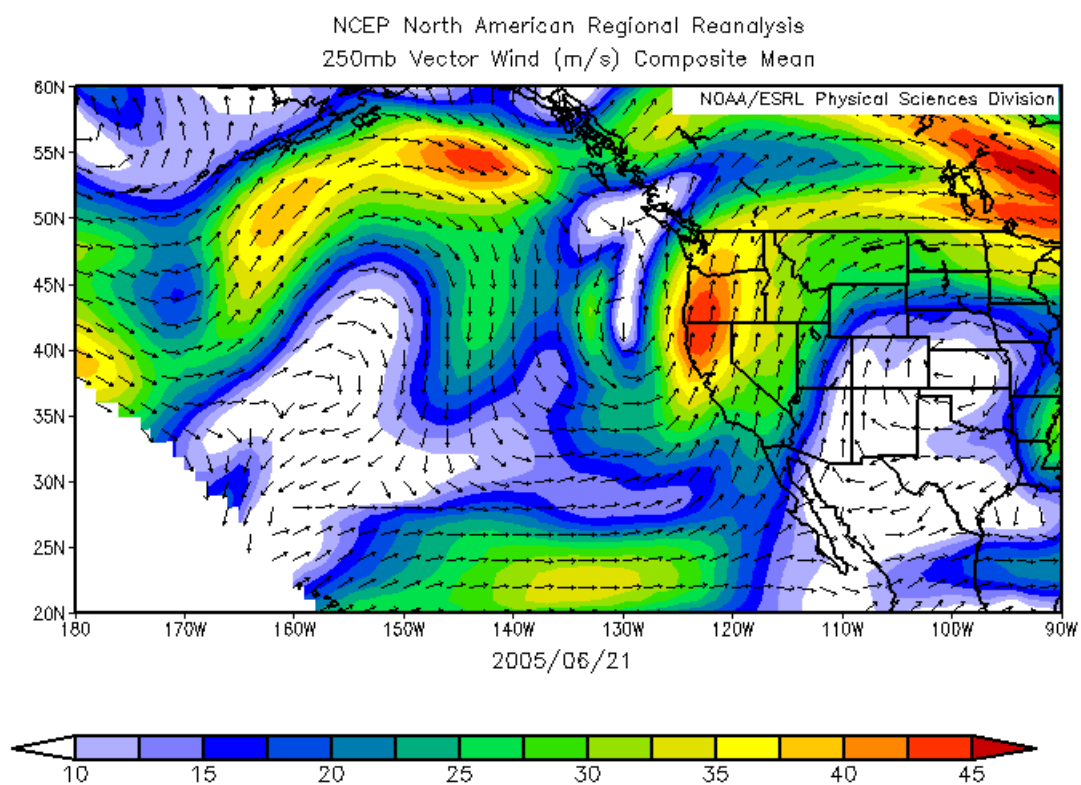


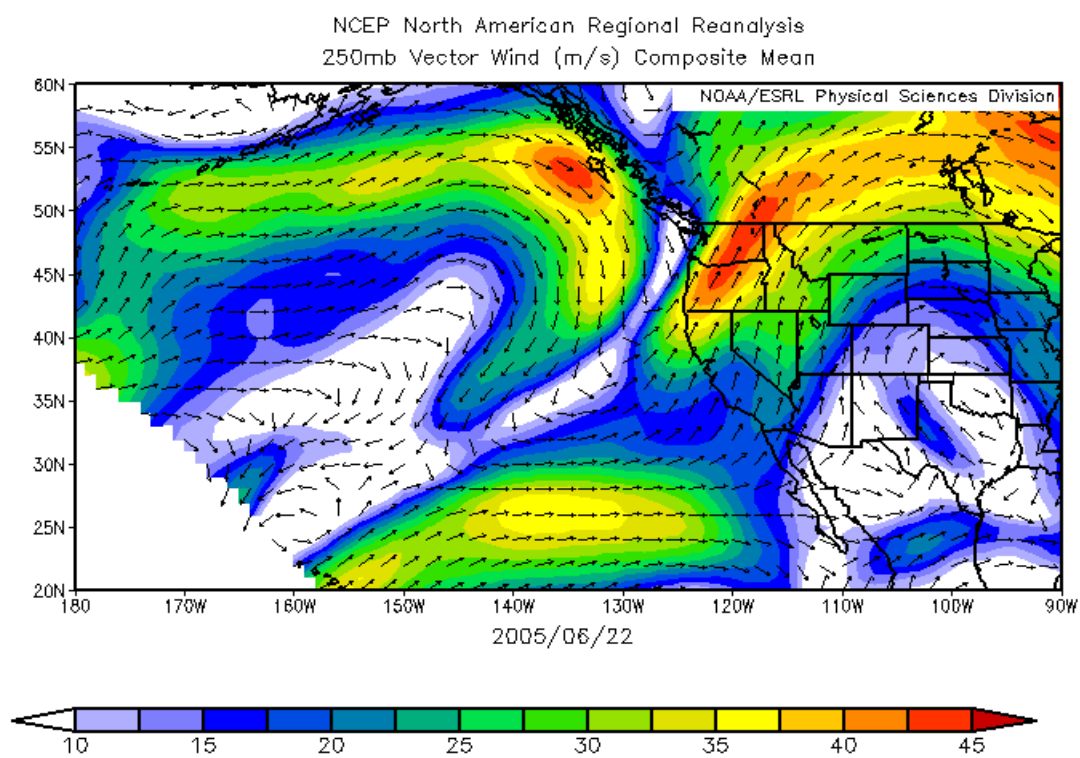
j

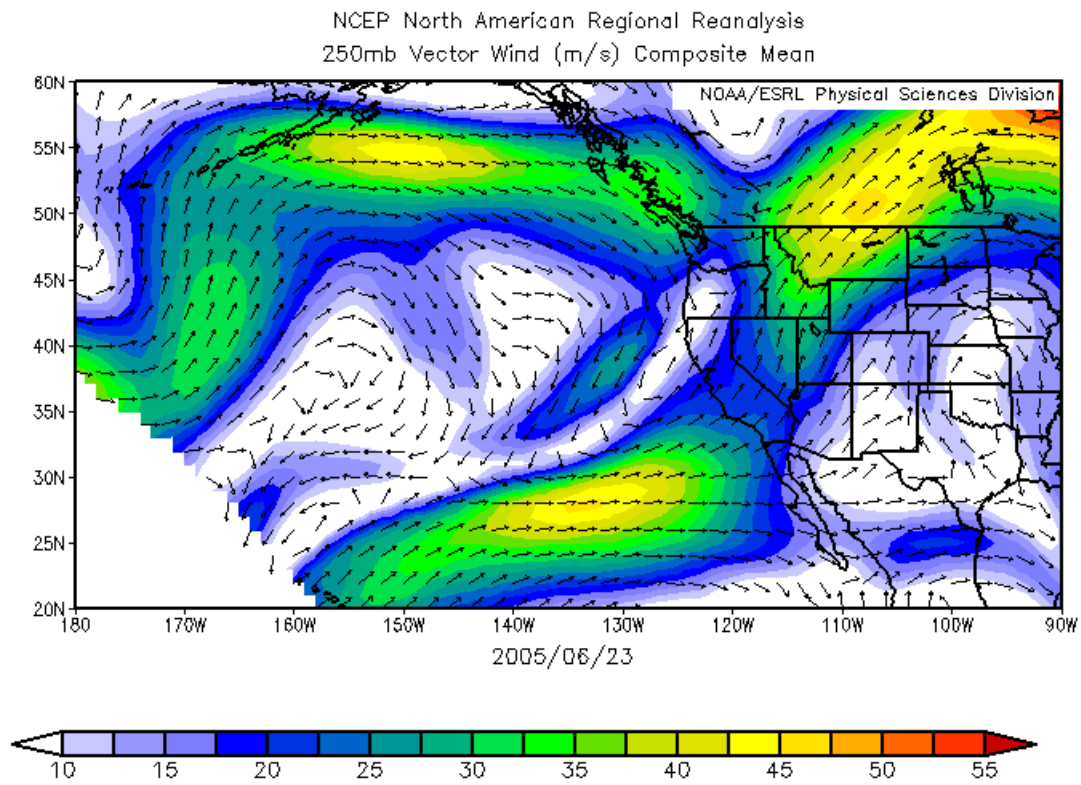
Figures C16. Ten consecutive 3hr time intervals of lightning intensity for WNA overlaid on the 700mb specific humidity for the July 21st, 2005 case study. Lightning intensity units and contour levels are shown in Figure Captions B1. Specific humidity units and contour levels are shown in Figure Captions B3. Plots for (a) June 20th 20:00 PST, (b) June 20th 23:00 PST, (c) June 21st 02:00 PST, (d) June 21st 05:00 PST, (e) June 21st 08:00 PST, (f) June 21st 11:00 PST, (g) June 21st 14:00 PST, (h) June 21st 17:00 PST, (i) June 21st 20:00 PST, (j) June 21st 23:00 PST,

**a**

**b**

**c**

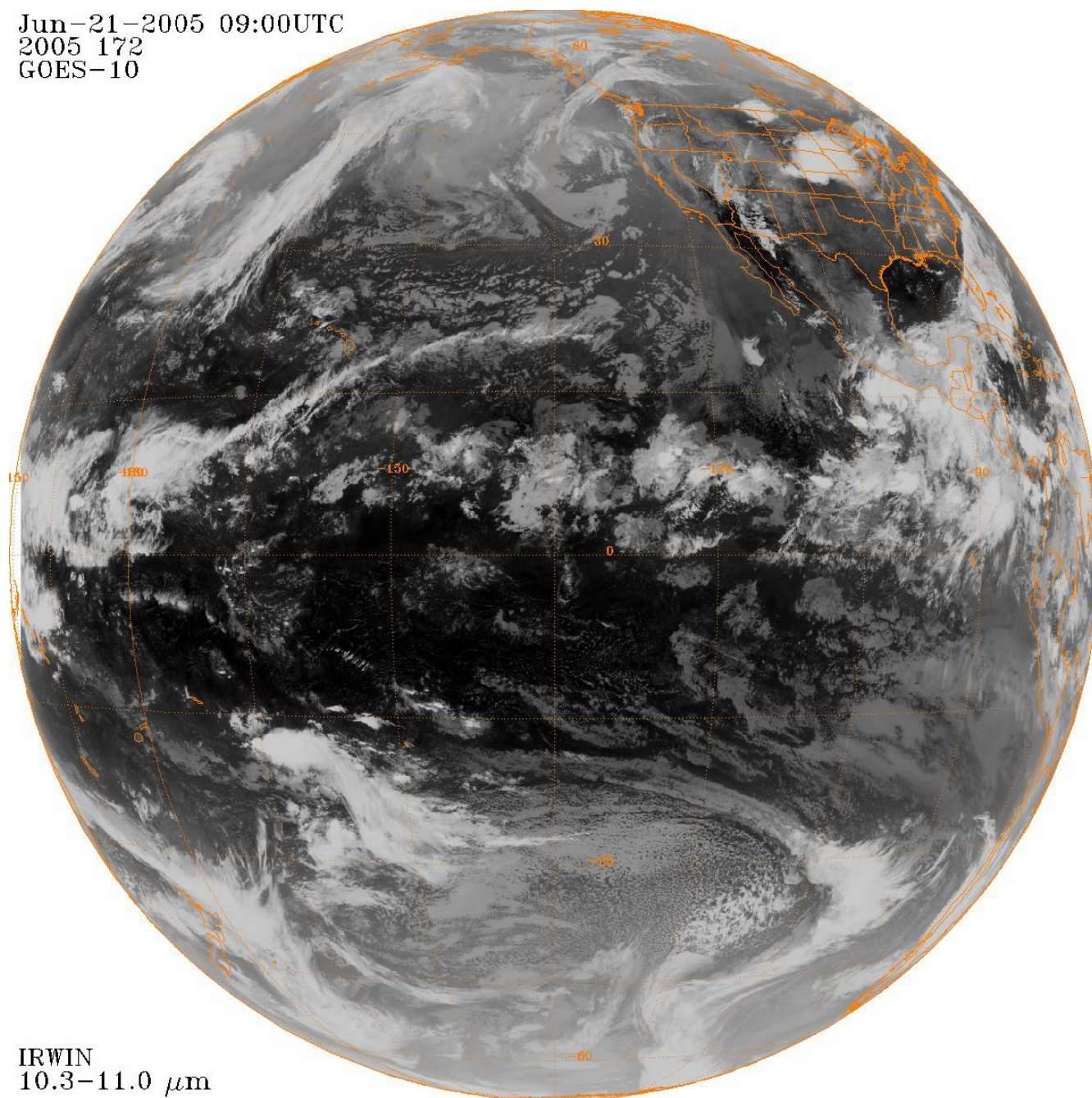
**d**



e

Figures C17. Daily averaged (GMT) 250Mb wind field. Plots for (a) July 19th, (b) July 20th, (c) July 21st, (d) July 22nd, (e) July 23rd.

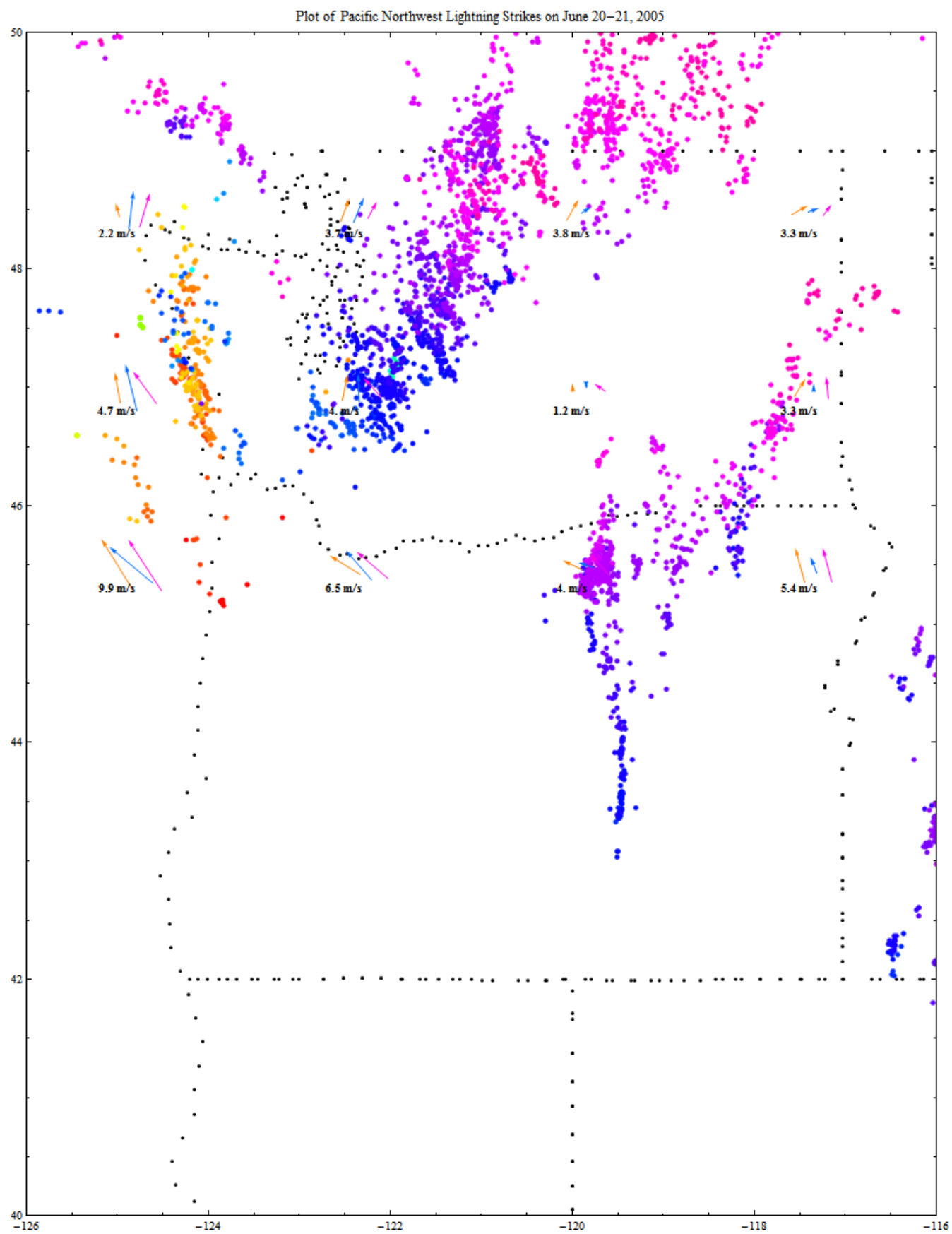
Jun-21-2005 09:00UTC
2005 172
GOES-10

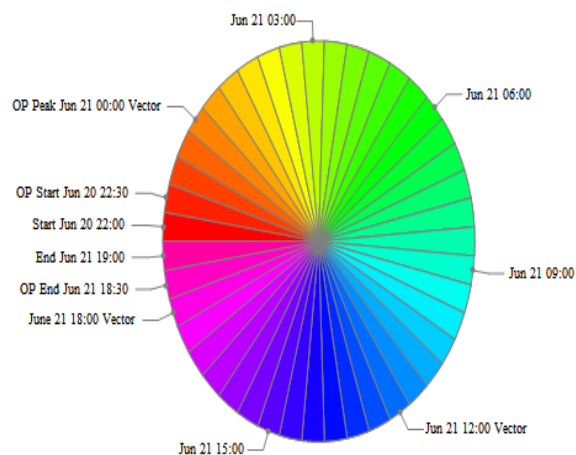


IRWIN
10.3-11.0 μm

Figure C18. Goes 10 infrared satellite image for July 21st, 2005 at 1:00 PST.

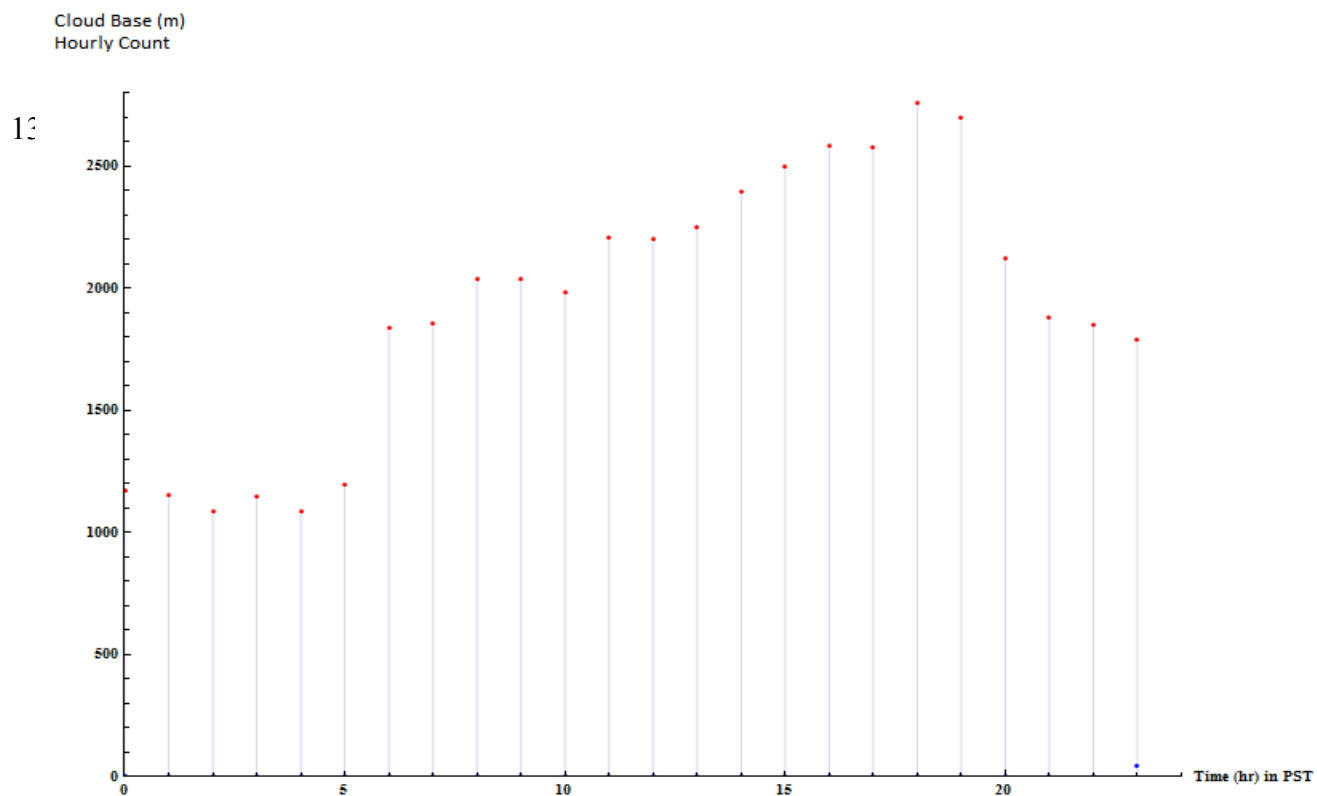
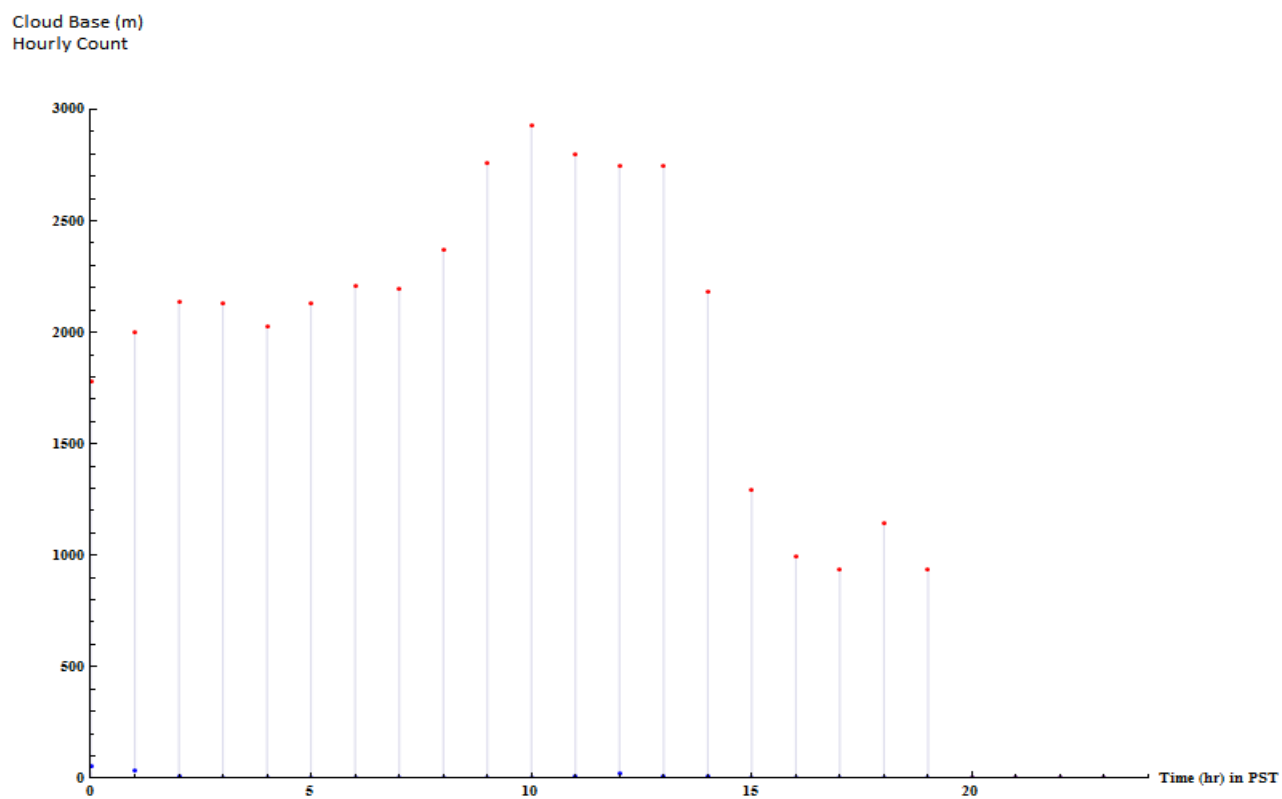
A plot of the individual strikes for Oregon and Washington is plotted in Figures C19 during the period of highest activity on the OP. Most of the OP activity is along the coast moving to northwest as suggested from the forgoing description. Later in this period, the activity to the east of the OP is moving to the northeast. Wind vectors for this period are plotted in the vicinity of this activity in Figure C19.





Figures C19. July 21st, 2005 case study. a) Strike locations in Oregon and Washington and surrounding locations during a period surrounding the time of peak activity. 700mb wind vectors are also displayed at the locations shown during the 30 minute intervals indicated in b). b) Wind vectors and strike locations are color coded for 30 minute time increments. The times of the initial, final, and peak increments are also indicated on the “color wheel”.

Cloud base plots have relatively high values during the periods of highest activity (Figures C20a&b). However, the lightning activity on the OP is largely restricted to the lower elevations of the coastal area. This observation suggests that the elevation of the strikes are primarily determined by the direction of the unstable advecting moist air, and only secondarily influenced by the cloud base ceiling.



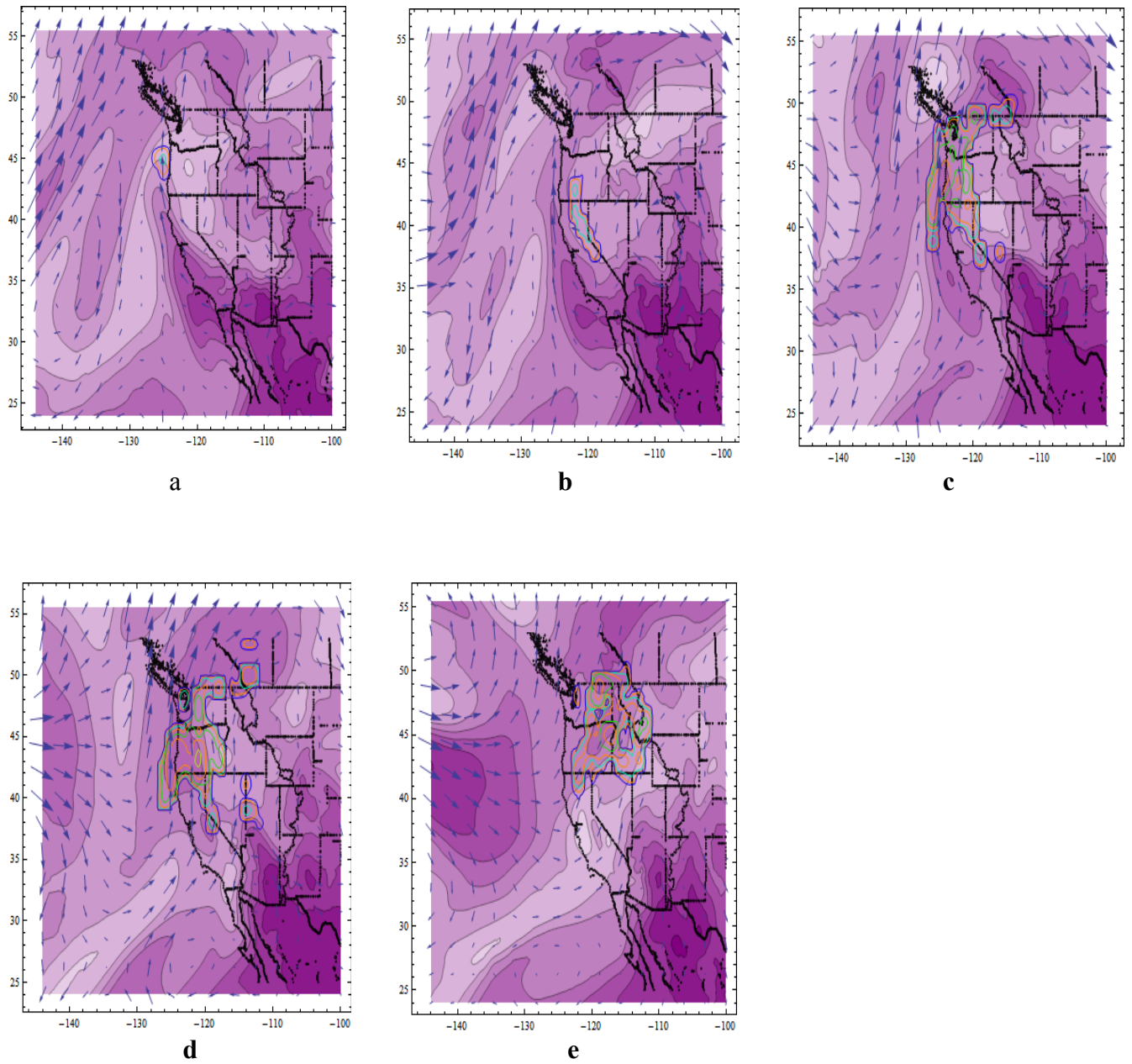
Figures C20. Same as Figures C3 for (a) June 20th, 2005 and (b) June 21st, 2005.

Afternoon Events During the Warm Season

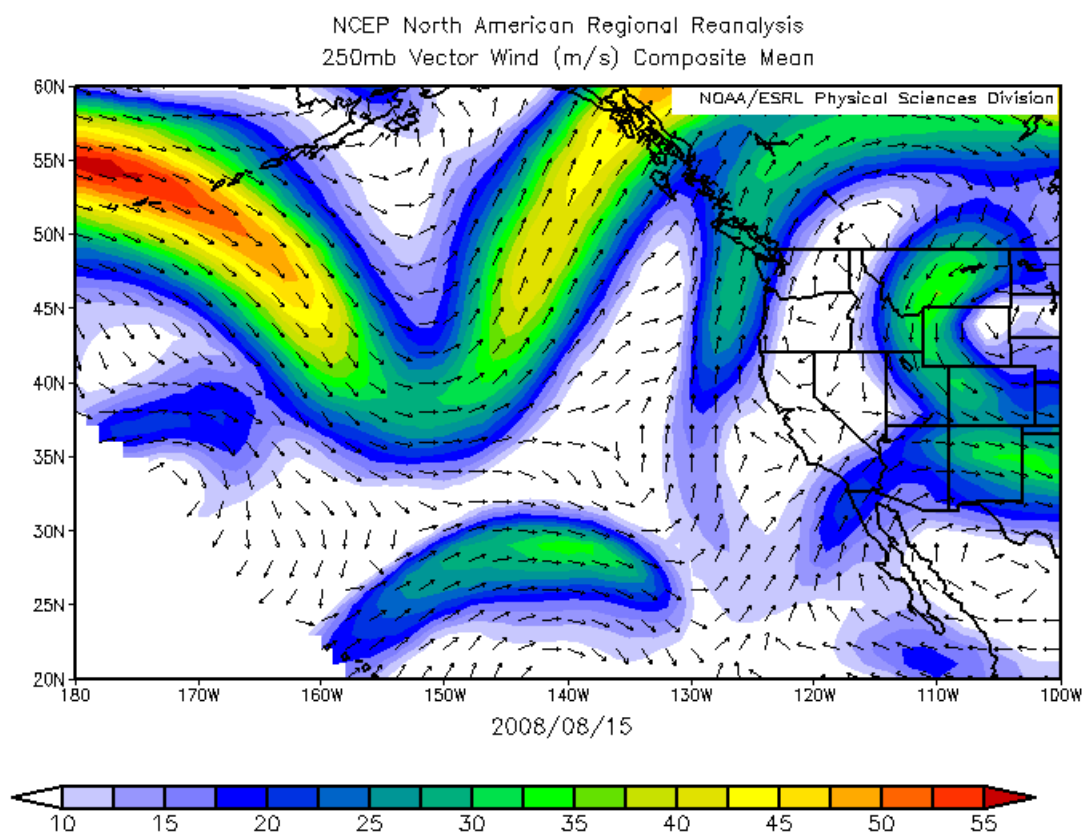
We also examined, as a separate group of warm season case studies, several events for which the peak OP lightning activity occurred in the afternoon (14:00-18:00 PST). As demonstrated in the Diurnal Distribution section, afternoon events accounted the largest percentage of OP lightning activity. With the exception of the first case study in this group, these events did not have total strike counts comparable to the largest OP events in the previous group. Their importance in the diurnal distribution implies that there were many more of these afternoon events than the relatively rare large events. The same analysis used in the previous section was used to explain storm direction data on the OP for these case studies. The analysis for this group of events did not strongly demonstrate the relationships suggested by the previous major warm season events. This is not surprising in the sense that the presence of afternoon surface heating, no matter what the moisture source, would be expected to lead to instability triggering lightning activity.

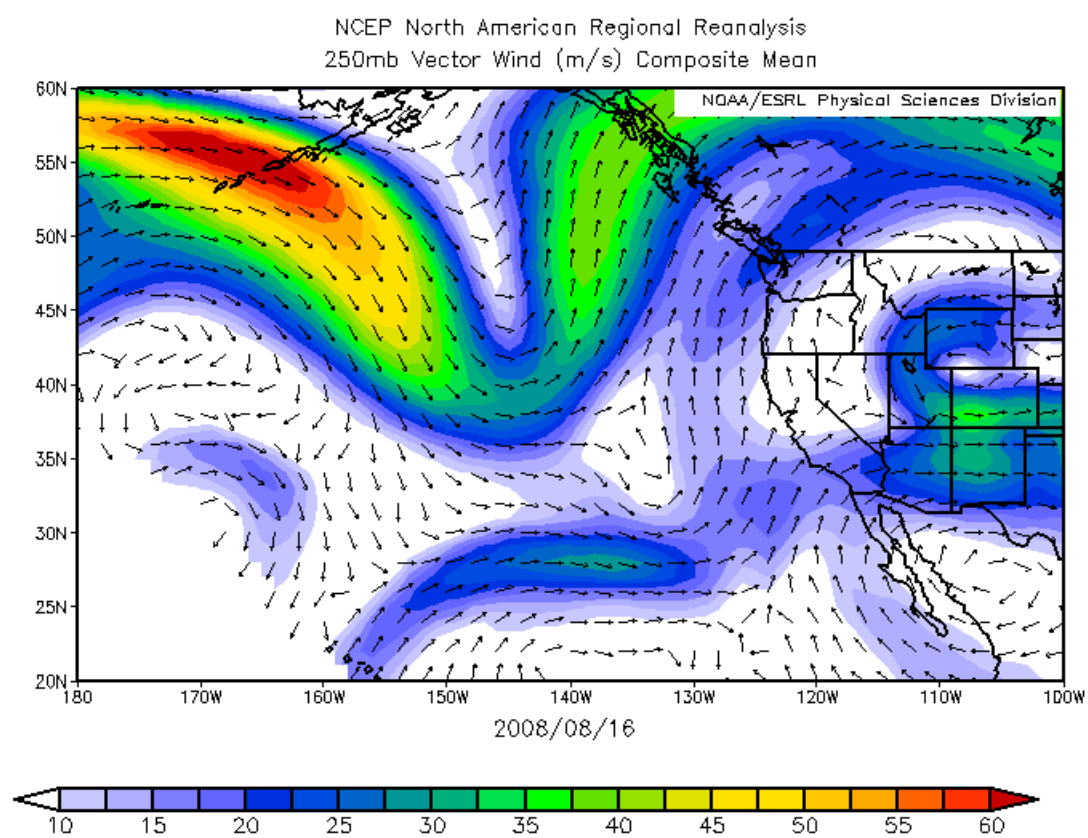
August 17, 2008

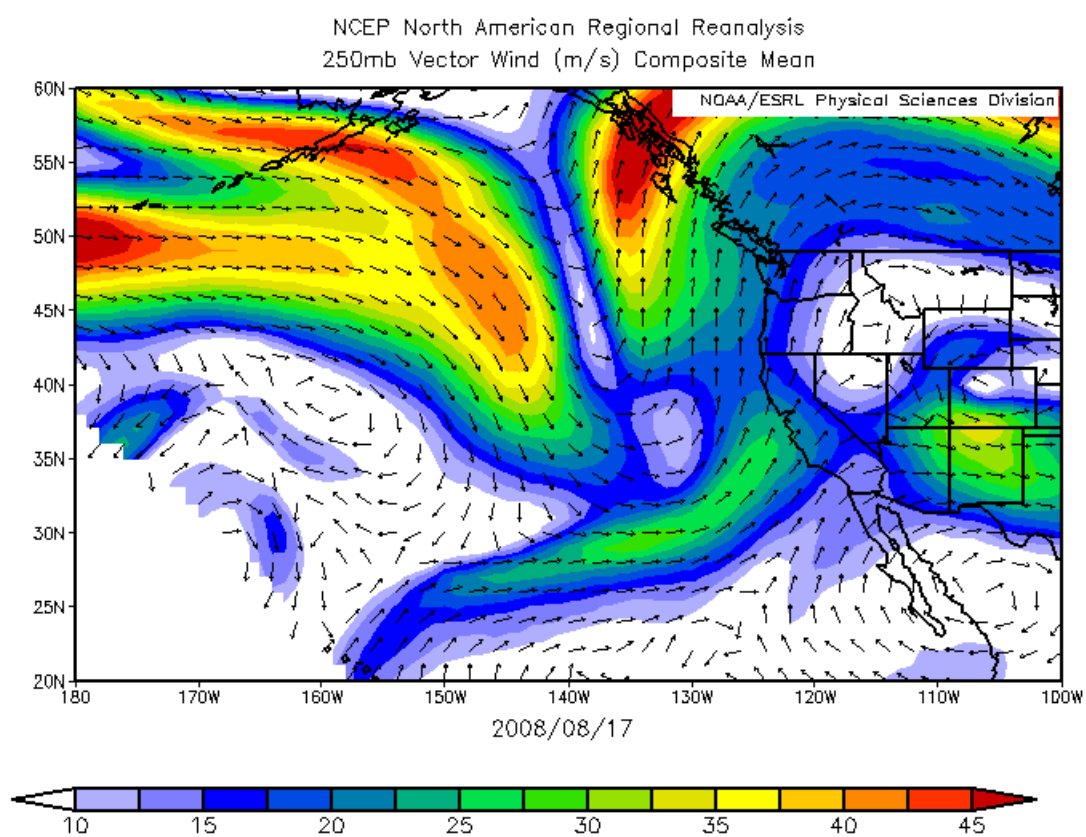
This event was actually among the largest events to occur on the OP (5th largest). The sequence daily activity overlaid on the 700mb data suggests that source of tropical moisture initially comes from the Gulfs of California and Mexico (Figures C21a-e). This source also moving westward associated with the propagation of a westward traveling tropical wave. Additional moisture appears to be coming from the eastern tropical Pacific by the second day. While no cyclonic vortex is apparent at temperate latitudes in the eastern Pacific, two eastward propagating, north-south oriented, troughs are apparent. The larger is located at about 144°W longitude. The smaller is centered at about 130°W longitude with south winds along the Oregon and Washington coast. By the 3rd day the two troughs have merged and carried tropical moisture north associated with lightning activity just offshore as well as inland. The lightning activity shifts east along with the center of the offshore trough on the following day. By the 5th day the winds along the coast are from the southwest. The lightning activity and the most concentrated moisture is now east of the Cascade Mountains. For this particular case, this 700mb temperate latitude dynamics appears to be well described as a reflection of the trough in the eastward propagating Rossby wave in the 250mb jet stream (Figures C22a-e).

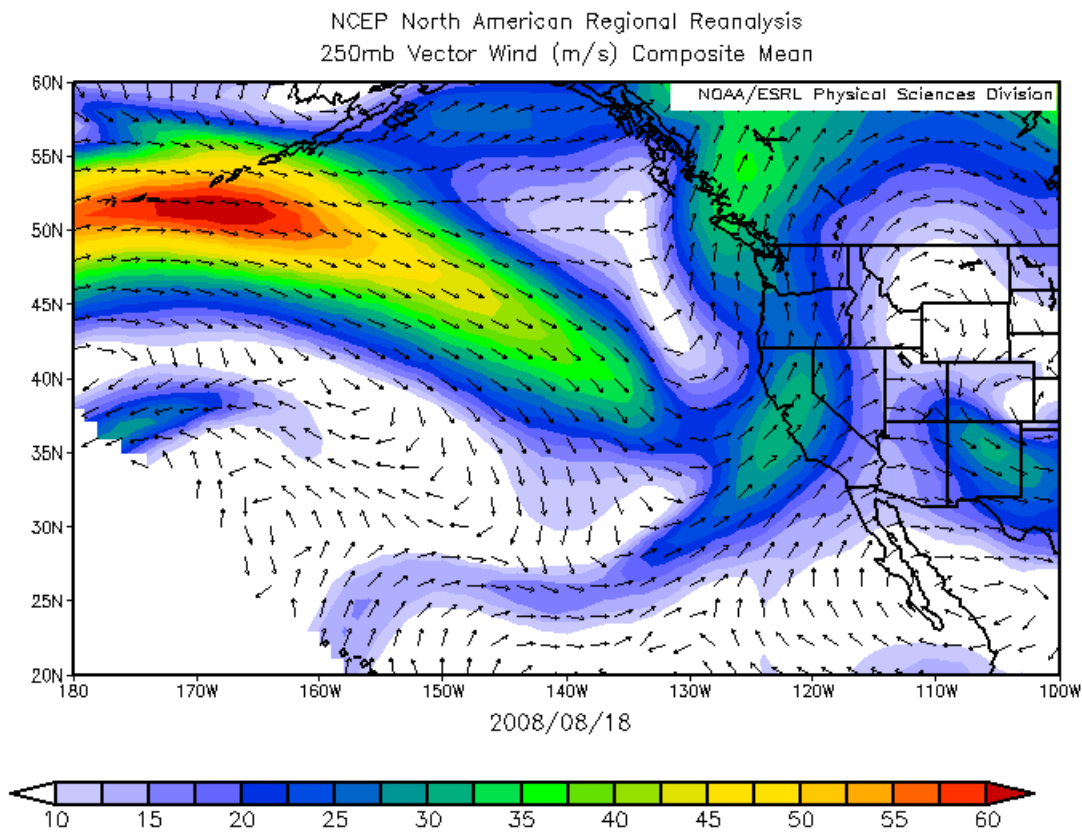


Figures C21. Same as Figure C1 except for the five day sequence surrounding the August 17th, 2008 case study.

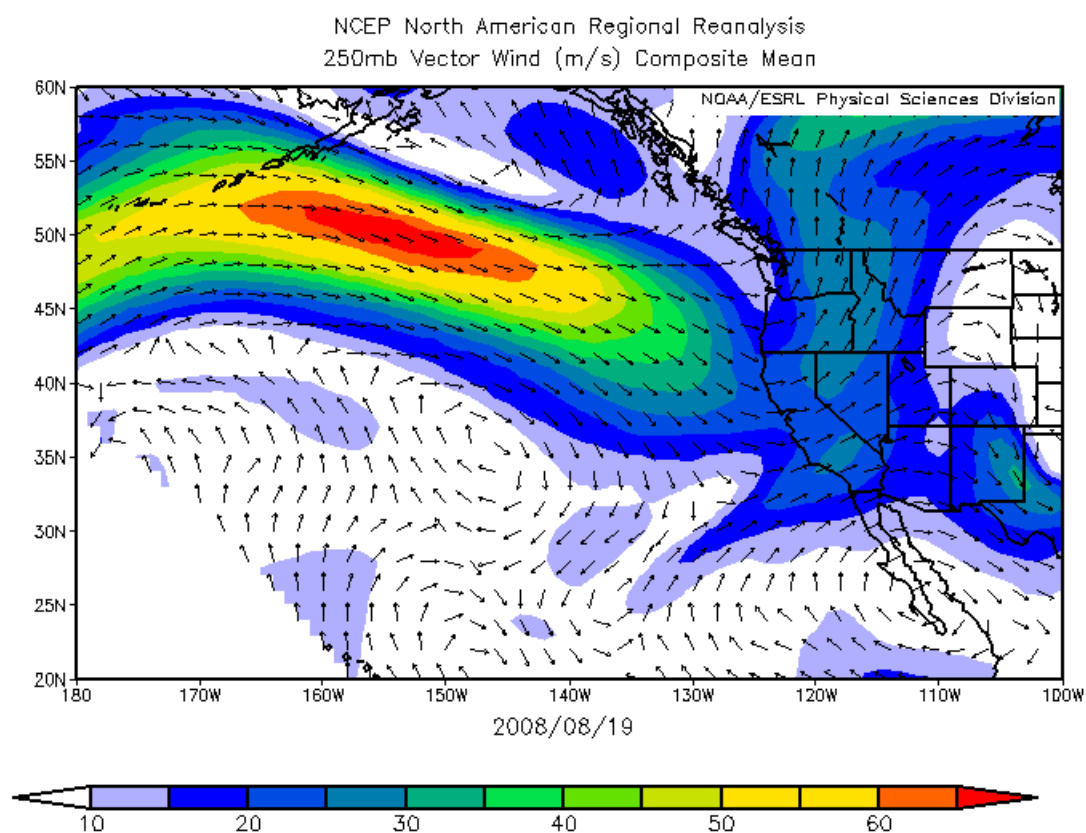
**a**

**b**

**c**



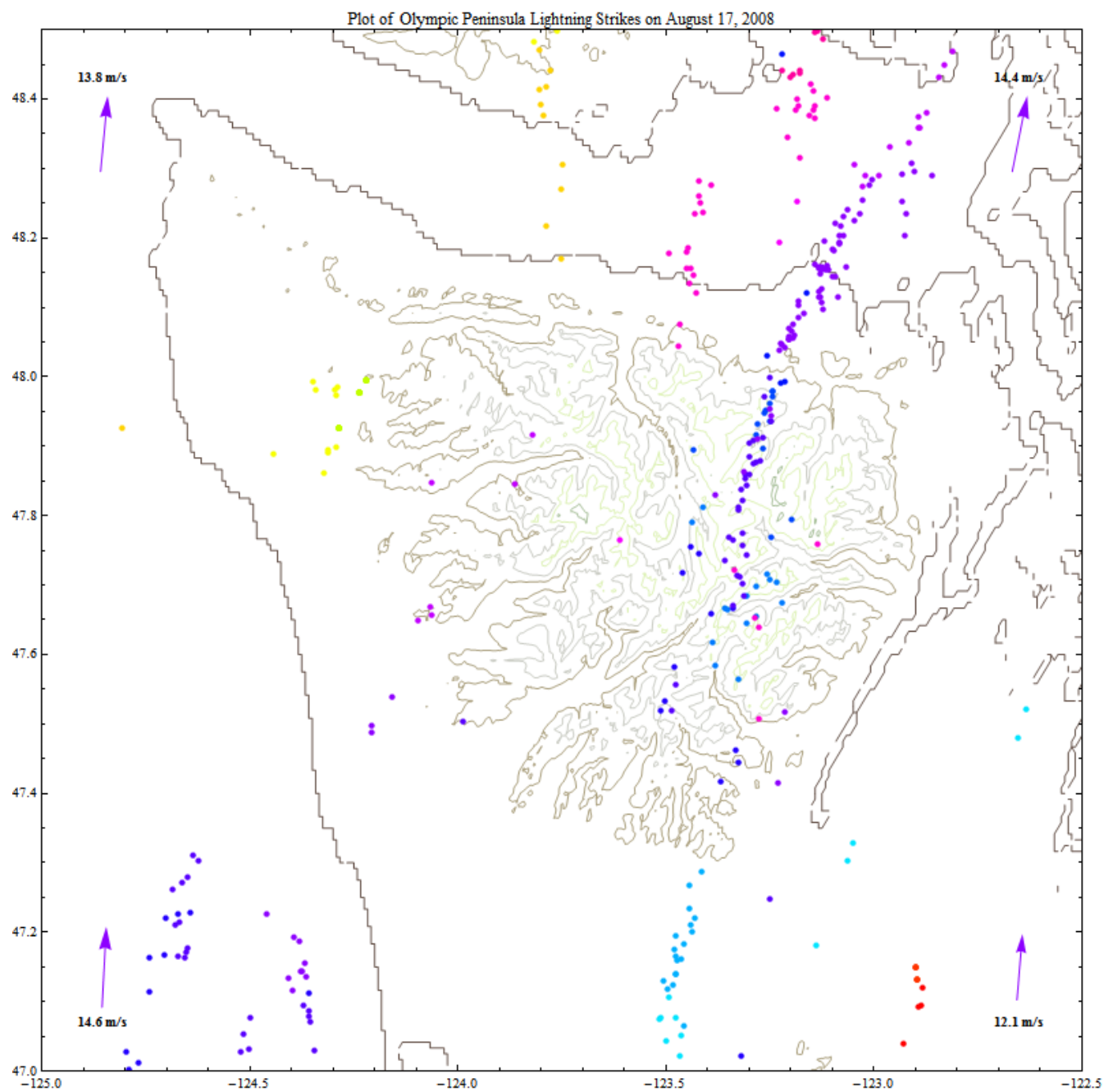
d

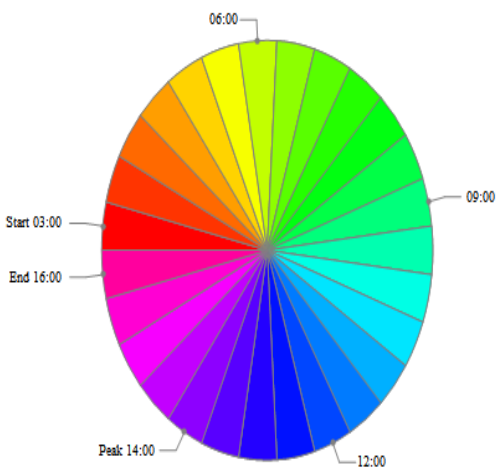


e

Figures C22. The 5 day sequence of 250mb NARR daily wind fields corresponding to the 700mb fields in Figures C21.

Individual strikes on the peak day are plotted in Figure C23. (Cloud to ground strikes resulted in numerous fire starts whose location provided information about the accuracy of these strike locations. This data is discussed in **Appendix C2**). The 700mb wind direction matches well the strike trajectory around the peak time. The trajectory also suggests a downslope concentration of strikes (rather than upslope) - as discussed in the July 5,1997 case above. The cloud base height during this morning period is remarkably high for this time of day (Figure C23). The strike elevations around this time are not inconsistent with the cloud base height data, and higher strike concentrations would be expected near the peak elevations and just below the cloud base, if the cloud base alone were responsible for the strike locations. Also, the strike distribution at the beginning of the peak activity period is just the opposite of what would be expected if cloud base heights alone were the determining factor in strike location. More upslope strikes would be expected than lower elevation strikes. The observed distribution on the south side of the OP is more likely a result of the evolution of moisture advection.





Figures C23. Same as Figure C2 for the August 17th, 2008 case study.

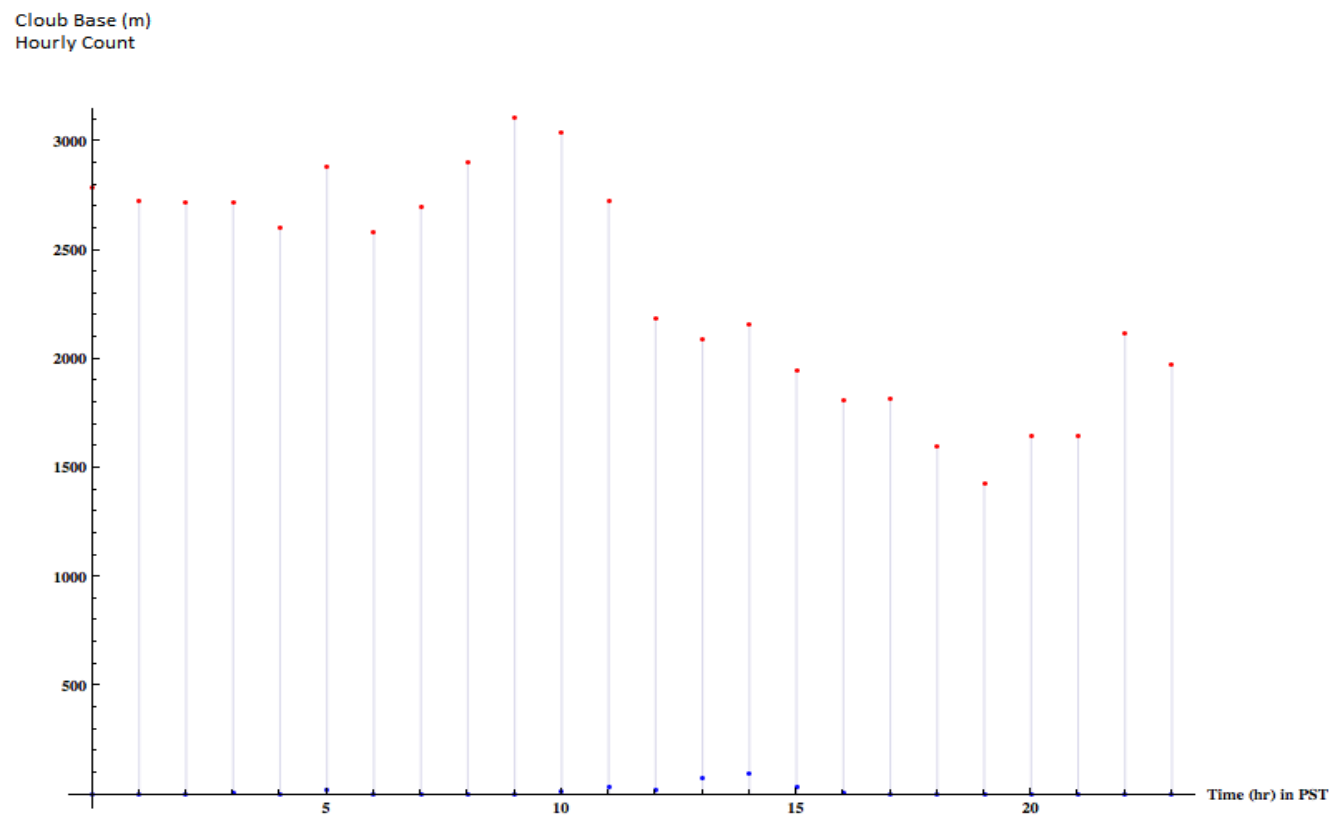
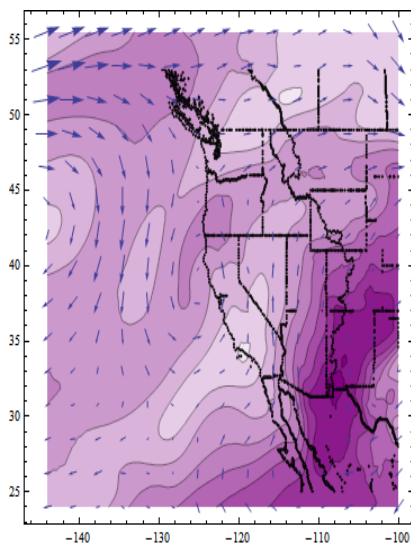


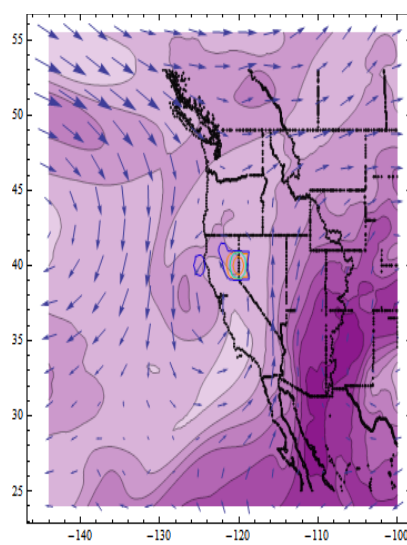
Figure C24. Same as figure C3 for August 17th, 2008.

September 9, 2005

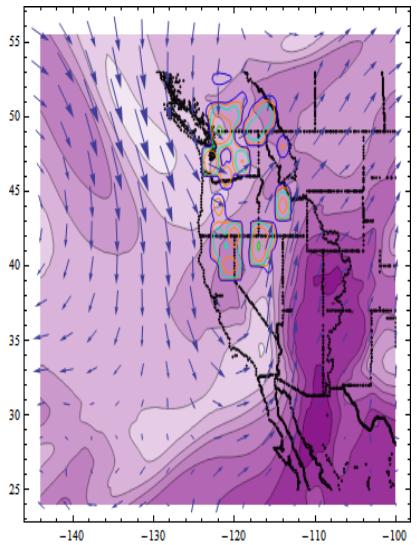
This is the 2nd largest afternoon event on the OP. The sequence of daily activity leading to this event (Figures C25a-e) suggests that moisture (probably from the eastern tropical Pacific) influenced by the cyclonic vortex located near the northern California coastline leads to instability of Northern California (Figure C25b). The activity over British Columbia and Washington the following day does not appear to come from the moisture circulating around this vortex (Figure C25c). It seems more likely that it results from the afternoon instability of the moisture which was already over this area the previous day. However, by the next day (Figure C25d), a cyclonic vortex centered, which has formed near the Canadian border near north central Washington, does appear to explain the subsequent advection over the OP of the moisture from the north in this vortex along with lightning activity moving to the south-southeast. This case study is the first example of lightning activity moving from the north to the south.



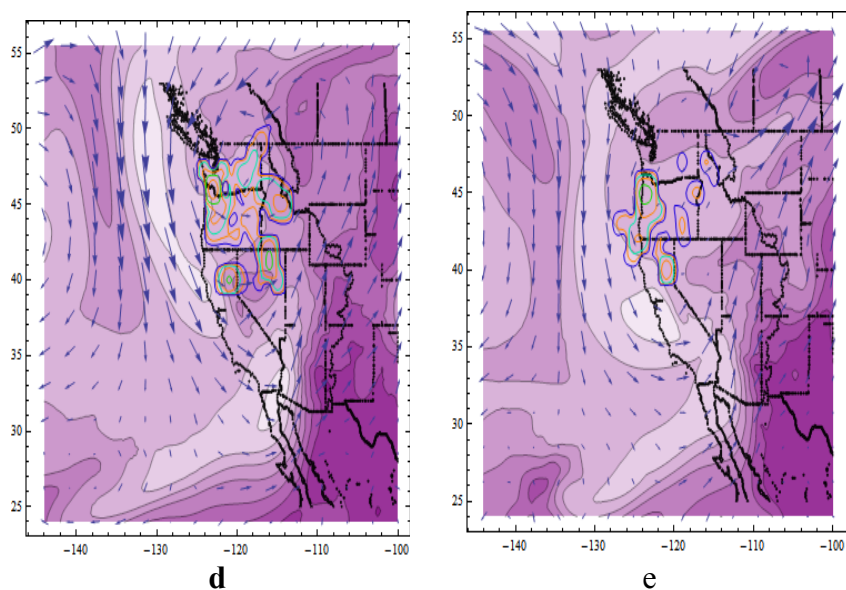
a



b

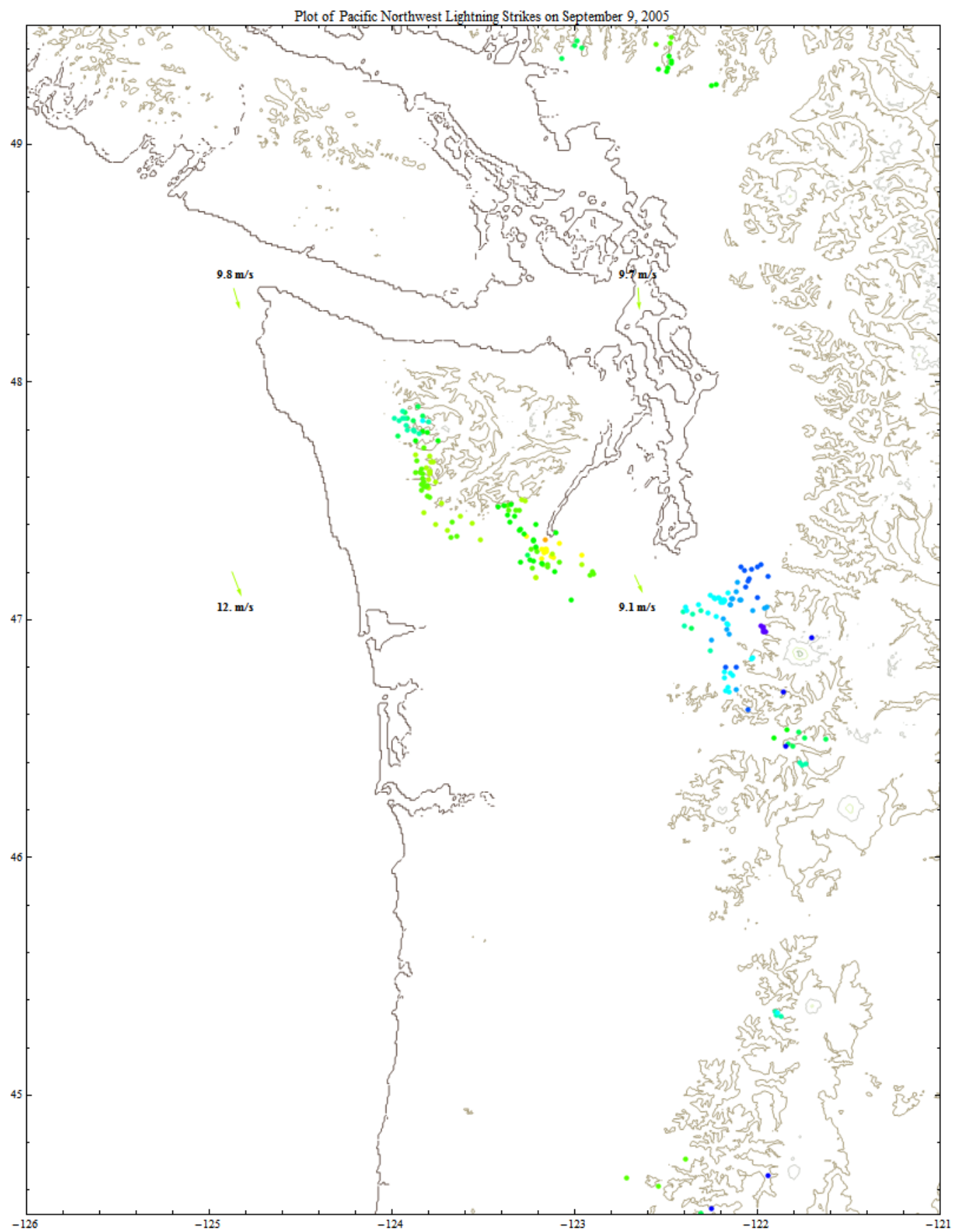


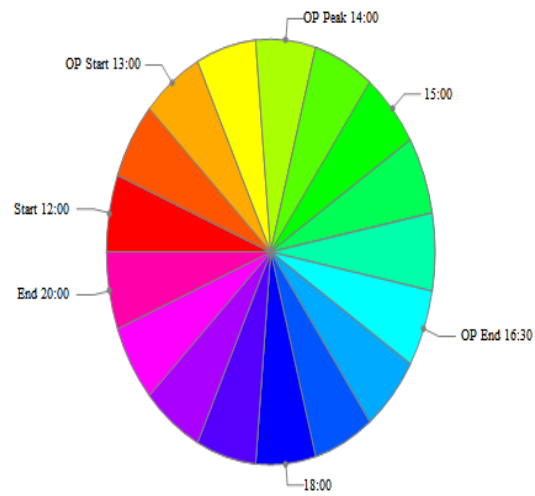
c



Figures C25. Same as Figure C1 except for the five day sequence surrounding the September 9th, 2005 case study.

The individual strike locations on the peak activity day are shown in Figures C26. An extended area beyond the OP boundary illustrates a progression of activity to the south-southeast - consistent with the circulation this 700mb circulation pattern. The high afternoon cloud base in Figure C27 would not constrain the activity to the west and south side of the of the Olympic Mountains. This suggests that the predominance of strikes in this region and their absence over the higher central and eastern elevations is due to differences in the details of the circulation of moisture. However, these differences are not revealed by the highest space and time resolution of the NARR 700mb specific humidity and wind data (not shown).





Figures C26. Same as Figure C2 for the September 9th, 2005 case study.

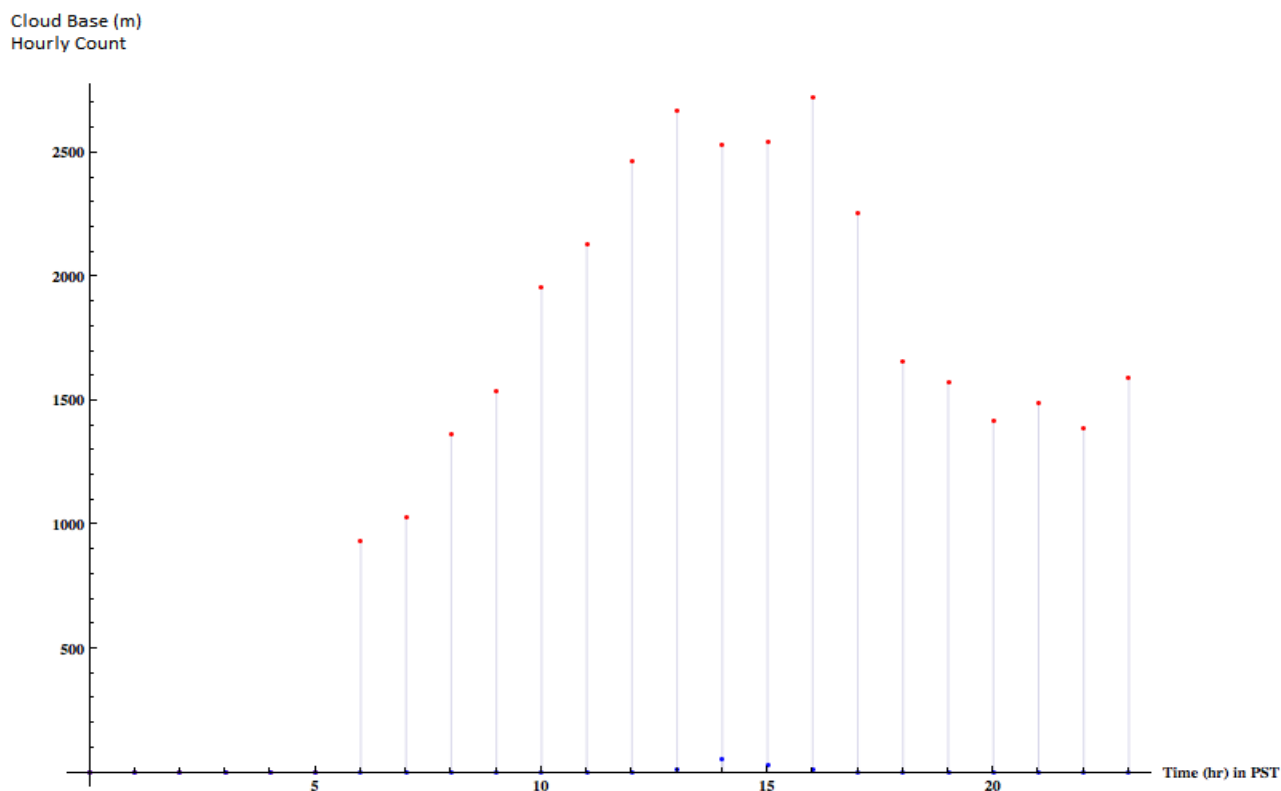
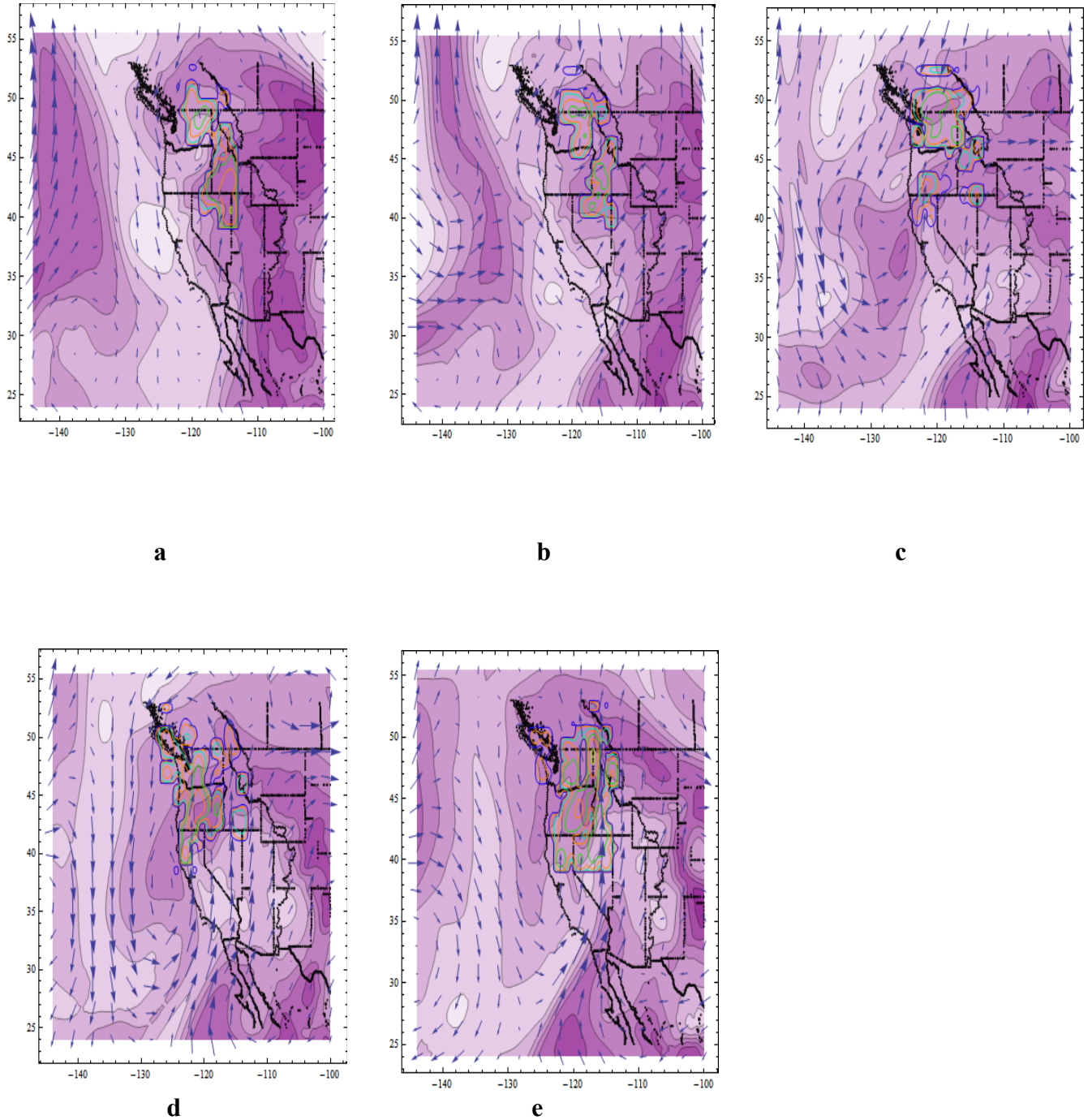


Figure C27. Same as figure C3 for September 9th, 2005.

June 11, 2006

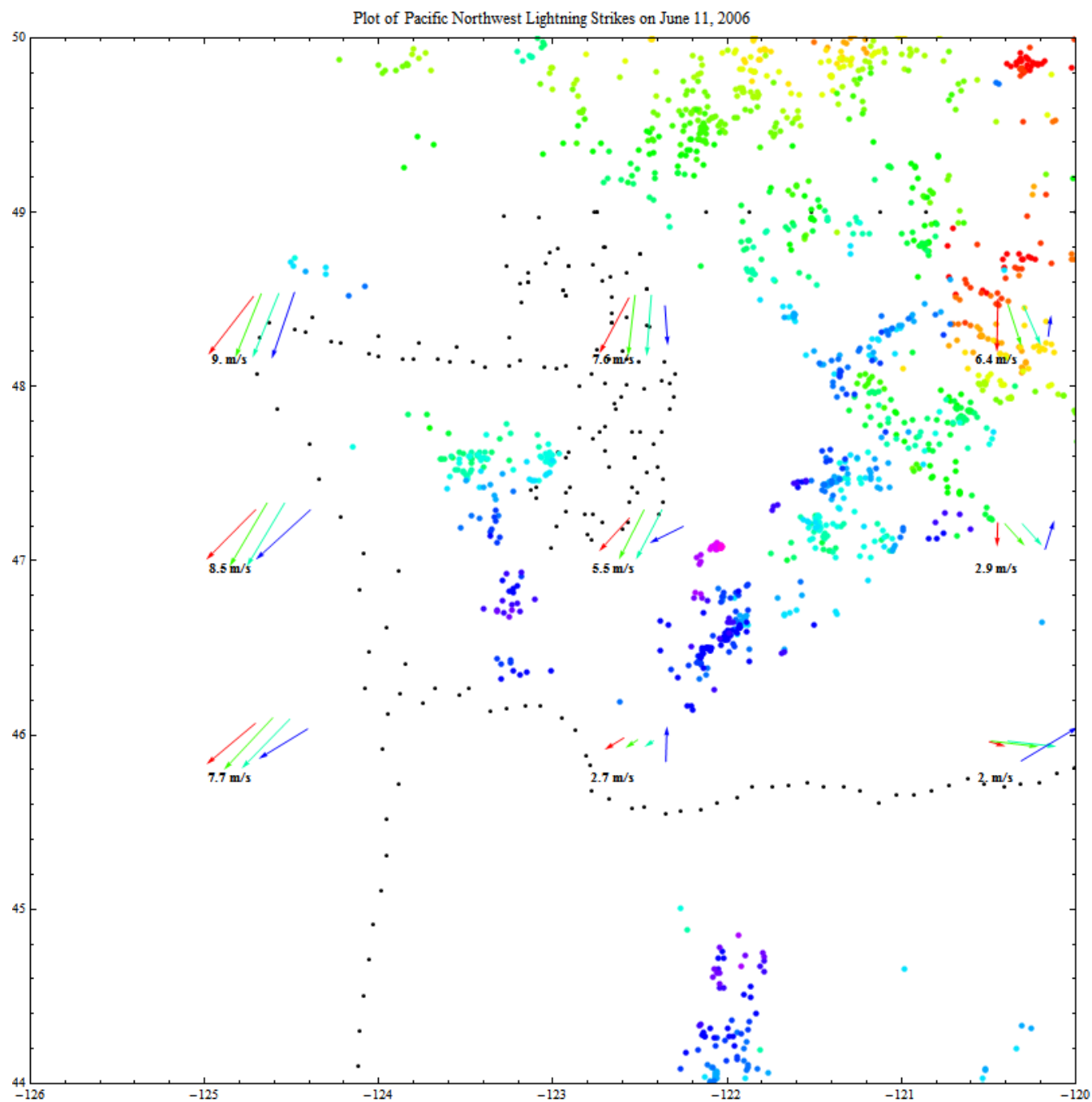
This 3rd largest event is also an example of lightning activity moving southward. The daily sequence of activity for WNA (Figures C28a-e) indicate a cyclonic vortex initially centered over eastern Washington. The source of moisture appears to be advected from a tropical source associated with an easterly wave. The moisture responsible for lightning activity rotates around to the west side of the vortex by the third day (coinciding with the day of maximum activity on the OP). By this day the center of the vortex has also moved south to just off the southern Oregon coast with some activity on

the southeastern side of the vortex. By the 4th day the vortex has become elongated in the north-south direction, extending from Vancouver Island to southern California. Consequently, the winds are from the south near the Cascade Mountain range.



Figures C28. Same as Figure C1 except for the five day sequence surrounding the June 11th, 2006 case study.

The actual strike locations of the extended plot, on the day of peak activity are consistent with this dynamic evolution of the 700mb atmosphere (Figure C29). The first half of the times on the plot of peak activity corresponds approximately to the 3rd daily (GMT) plot, and the remainder to the correspond to the 4th. Vector winds in the vicinity of the OP, and in the first time period are from the north northeast. The strike progression during this period are roughly consistent with these directions. But, by the middle of the second period (18:00 PST), the winds to the south and east of the OP are from the south. The progression of strike locations in the Cascade foothills, in closest proximity to the plotted wind vector, is consistent with this reversed direction.





Figures C29. Same as Figure C2 for the June 11th, 2006 case study.

The cloud base height time series for this event (Figure C30) indicates that the channeling phenomena used to explain some of the earlier case studies may at least play a partial role in the strike location progression. Some of the strikes occurring prior to the time of peak activity do occur at higher elevations consistent with the higher cloud base for this time. At the time of peak activity the cloud base drops rather quickly to elevations below 1500 meters. An examination of the strike elevations in the post peak time period are consistently lower also (not shown).

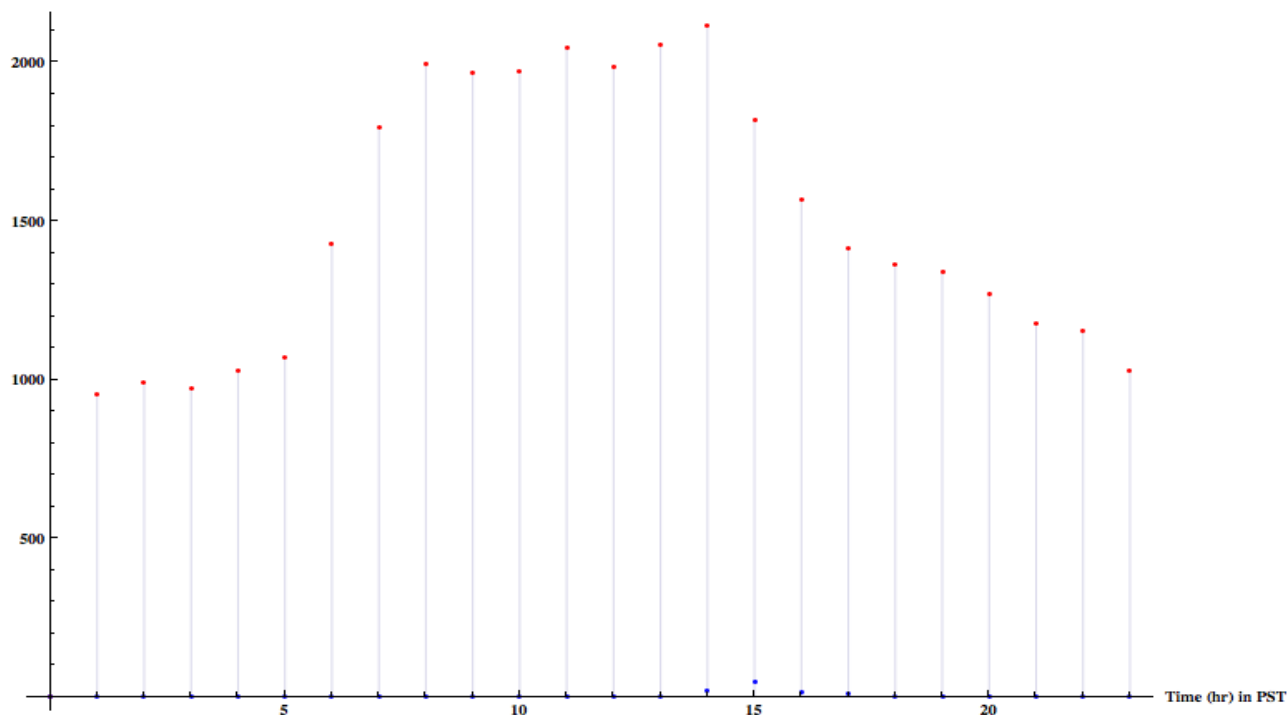
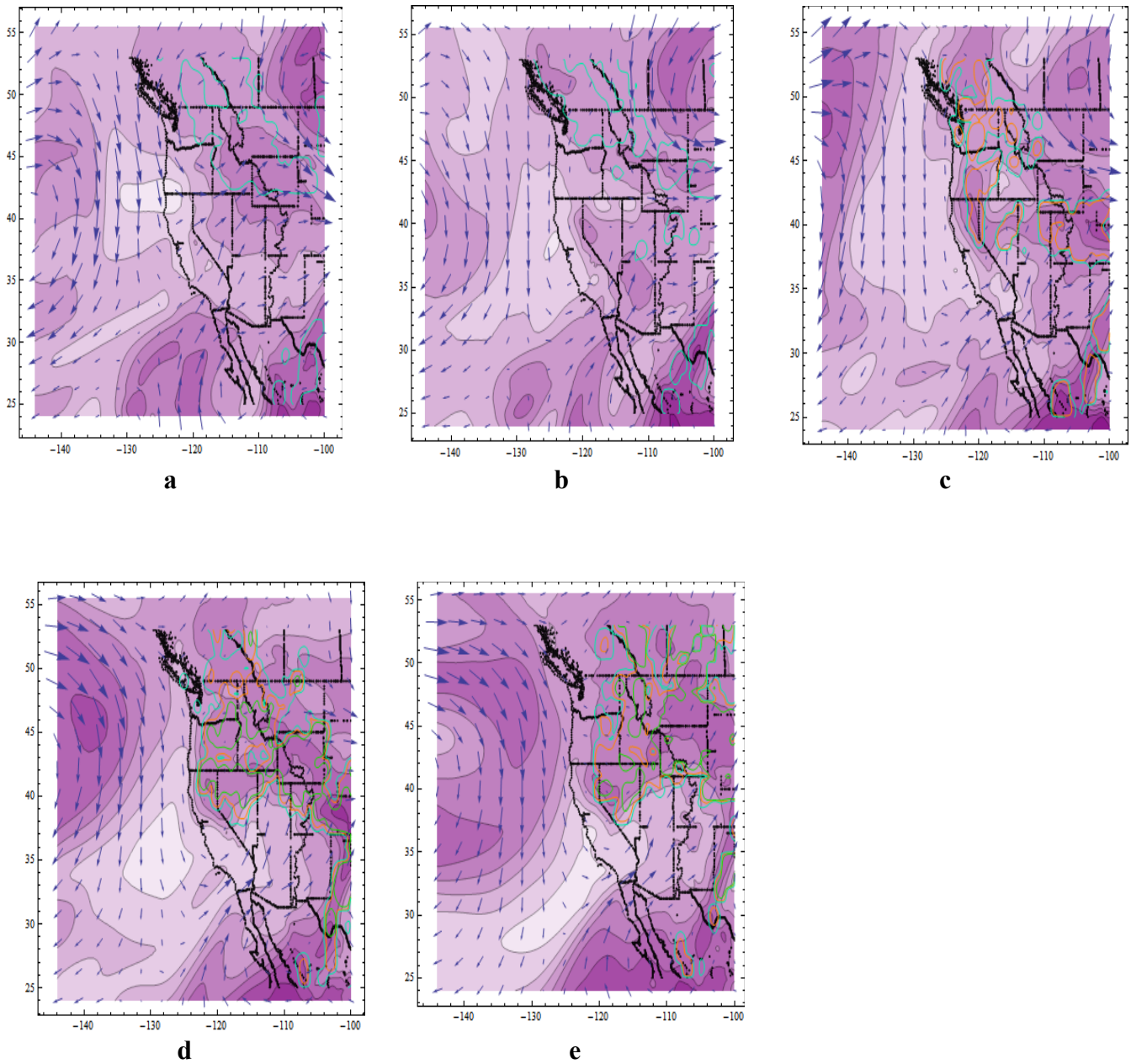


Figure C30. Same as figure C3 for June 11th, 2006.

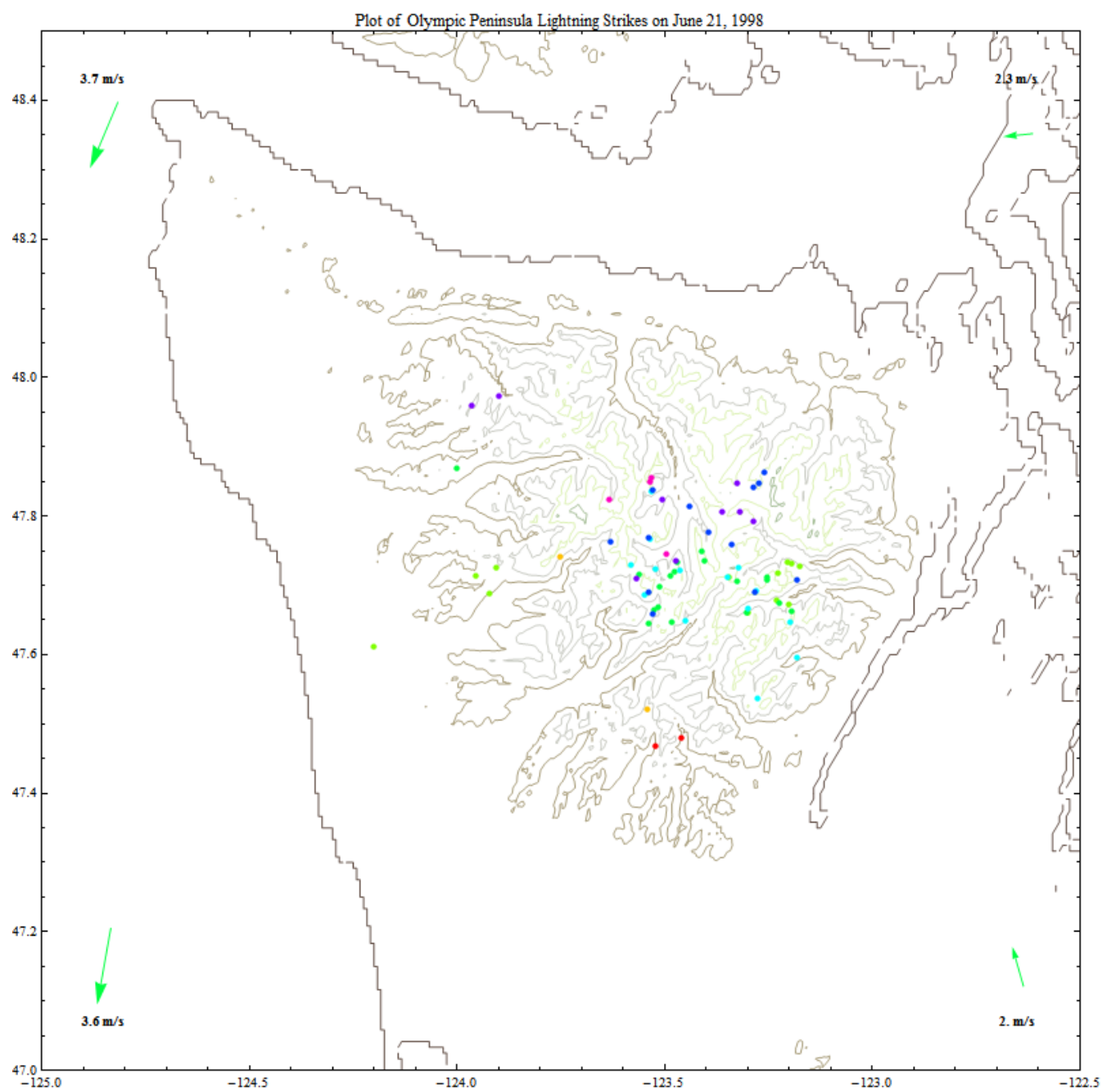
June 6, 1998

This event is another example of a 700mb cyclonic circulation near the west coast – centered on land. It is unique among the case studies in that on the peak day the circulation is centered over the OP. The daily evolution of this event is shown in Figures C31a-e. The strength of the circulation is quite weak and difficult to make out on some days. But, more detailed visualization of the NARR data does reveal this pattern (not shown). On the first day the center is around northeastern Washington. Moisture, which appears to originate from the tropical eastern Pacific Ocean, is concentrated to the east of this circulation. By the third day (Figure C31c) the vortex has become elongated and centered near the coast, stretching from Washington to southern California. The details of the winds at the northern

end of this vortex, which is now centered over the OP can be seen on the plot of the individual strikes for this day (Figure C32). By the 4th and 5th day this feature moves eastward and by the 5th day has largely disappeared.



Figures C31. Same as Figure C1 except for the five day sequence surrounding the June 6th, 1998 case study.





Figures C32. Same as Figure C2 except for the June 6th, 1998 case study.

Figures C32 indicate almost none of the progression of the other cases. What little motion there is can, perhaps best be characterized as a slow progression of a limited frontal region of strikes on the upslope side the central Olympic Mountains progressing northward. Many of the strikes are at higher elevations - consistent with the elevated cloud base “ceiling” at the peak time period (Figure C33).

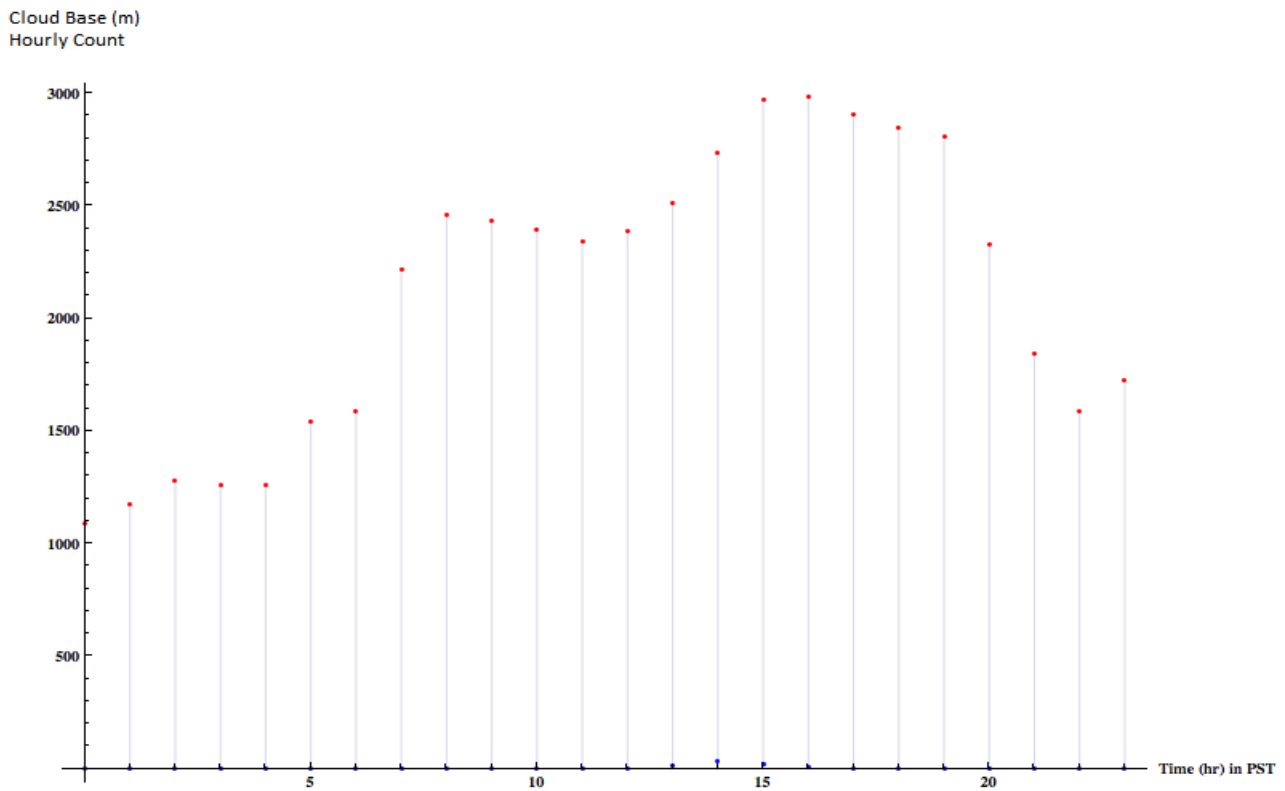
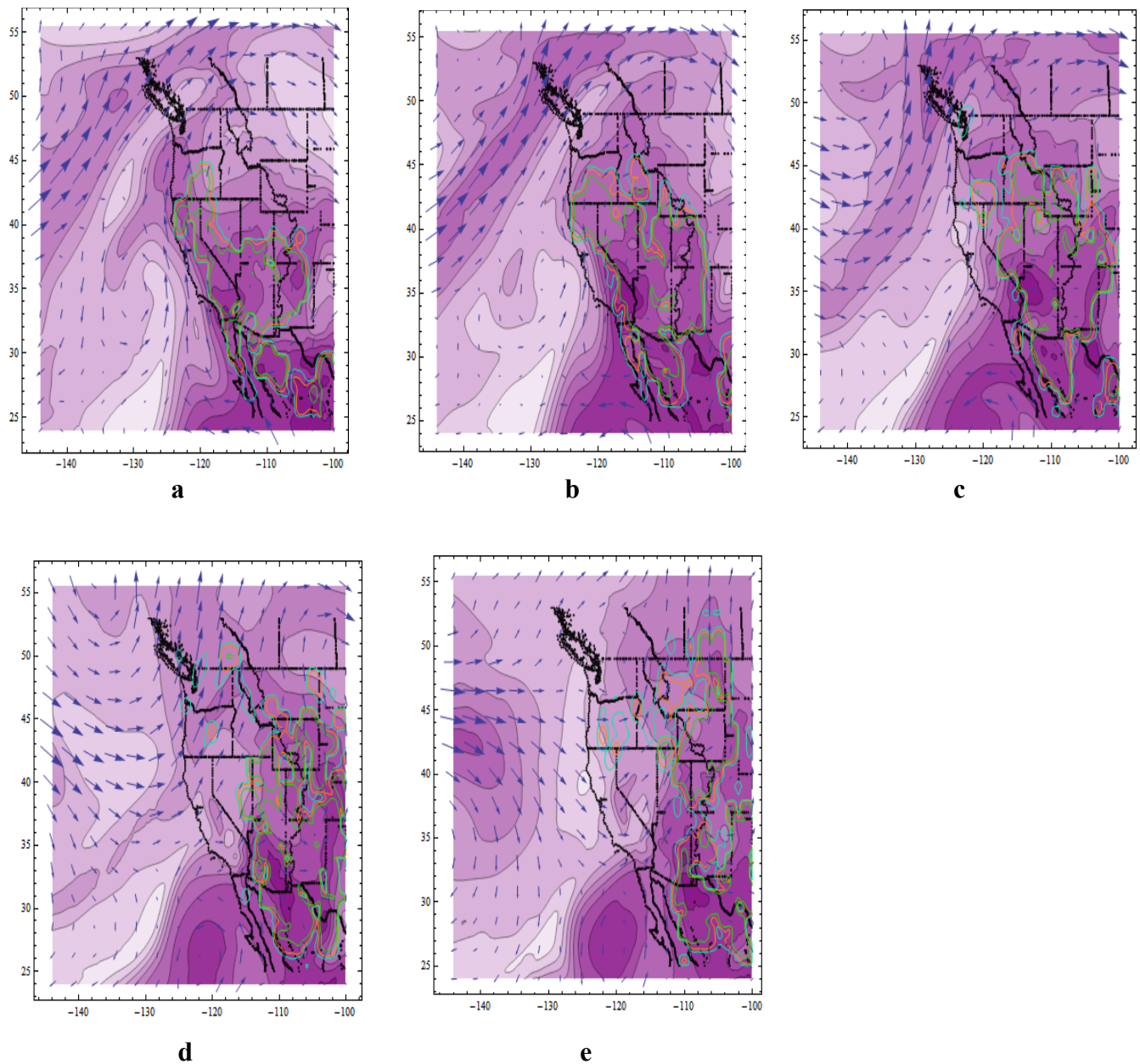


Figure C33. Same as figure C3 for June 6th, 1998.

September 6, 2003

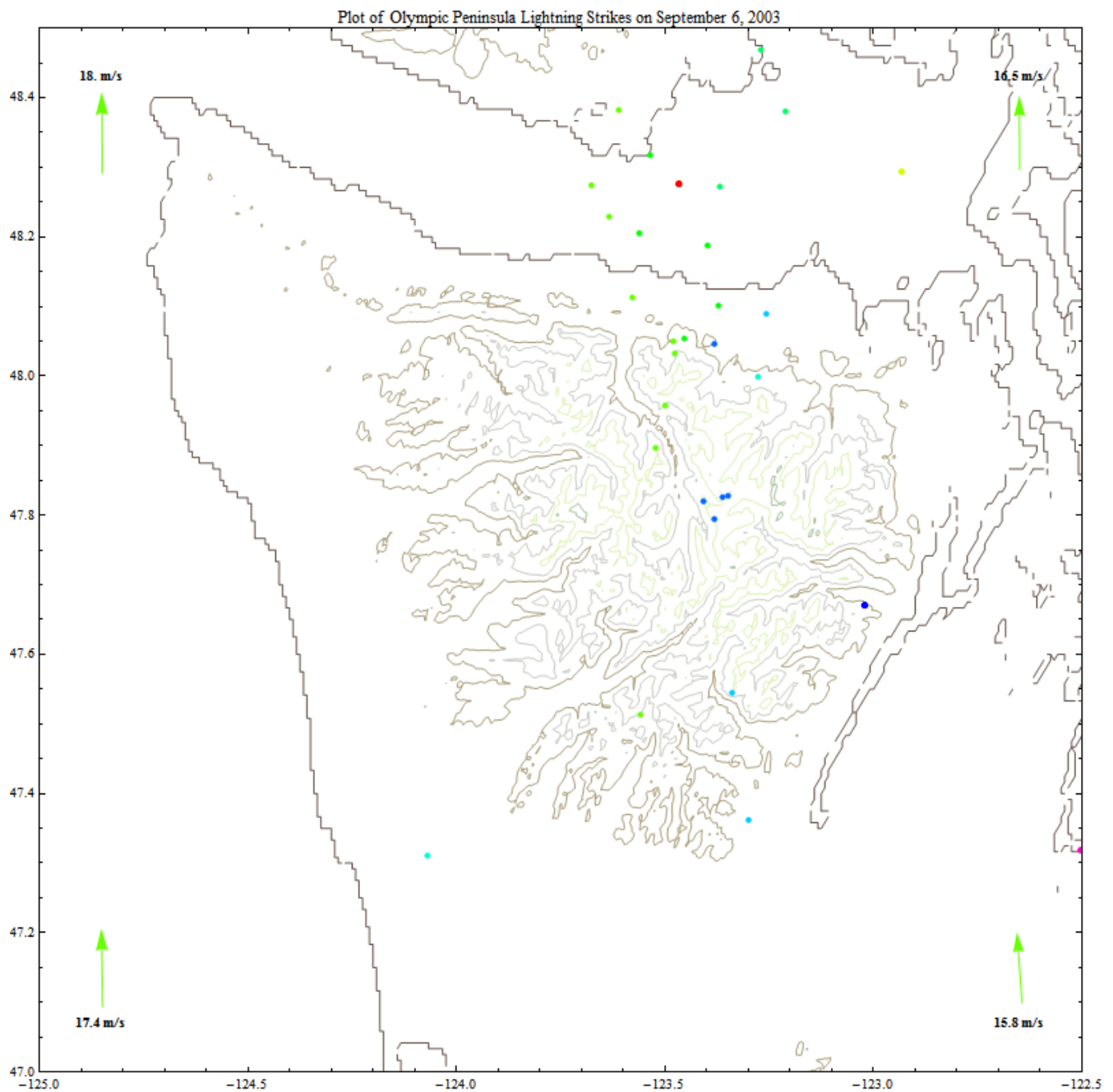
This last afternoon event was a relatively minor event (seventeenth largest). It was chosen because it caused the largest OP lightning fire in the study period – the Griff Peak Fire. The daily WNA progression of the event is shown in Figures C34a-e. Moisture from an easterly tropical wave progresses northward from the western desert southwest reaching the OP by the third day. Initially a cyclonic vortex off the California coast appears to be responsible for the lightning in much of California. However, by the third day this vortex has dissipated. But, a stronger cyclonic circulation appears to the north, centered at around 53°N latitude and 140°W longitude. The 700mb wind at the hour of peak activity is almost directly from the south on the OP (Figures C34c). On the 4th and 5th days the activity is swept further east and the vorticity has dissipated by the 5th day (Figures C34d&C34e).

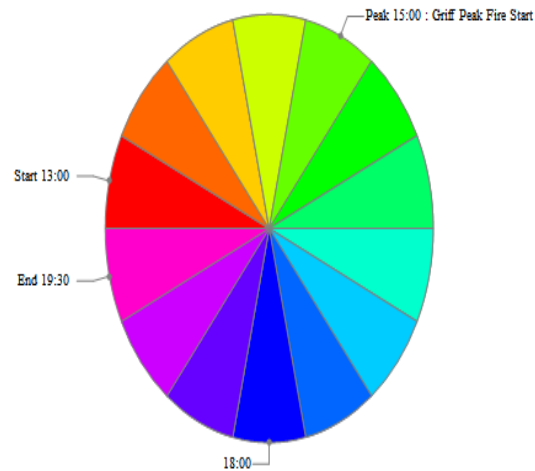


Figures C34. Same as Figure C1 except for the five day sequence surrounding the September 6th, 2003 case study.

The individual strike locations at the time of peak activity on the OP are on the north facing side of the Olympic Mountains and to the north in the Strait of Juan de Fuca (Figure C35). (As in the *August 17, 2008* case study, the Griff Peak fire start location provides some information about the

accuracy of the strike locations (**Appendix C2**)). This peak activity is once again (as in several of the previous case studies) on the downslope side of the mountains. However, there is some later activity on the upslope side.





Figures C35. Same as Figure C2 except for the September 6th, 2003 case study.

Strike activity varies considerably with elevation over the period of activity and seems not to be well correlated with the cloud base height in this case (Figure C36). However, it remains consistently below the cloud base height for this time period.

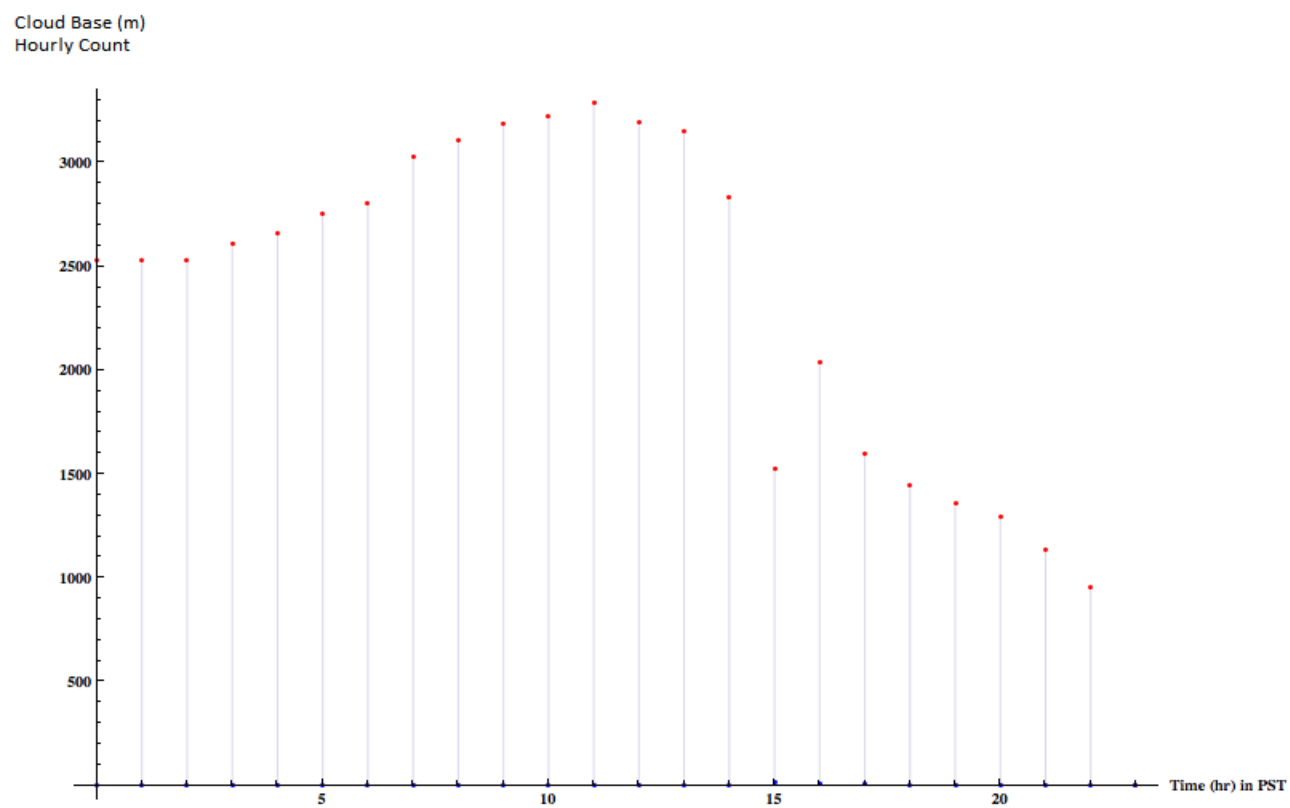


Figure C36. Same as figure C3 for September 6th, 2003.

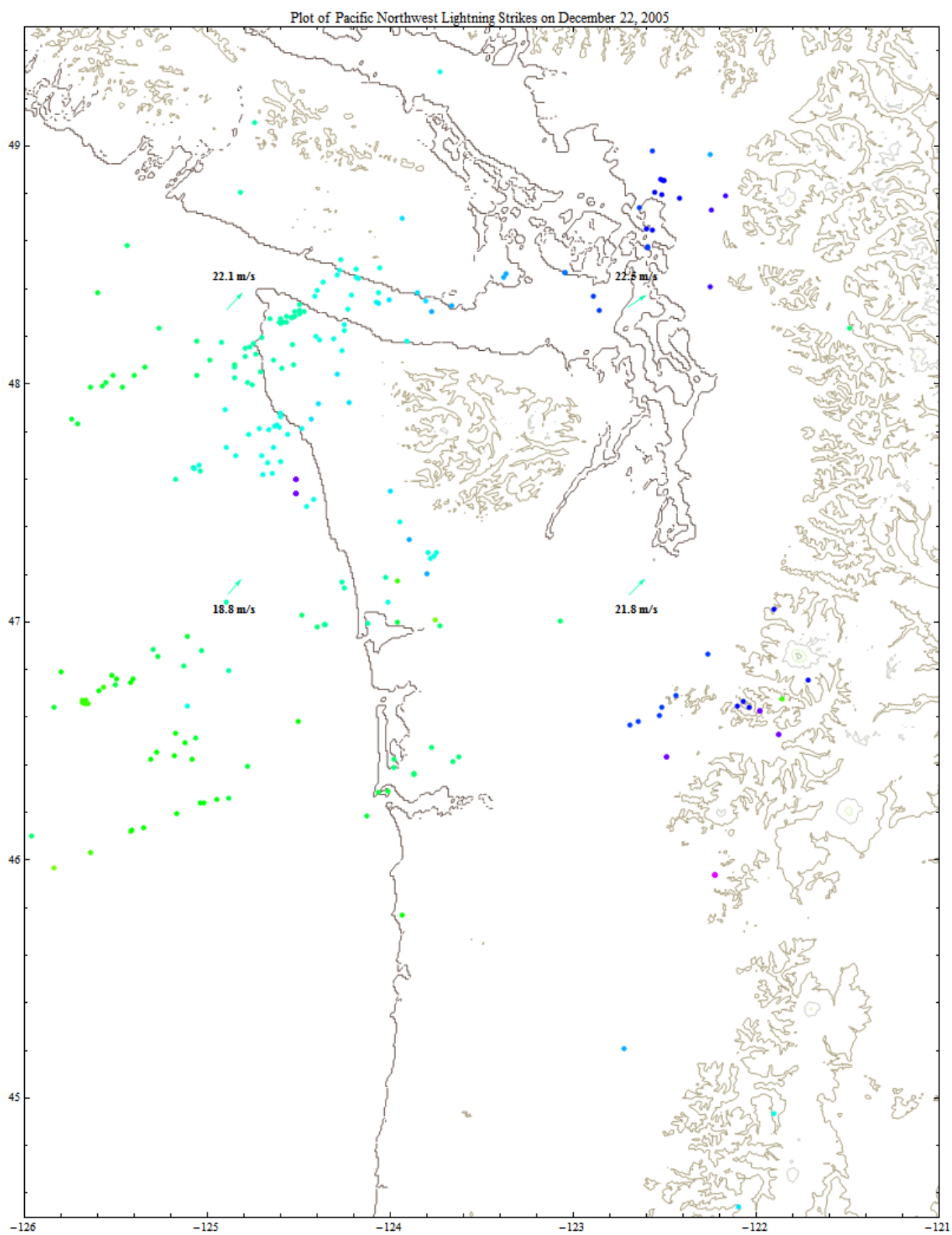
Wet Season

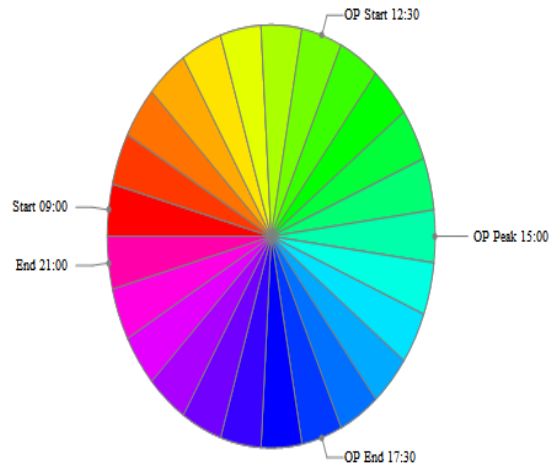
The two largest events that occurred on the OP during the wet season are also examined. Several authors have associated wet season lightning activity with frontal boundaries in northern hemisphere ocean cyclonic storms (McMurdie 2013, Makela et al 2013, Pessi and Businger 2009). We investigated this association for these two events as well as the progression of lightning activity across the OP.

December 22, 2005

This was the largest wet season event on the OP for the study period. Figure C37 indicate the strike locations during the period of peak activity over a region that extends north, south and east of the OP. This was done in order to make it easier to associate this event with synoptic scale cyclonic storm events. Figure C38 is a surface weather map indicating a frontal boundary off the Oregon Washington coast 11 hours preceding the time of peak lightning on the OP (http://www.hpc.ncep.noaa.gov/dailywxmap/index_20090601.html). This front would be rotating cyclonically about the low pressure area off of the British Columbia coast. Figure C39 is the Goes 10 IR satellite image for this time. Cloudiness associated with this low pressure area (which is somewhat enhanced along the frontal boundary) is apparent in the image. This feature appears to have moved onshore at the OP and roughly aligned with the shoreline in the satellite image for a time that corresponds to one hour after the time of peak lightning activity on the OP (Figure C40). One other piece of evidence supporting this association is the alignment of strike activity at the several specific times (12:30, 15:00, 17:30 (Figure C37)) as this activity moves to the northeast. The alignment at all three of these times appears to coincide roughly with the shore line (Figure C37).

As was the case for the warm season events discussed above, Figure C37 also indicates that active cells imbedded in these fronts appear to be moving in the direction of the 700mb winds, which are plotted at 4 locations on the OP (corresponding to the time of peak activity). Specifically, the vector in the northwest quadrant is located near an active cell progressing in the same direction – with a frontal boundary nearly perpendicular to the cell motion.





Figures C37. December 22nd, 2005 case study. a) Strike locations on the OP and surrounding locations during a period surrounding the time of peak activity. b) Wind vectors and strike locations are color coded for 30 minute time increments. The times of the initial, final, and peak increments are also indicated on the “color wheel”.

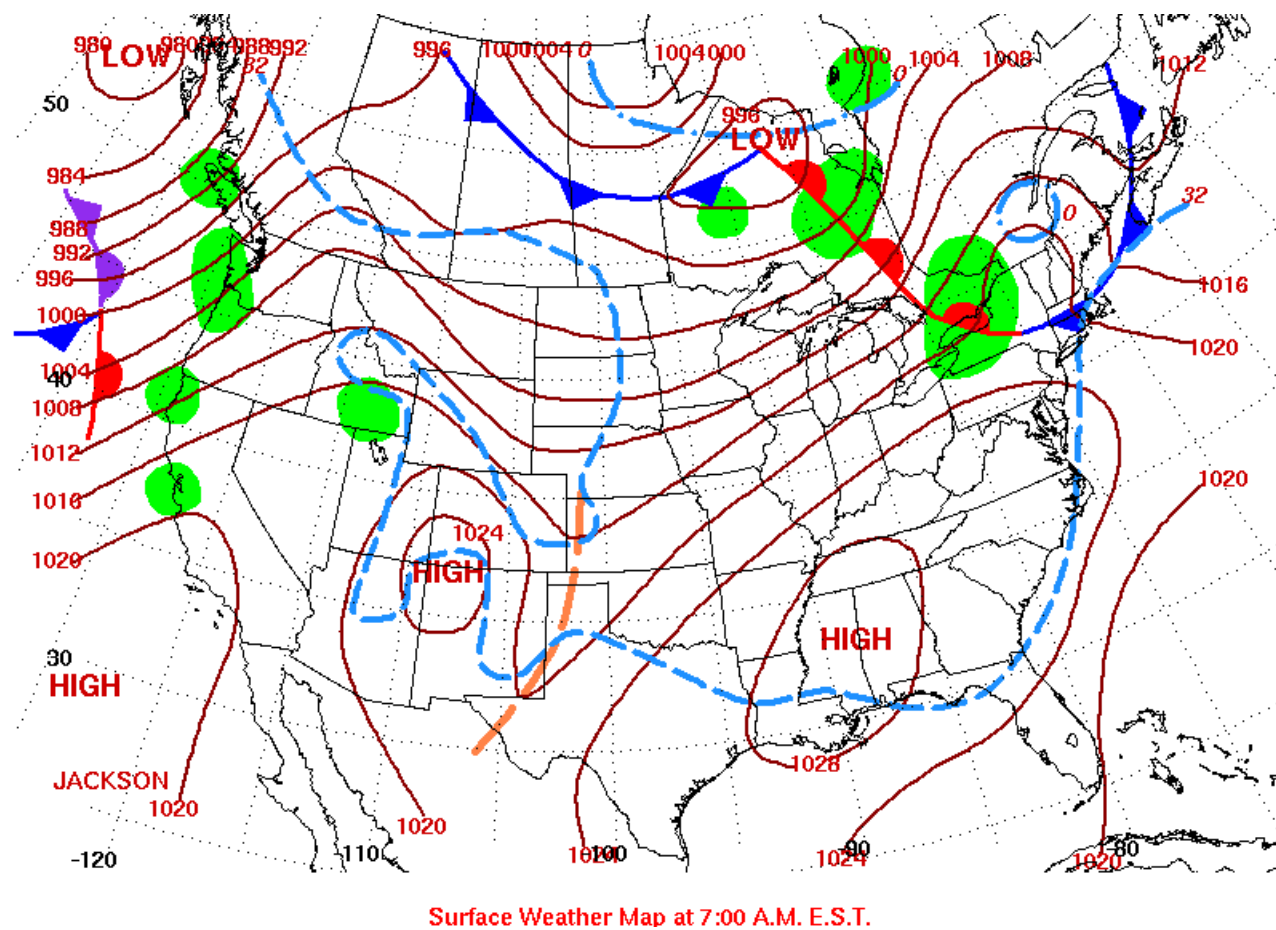
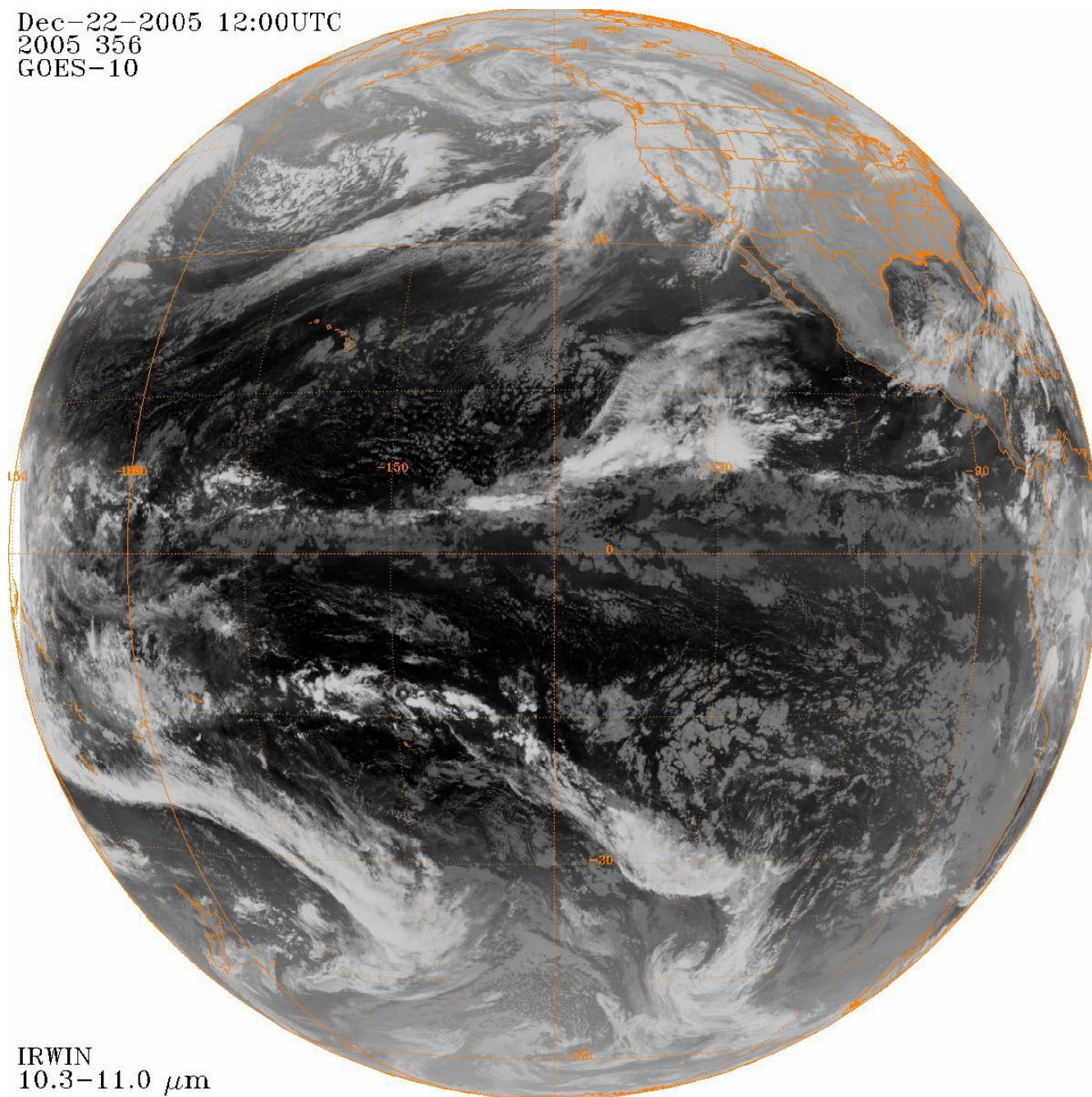


Figure C38. Contiguous United States and surrounding area surface weather map for 4am PST, December 22nd, 2005.

Dec-22-2005 12:00UTC
2005 356
GOES-10



IRWIN
10.3–11.0 μm

Figure C39. GOES infrared satellite image for 4am PST, December 22nd, 2005.

Dec-23-2005 00:00UTC
2005 357
GOES-10

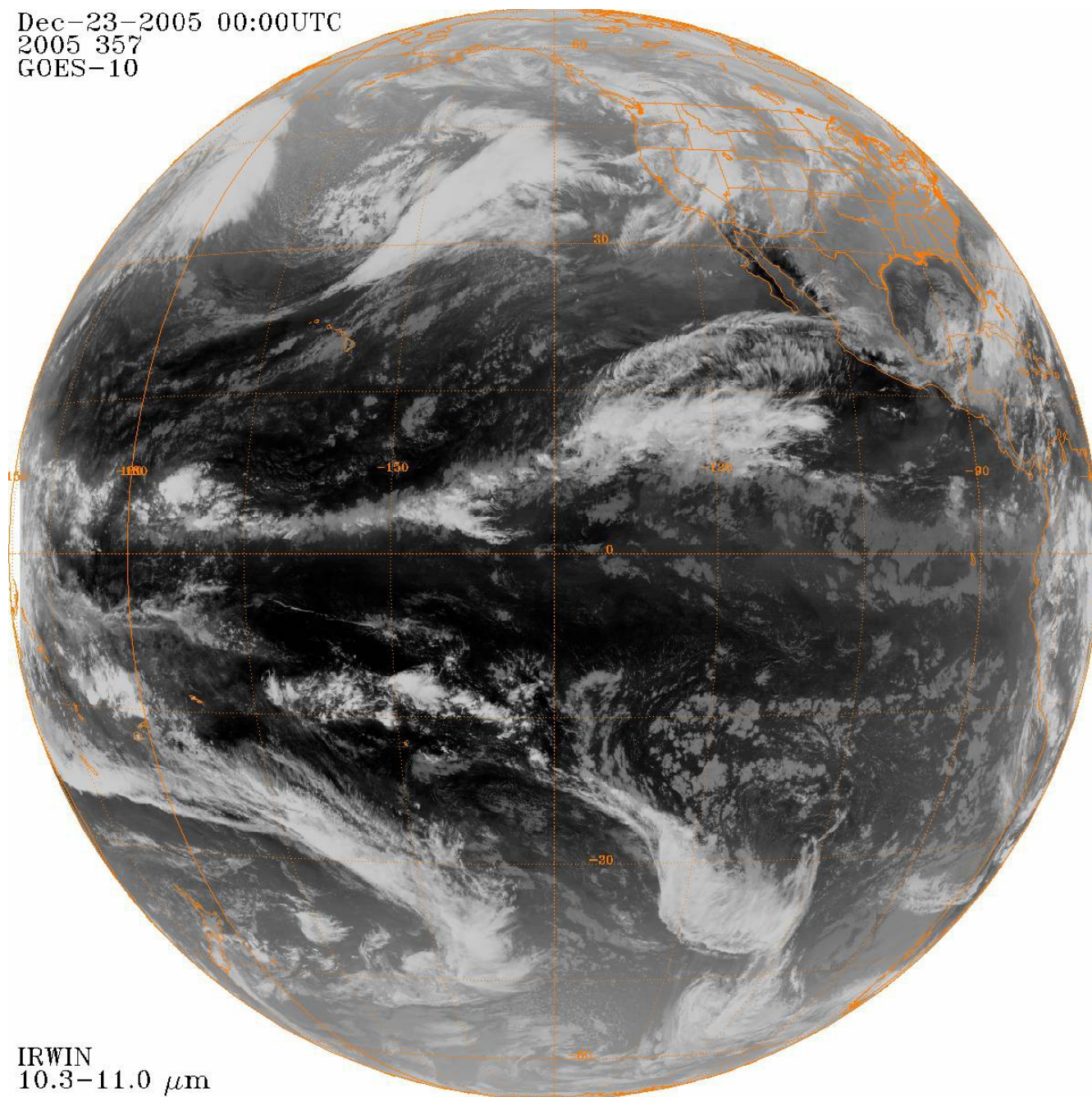
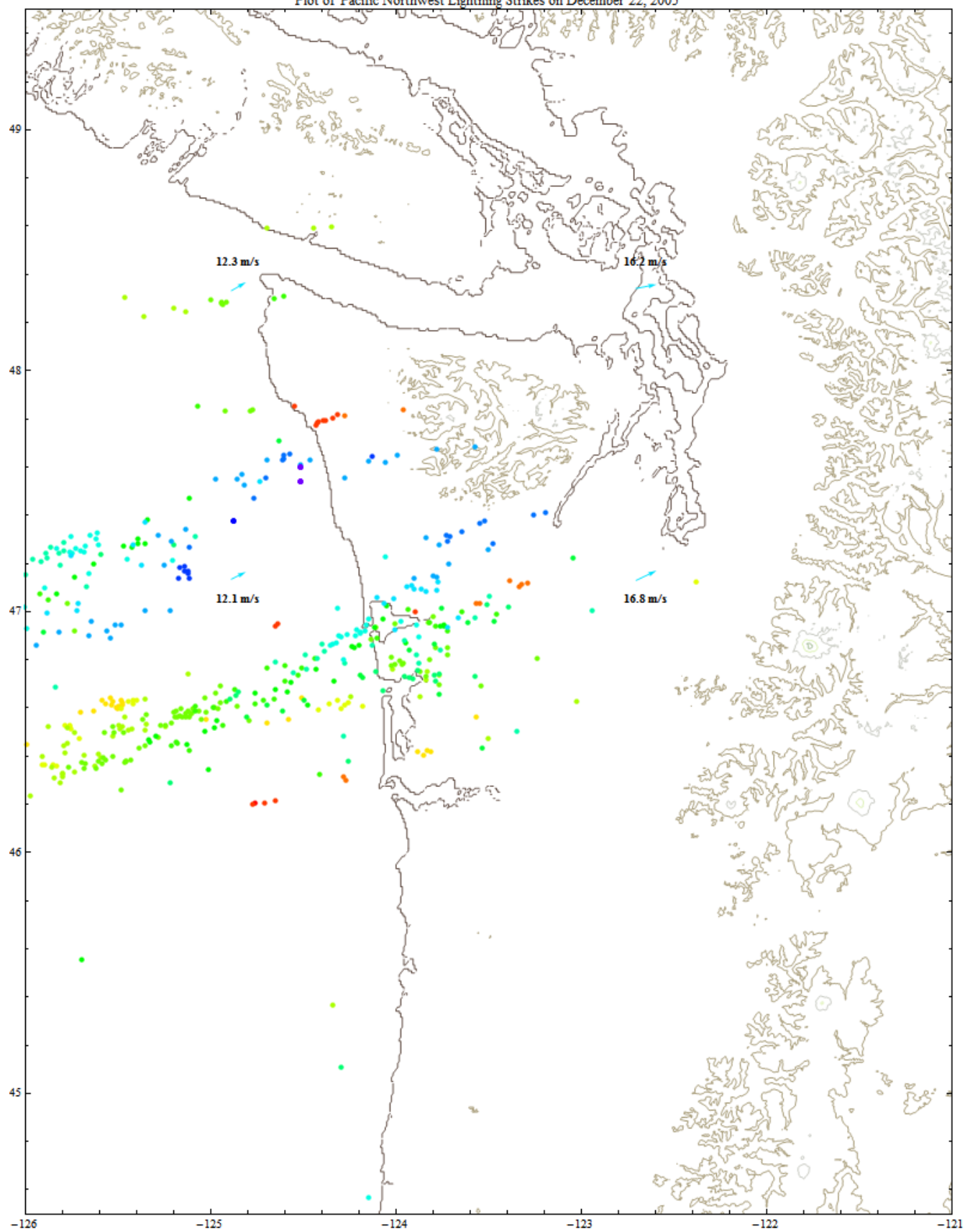


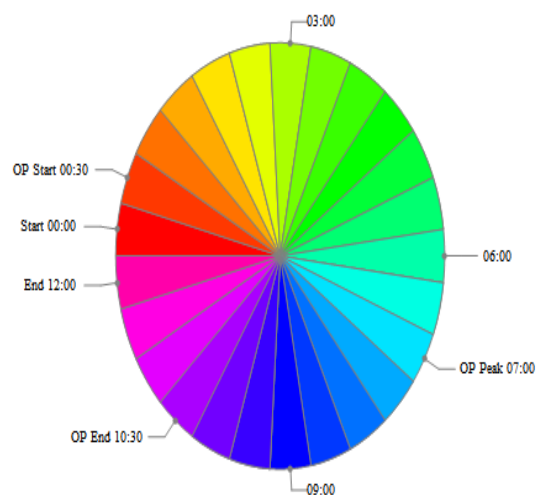
Figure C40. GOES infrared satellite image for 4pm PST, December 23rd, 2005.

November 12, 2006

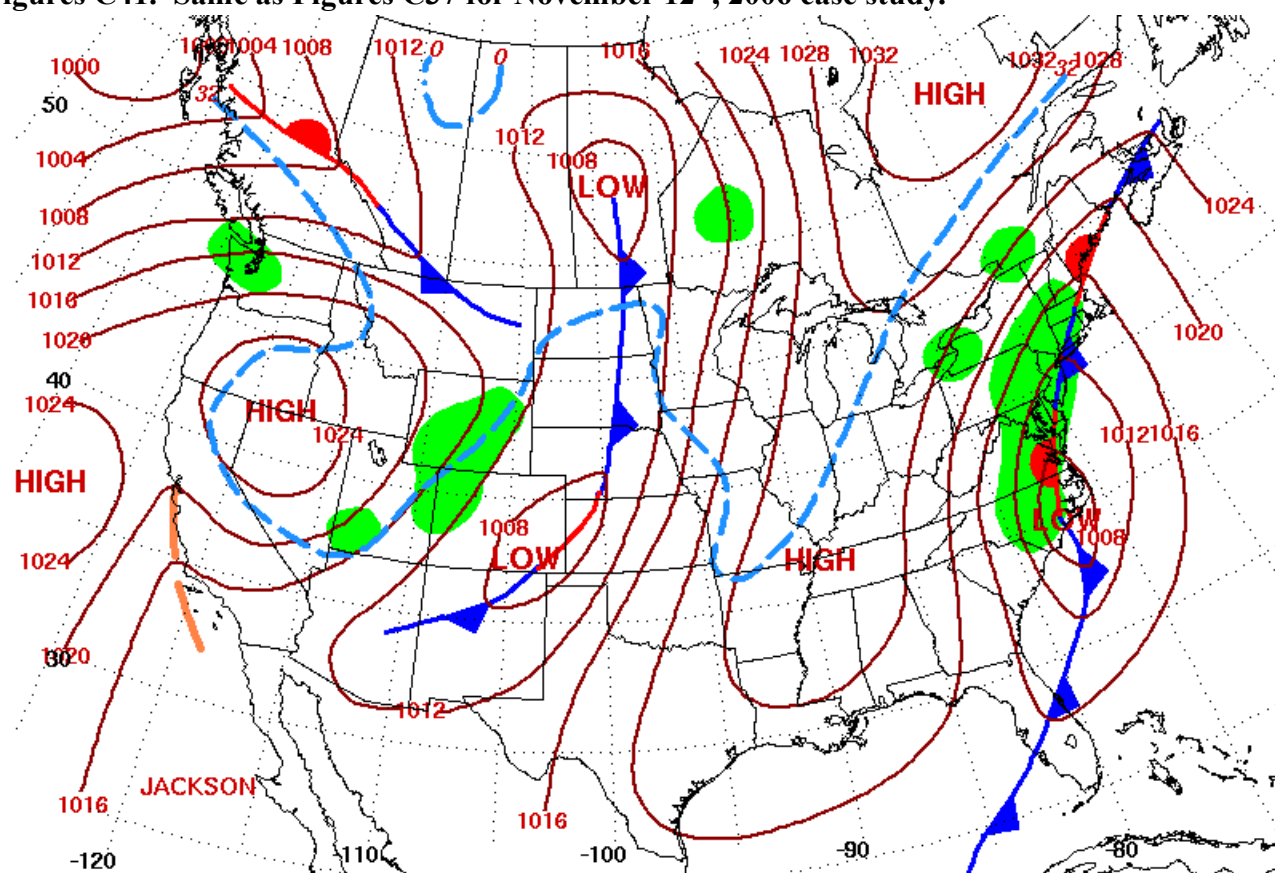
This second largest wet season event has a somewhat different character than the previous case study. The two strike patterns are similar in that strike activity approaches from the southwest and is confined to lower elevations (see the Elevation Distribution section). The actual strike pattern on the peak day of activity looks remarkably different (Figure C41). Near the peak time, the strikes are concentrated along two distinct lines of activity moving from the southwest across the coast line -as opposed to the concentration of activity along an apparent frontal boundary in the previous case (Figure C37). Even though no surface frontal boundary appears for this event (Figure C42), a weak frontal line of lightning activity can be detected in these two lines of lightning activity. Looking at the activity at times 6:00, 7:00, and 9:00 in Figures C41, frontal lines associated with these times can be thought of as extending from the west northwest to the east southeast. At the time of peak activity the GOES 11 satellite IR image reveals a distinct line of clouds over the activity area and oriented in the same direction of the “frontal” lines of lightning activity (Figure C43). The three hour sequence of IR images preceeding and succeeding this peak time (not shown) indicates that the cloud line advances in the same direction of these “frontal” lines. Furthermore, this progression can be thought of as rotating between the surface low off the British Columbia Coast and the surface high over the desert southwest (Figure C42). (A similar pressure dipole was present in the previous case (Figure C38), but the low pressure center contained a deeper low and consequently resulted in a stronger pressure gradient between the dipole centers.) The other common feature with all of the warm and wet season previous cases is that the direction of motion cells of lightning activity is well described by the 700mb wind direction (Figure C41).

Plot of Pacific Northwest Lightning Strikes on December 22, 2005





Figures C41. Same as Figures C37 for November 12th, 2006 case study.



Surface Weather Map at 7:00 A.M. E.S.T.

Figure C42. Same as Figure C38 for November 12th, 2006.

Nov-12-2006 15:00UTC
2006 316
GOES-11

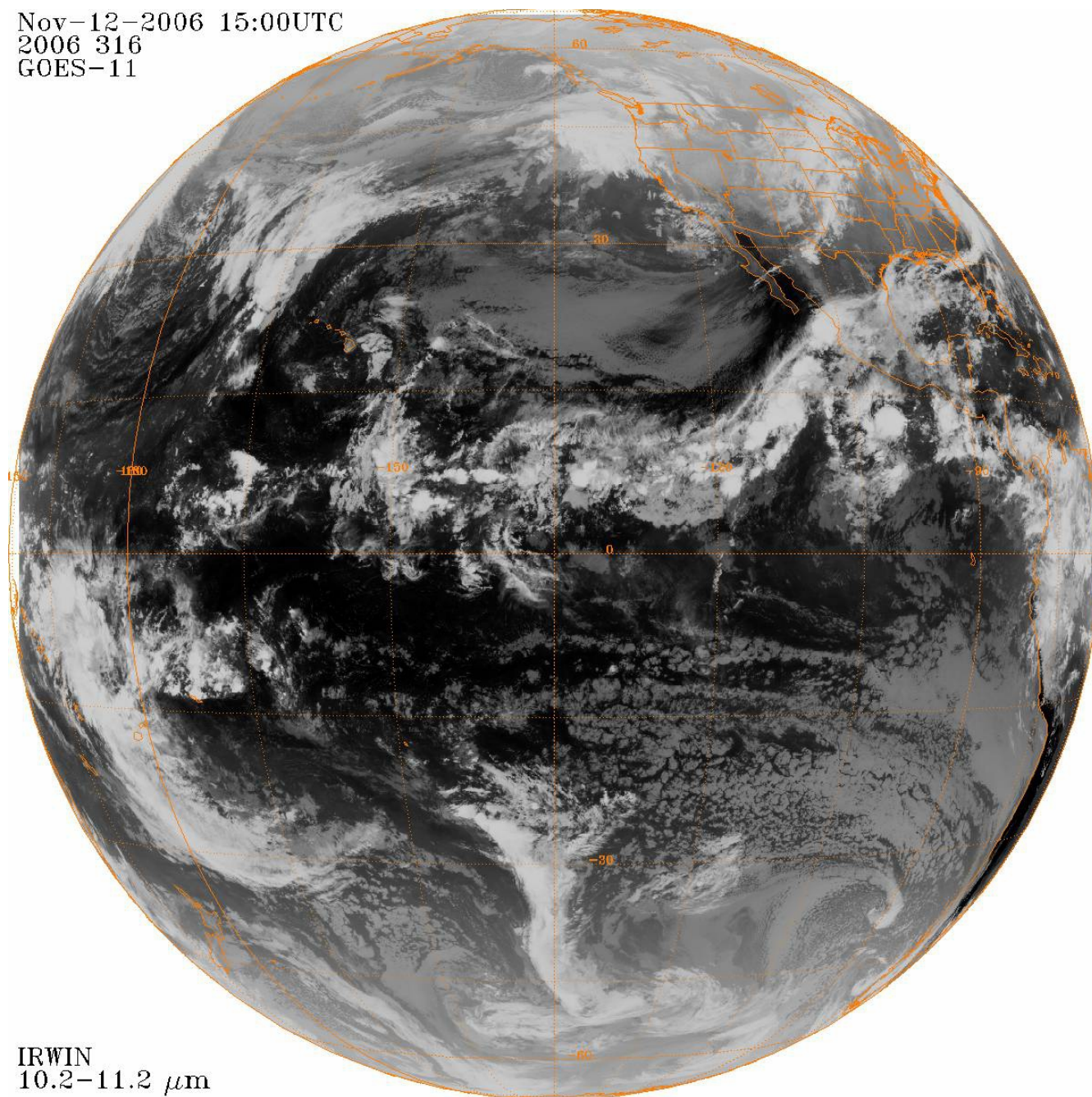


Figure C43. GOES infrared satellite image for 7am PST, November 12th, 2006.

D. Interannual Behavior

The 25 year OP lightning data set provides an opportunity to speculate about causes of interannual variability. We investigated three characteristics of the annual lightning season: the yearly start date of the warm season, the annual warm season totals, and the wet season totals. Given the relatively small number of annual lightning events on the OP, either a much larger study area or much longer time series is needed to begin to assign statistical certainty estimates to interannual variability. We took the deviations from the mean annual cycle (Figure A1) as a starting point to initiate this investigation.

The daily total OP lightning strikes for the year 2009 (Figure D1) might seem to represent a typical annual cycle contributing to the mean annual distribution. This is not the case, as suggested by the daily total for 2001 (Figure D2). The dominance of wet season strikes for this year indicates that the influence of the mid latitude eastern Pacific Ocean plays a significant role in the interannual variability of the annual distribution. The error bars in Figure A1 imply that this variability is not only due to interannual variation of the wet season, but also that of the warm season. This observation is summarized in Table D1; the variation of the annual ratio of wet season to warm season lightning (We/WA) can be seen to be influenced by the annual variation of both of these components of the total annual lightning. An examination of each 25 years of daily total lightning (not shown) also indicates that the separation of the end of the warm season and beginning of the wet season by only one month makes it impossible to identify a day of transition from end warm season type events to beginning wet season events. However, the intervening spring season makes it possible to identify a day of initiation of warm season events. The daily total lightning for the year 2007 (Figure D3) illustrates the problem in identifying an end day for the warm season as well as the possibility of identifying a beginning day of the warm season (day 194, July 12th). This is an issue of current interest in wildfire research because of the recent earlier fire season start time, and its association with climate change (Westerling et al 2006).

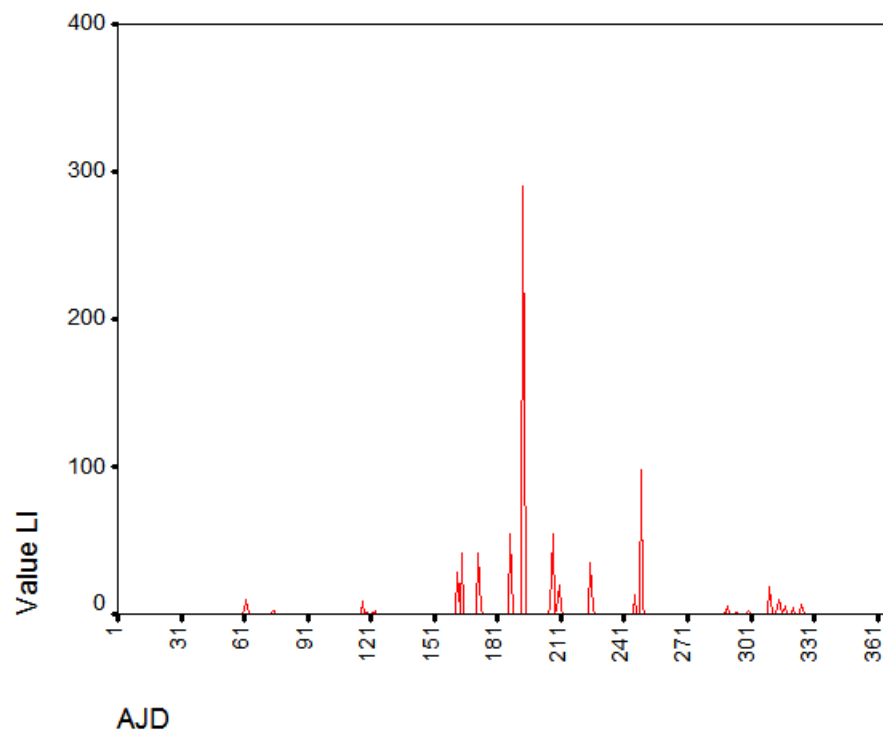


Figure D1. Total daily strikes on the OP as a function of days (AJD) of the year for 2009.

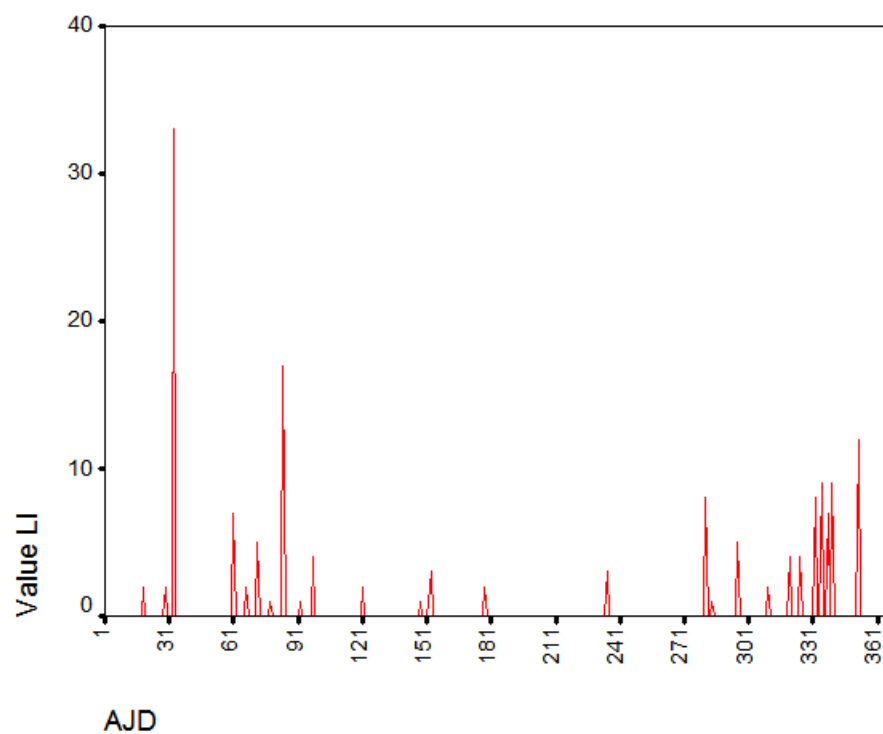


Figure D2. Same as Figure D1 for 2001.

Year	Wa li	We li	We/WA
1985	102.72		
1986	801.22	46.22	.06
1987	239.68	176.34	.74
1988	111.28	135.25	1.22
1989	647.14	15.41	.02
1990	410.88	23.97	.06
1991	854.29	205.44	.24
1992	881.68	89.02	.10
1993	268.78	7.85	.03
1994	571.00	19.00	.03
1995	678.00	63.00	.09
1996	107.00	50.00	.47
1997	2695.00	133.00	.05
1998	170.00	519.00	3.05
1999	2207.00	42.00	.02
2000	161.00	73.00	.45
2001	9.00	75.00	8.33
2002	179.00	78.00	.44
2003	237.00	90.00	.38
2004	288.00	41.00	.14
2005	487.00	206.00	.42
2006	199.00	306.00	1.54
2007	151.00	45.00	.30
2008	650.00	14.00	.02
2009	699.00	50.00	.07

Table D1. Warm and Wet season OP annual total strike counts and count ratios for the study period. (The detection system was not operational for the whole 1985 wet season).

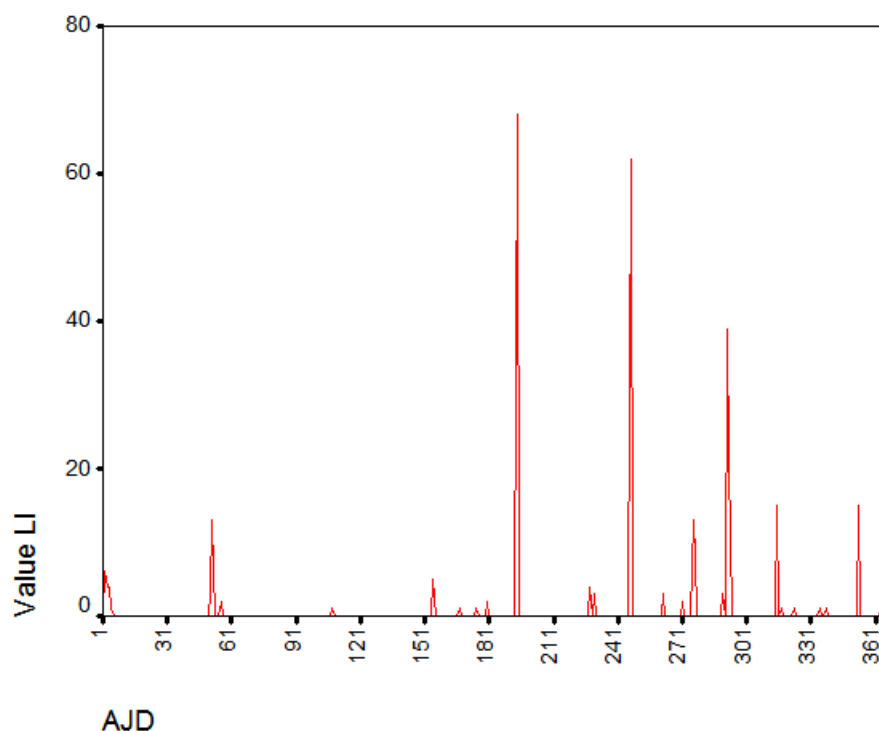


Figure D3. Same as Figure D1 for 2007.

Almost all seasons in the 25 year sequence exhibit a significant rise in cloud to ground lightning activity late in the spring. From the perspective of moisture as the main driver of instability leading to lightning activity, this surge of activity suggests a transition from mid latitude sources of moisture to tropical sources characterizing summer activity. For each year the actual daily lightning strike counts were first converted to z scores to obtain a unified measure of the annual daily activity time series. Figure D4 is a plot of this time series for 2007. A detailed examination of the time series indicates that the first day when the z score exceeds 2.25 is day 194. While this criterion is subjective, it can be used to identify a warm season start day for all but 5 of the years in the time series. Those years for which a start day could not be identified by this criterion had unusually strong end of winter or spring season lightning events. (The 2001 year (Figure D2) is an example of such a year). Figure D5 is a plot of the start days for each year for which a start day could be assigned by this criteria. No clear trend is apparent in this time series – and certainly not a trend toward earlier start days. The mean start day is day 167 which corresponds to June 16th (for non leap years).

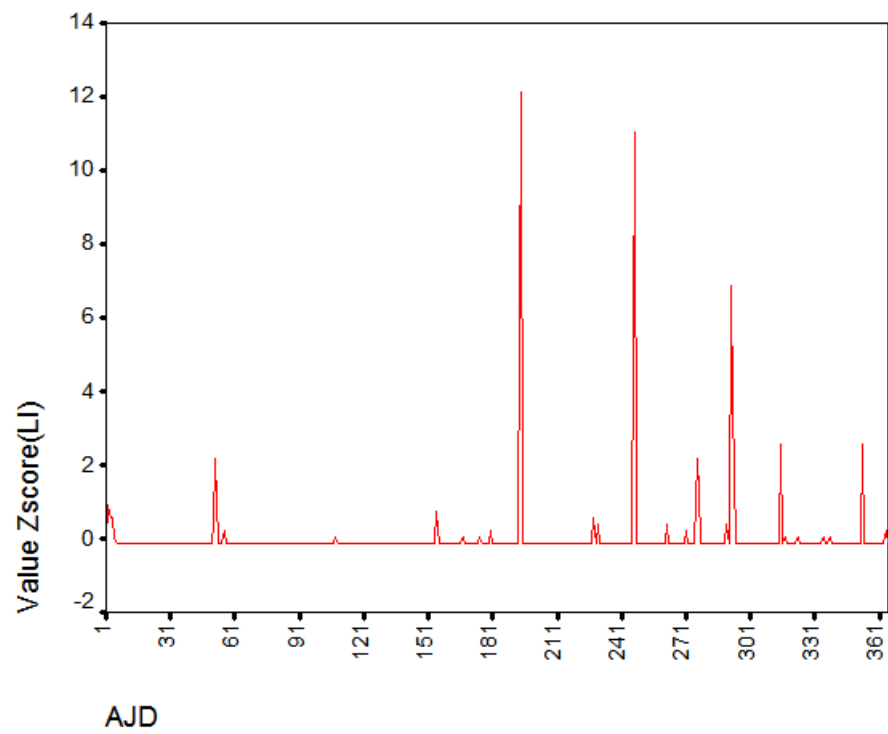


Figure D4. Z scores of total daily strikes on the OP as a function of days of the year for 2007.

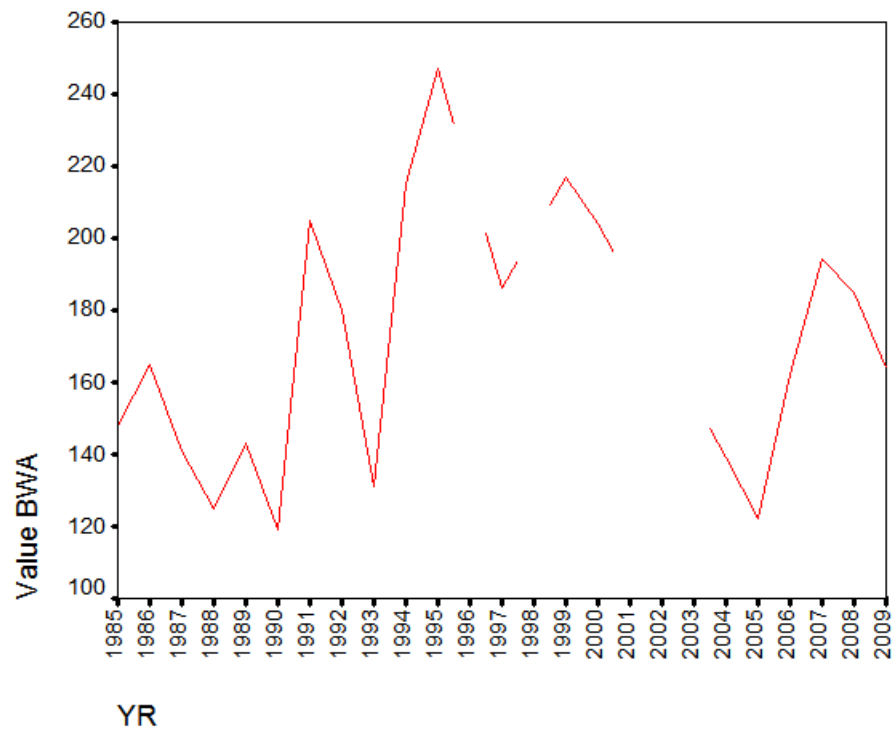


Figure D5. First days of the year for which the daily strike z score was greater or equal to 2.25. Years for which this measure could not be applied are not plotted.

The subset of warm season lightning events which occur in the afternoon displayed more complex storm motion behaviors than the major events during the warm season (discussed in the **Storm Motion** subsection “Afternoon Events During the Warm Season”). The suggestion that diurnal heating was a possible cause for the variability of these events was tested on an interannual time scale by plotting the time series of the z scores of the annual average afternoon warm season temperatures from the Cougar Mountain data set as well as the z scores of the total afternoon lightning (Figure D6). No strong relationship is apparent. (Although, there does seem to be a weak inverse relationship in the general trend of the two time series, with a general trend toward higher temperatures and decreased lightning.) However, a correspondence is apparent between the annual total warm season lightning and the afternoon lightning (Figure D7). This suggests that the tropical moisture which is an important determinant of the major warm season lightning activity also is a determinant of the subset of afternoon lightning activity.

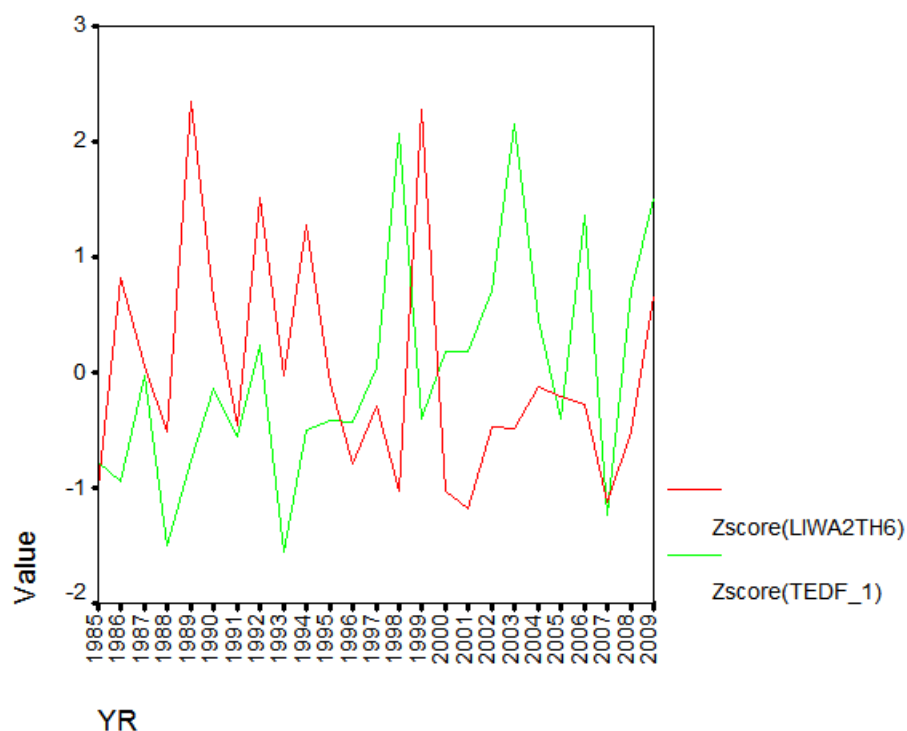


Figure D6. Time series of the z scores of the average afternoon (2-6pm) temperatures for the warm season (measured at Cougar Mountain) – green, and the z scores of total afternoon warm

season lightning strikes on the OP – red.

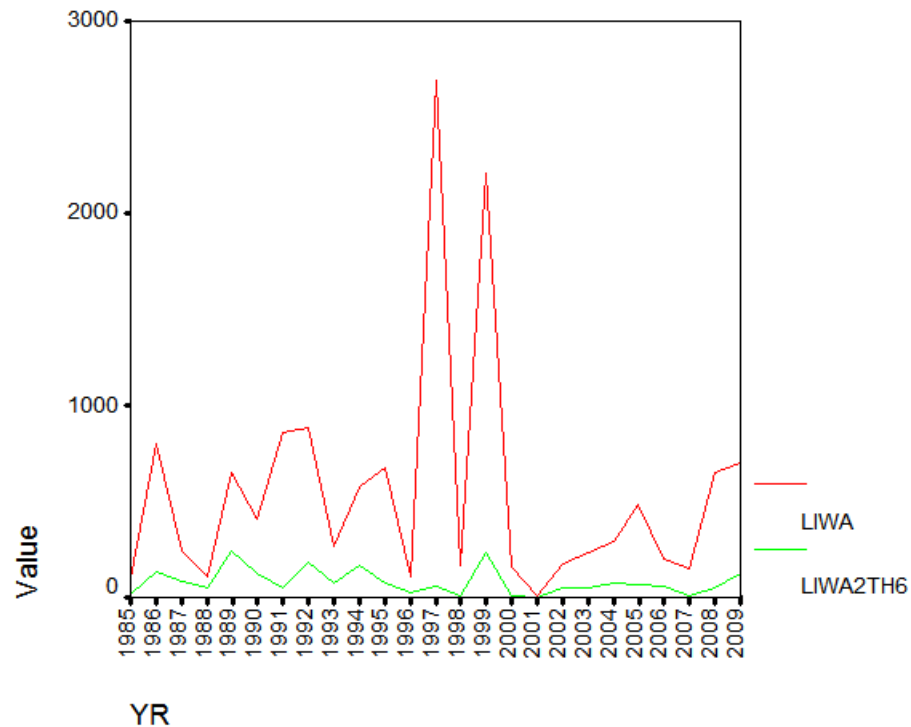


Figure D7. Time series of the annual total warm season lightning – red, and the annual total afternoon warm season lightning – green.

One of the fundamental characteristics of an El Nino is the increase in surface ocean temperatures in the eastern tropical Pacific Ocean (Trenberth 1997). It would be reasonable to expect that these events would play a role in increasing atmospheric tropical moisture and consequently increasing lightning activity on an interannual time scale of several years. We took the Nino 3.4 monthly ocean surface temperature data as a measure of El Nino activity (Trenberth 1997). We averaged the warm season Nino 3.4 temperatures and compared them to the warm season lightning activity by computing their z scores for each of the 25 years (Figure D8). The correlation between the two time series is quite good with the singular exception of the large peak in lightning activity in 1999. An examination of the warm season activity for this year reveals that 81% of the strikes occurred

during the August 4th event discussed above in the **Storm Motion** section. Not only is it the largest single event in the 25 year study period, but the source of its moisture appears to have originated in the Gulf of Mexico. This is in contrast to the larger 1997 year whose major event appears to have a moisture source from the eastern tropical Pacific. Indeed, many of the warm season case studies in the **Storm Motion** section exhibit this tropical moisture source. This generally more western source tropical moisture relative to those of the desert southwest monsoon area might be expected since the OP events themselves are west of this active monsoon area (Adams and Comrie 1997). Since the 1999 season is dominated by an event with moisture origins in the westernmost Atlantic Ocean whose temperatures would be expected to be enhanced by La Nina conditions (Alexander et al, 2002), it is not surprising that this year appears as an exception in Figure D8. If this data point is removed from the time series, the Pearson Correlation becomes .55.

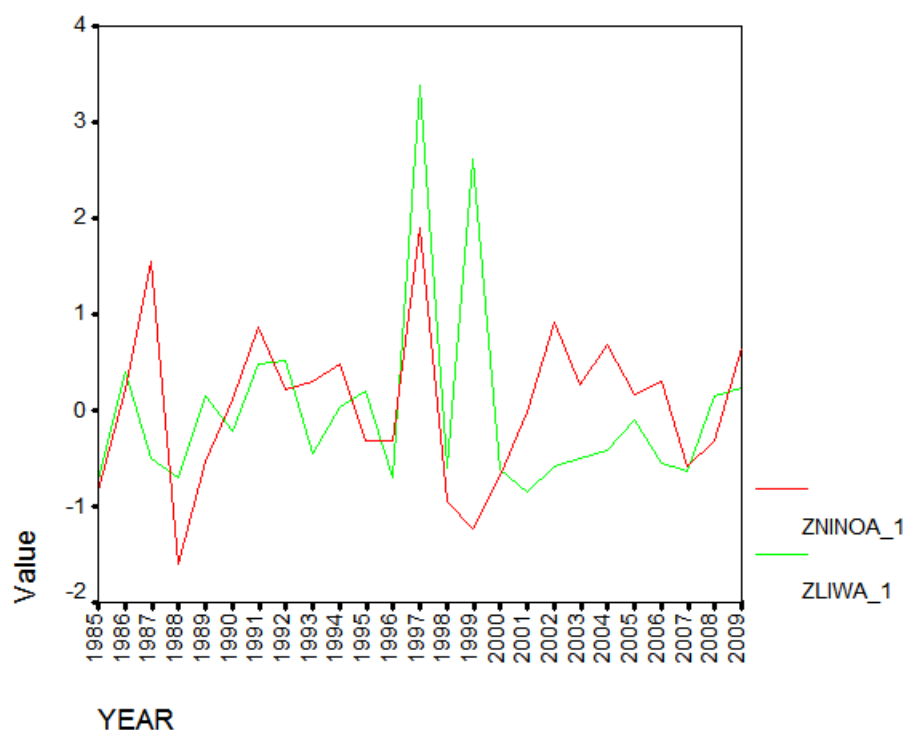


Figure D8. Time series of the z scores of the annual total warm season lightning – green, and the z scores of the annual average warm season Nino 3.4 ocean temperature – red.

Lower cloud bases in wet season lightning events might better be associated with moisture nearer the surface of the earth than at the 700mb level moisture which characterizes the moisture source for warm season events. A data set of specific humidity from actual measurements near 2m that includes the 25 year period of this study has recently been published (Willett et al 2013). The measurements were made over land, with the vast majority at sites in the Northern Hemisphere. Figure D9 is a plot of the z scores of the annual wet season average of these measurements as well as the z scores of the wet season lightning. The correlation between these two time series is .61. While the wet season lightning has not increased significantly over the 25 year time period the specific humidity does appear to be increasing. This increase is even more apparent over the whole period of the specific humidity time series (from 1973 through 2012) (Willett et al 2013).

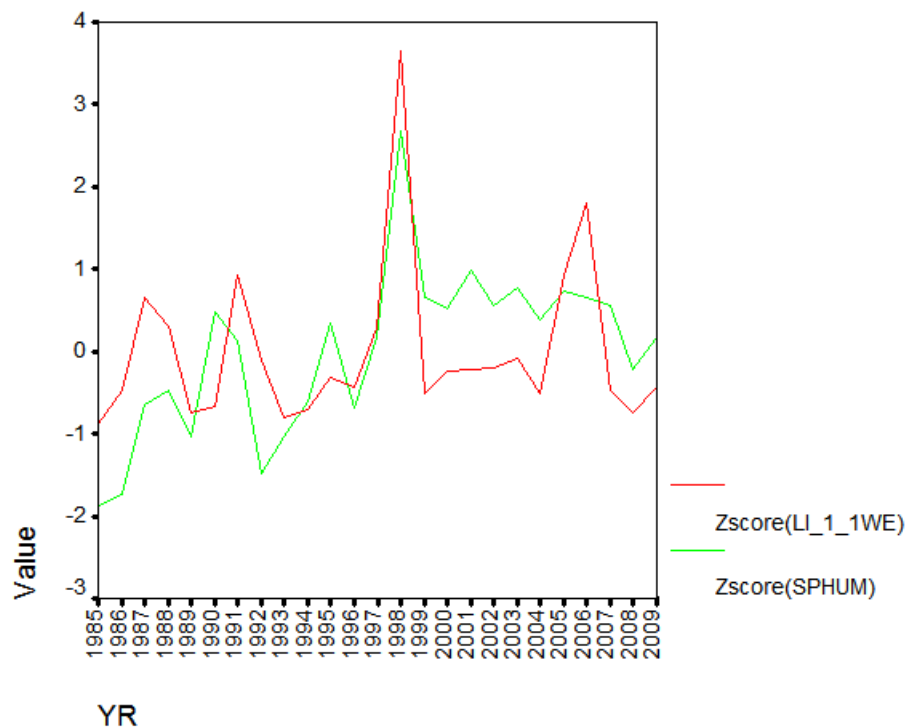


Figure D9. Time series of the z scores of the annual total wet season lightning – red, and the z scores of the annual averaged 10m specific humidity over land – green (adapted from Fig. 2.10, Blunden and Arndt, Eds. 2013).

Mears et al (2013) discuss the interannual variation in water vapor near the surface of the earth in the context of El Nino, La Nina events in. Specifically they identify a 1998 peak as being associated with the 1997 El Nino – the most significant event of the 25 year period. This association would suggest that the near surface water vapor increase may show up approximately 1 year after the appearance of the 1997 El Nino. We examined the relationship between the lightning events for the warm season and the wet season 1 year later in (Figure D10). With the exception of the 1999 year, the relationship between the two is quite remarkable. If, once again, the 1999 warm season lightning is removed, the correlation between the two time series is .70.

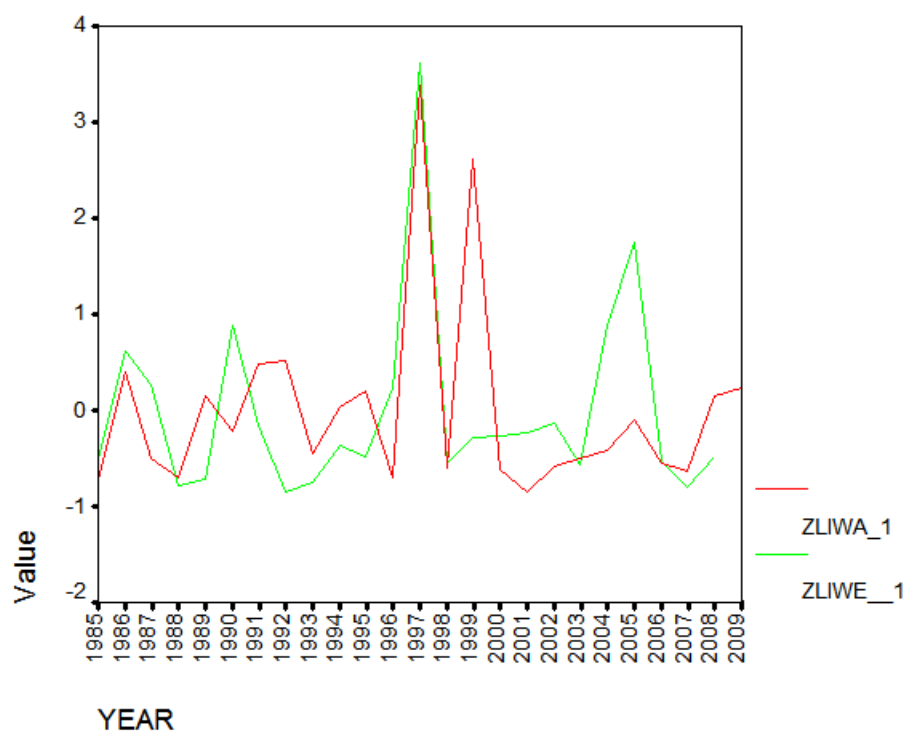


Figure D10. Time series of the z scores of the annual total warm season lightning – red, and the z scores of the annual total wet season lightning one year later – green.

All three categories of events (warm season major events, warm season afternoon events, and wet season events) appear to be primarily driven by atmospheric moisture. This moisture seems to be primarily related to El Nino/La Nina activity. This result is consistent with interannual study of lightning over the PNW (Estberg et al 2008). Other factors would be expected to show up with statistical significance in larger, more active study areas. Recently for example, a relationship between the tropical Madden-Julian oscillation (MJO) and cloud-to-ground lightning activity over the continental United States has been demonstrated (Abatzoglou and Brown 2009). While overall trends in lightning activity are not apparent for the 25 year time series used for this study, the association between lightning and atmospheric moisture (which does appear to be increasing), suggests that a long term trend in lightning activity may be revealed.

Conclusions

The lightning climatology of the OP offers a slightly different perspective than most regional climatologies, primarily because of the influence of its eastern mid latitude Pacific marine environment. Rarer and more rapidly curtailed lightning episodes as well as dramatic seasonal shifts in polarity and elevation distributions are examples that distinguish this climatology from those of non-coastal environments. On the other hand, two of the approaches developed in this investigation suggest an improved understanding of thunderstorm development in any mid latitude coastal environment, and, more generally, in any environment especially where orography is a significant factor.

The first approach has been to investigate moisture dynamics as a fundamental cause of instability leading to thunderstorm development rather than emphasizing measures of vertical instability themselves such as the Lifted Index and CAPE. The investigation of the dynamics of the northward propagation of tropical moisture leading to the North American Monsoon has been studied by many investigators (Adams and Comrie 1997). On a more local synoptic scale, we have examined the dynamics of tropical moisture propagation leading to warm season OP lightning events. Our primary finding is that of the influence of a 700mb cyclonic mid latitude eastern Pacific circulation on the specific location tropical moisture propagation into the PNW. The location of these “cyclonic vortices” seems to influence the location of major thunderstorms which develop near the coast. The development of this cyclonic circulation is generally dictated by upper troposphere atmospheric dynamics and typically is swept eastward by Rossby waves in the 250mb jet stream. But, in some cases, the cyclonic vortex can remain remarkably stable and lead to prolonged lightning events such as in the June 21st, 2005 case study presented in the **Storm Motion** section. In a few of the case studies the cyclonic circulation was actually on land, but near the coast, resulting in storm motions not from the south (for example, the June 11th, 2006 case study, where the storm direction is from the north-northeast). In all warm season cases investigated, the lightning events ultimately ended with the

moisture being swept to the east by cooler onshore winds. Given the success using this approach to understand OP lightning events, developing a more sophisticated hydrological model of tropical moisture dynamics might improve current major lightning event forecasting skills.

The arrival of these major warm season surges of tropical moisture to the PNW would be expected at any time because of the complex factors influencing them (see Figures A6-A8). However, there is a distinct afternoon diurnal distribution of the majority of lightning strikes (Figure A10), and an even more dramatically apparent afternoon peak in the spring (Figure A17). The afternoon event case studies presented in the Storm Motion section, above, do not conform to the model developed for major lightning events. These less intense, but more numerous lightning events are probably best described and predicted – at least in the short range by measures of vertical instability such as the Lifted Index and CAPE.

The second approach was to confirm the speculation by Schulz and Diendorfer (1999) that the elevation of the lightning intensity peak is just below the local cloud base. We did this by calculating the mean cloud base for the peak hour of every large warm season lightning event day (**Appendix A1**). We compared this height to the warm season lightning elevation distribution peak (Figure A21). The cloud base height was greater than the lightning elevation peak, but taking into account the error bars from both calculations, the two ranges overlapped (see the Elevation Distribution section above). Neither we nor Schulz and Diendorfer attempted to resolve the issue of whether or not the decline in intensity about the cloud base is real or reflects a decline in ground base lightning detector efficiency above the cloud base. This cloud base height limitation only occurs in the warm season and only in negative polarity elevation distribution (Figure A28) - not the positive polarity distribution Figure A29). This observation suggests that the difference is explained by the internal cloud charge distribution. The height limitation phenomena seems to be reflected in the diurnal cloud base height time series and in several of the case studies in the **Storm Motion** section – most notably in the low elevation path of the August 3rd, 1994 event.

An additional detector efficiency issue also has a bearing on this result. The spatial location accuracy of the detectors may be less than claimed in the detector specifications. This is suggested by a limited sample of steep terrain actual strike locations in **Appendix C2**. A larger strike location error would mean that the confidence intervals in the elevation distributions would be affected and consequently the certainty of the relationship of cloud base height and peak lightning intensity.

The relationship between spatial atmospheric moisture distribution and cloud base height in determining actual strike intensities needs further investigation. Many of the case studies presented in the Storm Motion section suggest that constraint of lightning intensity to regions of high moisture concentration appears to be the more fundamental determinant of lightning intensity distributions. Within the bounds of this constraint the cloud base heights add a secondary constraint to actual strike locations. The August 4th, 1999 and July 5th, 1997 case studies in the Storm Motion section provide insight about the relationship between these two constraint mechanisms.

Appendices

Appendix A1. Cloud Base Height Calculation

We calculated the cloud base for the peak hour of every large warm season event day. The peak hour was defined as the highest single hour of strike counts. We chose two strikes per hour as the minimum strike peak hour count to weed out any minor lightning events that may not be indicative of a Peninsula-wide lightning pattern. To prevent double-counting of single lightning events we chose only one hour - the peak hour - for each event day. There were 225 event days with two or more lightning strikes occurring in one hour.

We used two data sets to calculate the cloud base. There were 5 event days in June 1986 that neither dataset had values for, these days were removed and we were left with 220 event days in our total dataset. The first data set, accounting for 161 event days, was taken at Cougar Mountain, location 47.917 N, 123.117 W and elevation 914.4 m. The Cougar Mountain data was collected by the US Forest Service (<http://www.raws.dri.edu/cgi-bin/rawMAIN.pl?waWCOU>). A calculated cloud base height of 914 m – the elevation of the Cougar Mountain station - is the lowest possible calculated LCL value and indicates an event that occurred below the Cougar Mountain station. The second data set, accounting for 59 event days, was used to fill in the dates that were either missing in the Cougar Mountain data or had calculated cloud base heights of 914 m. This second data set was taken at Bremerton National Airport, location 47.483 N, 122.750 W and elevation 135 m (<http://www.ncdc.noaa.gov/cdo-web/>). The Cougar Mountain data was prioritized over the Bremerton data because of Cougar Mountain's location. Cougar Mountain is located at a higher elevation than Bremerton National airport and is therefore closer to the height at which we would expect to see the cloud base. Also, the Cougar Mountain station is in the eastern side of the Olympic Mountains where most of the lightning strikes occur and it is the largest, most complete and well-documented RAWS data set in the local area. The Bremerton National Airport station is located at a lower elevation and

near the water and is possibly less reliable due to its location. Additionally, the Bremerton data did not have temperature and dew point values for some of the peak hours of the 59 event days missing from Cougar Mountain; when this occurred we substituted the temperature values from the nearest available hour up to a 3 hour difference between the peak and actual hours. Three event days did not have data within 3 hours of the peak hour and were discarded from the dataset. The final cloud base data is composed of 217 event days.*

The cloud base height above the location where the temperature and dew point temperatures are measured can usually be approximated by the Lifted Condensation Level (LCL). We chose to use a simple approximation for the LCL originally discovered by James Pollard Espy for our calculation. This formula is accurate for the LCL to about 1% under normal atmospheric conditions (Lawrence 2005). The height above sea level is then,

$$h_LCL = h_location + 125(T_location - T_dewpt)$$

where h_LCL is Lifted Condensation Level [m], $h_location$ is the elevation of the station where the temperature was taken [m], $T_location$ is that temperature [°C] and T_dewpt is the dew point temperature [°C]. The Cougar Mountain data did not have dew point temperature values so we had to estimate the dew point temperature from relative humidity data.**

We calculated the lifted condensation level for all 217 peak hours and event days and found the average cloud base. The average cloud base for the Olympic Peninsula is 1450 ± 71 meters.***

*We calculated the standard deviation of the final 217 hour data set to verify how far off the peak hour is from the actual hour we ended up using for the cloud base calculation. The standard deviation was 0.395 hours. We feel confident that a standard deviation under one hour does not alter our cloud base calculation results significantly.

**To approximate the dew point we used a derivation of the Magnus Tetens formula with values given by Paroscientific, Inc. (<http://www.paroscientific.com/dewpoint.htm>). Over the range $0^{\circ} \text{C} < \text{temperature} < 60^{\circ} \text{C}$, $0.01 < \text{relative humidity} < 1.00$, $0^{\circ} \text{C} < \text{dew point temperature} < 50^{\circ} \text{C}$, the dew point temperature is

$$T_d = \frac{b \cdot \alpha(T, RH)}{a - \alpha(T, RH)}$$

$$\alpha(T, RH) = \frac{a \cdot T}{b + T} + \ln(RH)$$

with $a = 17.27$ and $b = 237.7$ [°C]. According to Paroscientific, Inc. the uncertainty in the calculated dew point temperature is $\pm 0.4^\circ \text{C}$.

***From the Cougar Mountain systematic error and the standard deviation of the cloud base mean, we calculated the total uncertainty in the cloud base. The total uncertainty is (Taylor 1997)

$\Delta_{\text{total}} = [(\Delta_{\text{systematic}})^2 + (\Delta_{\text{random}})^2]^{1/2}$, where $\Delta_{\text{systematic}}$ is the systematic error for Cougar Mountain data (3.37 m – computed from the systematic error in temperature data) and Δ_{random} is the standard deviation of the cloud base mean for all data (50 m). However, one would expect a certain amount of serial correlation in the cloud base time series since the data set can contain cloud base data separated by as little as 1 day (Von Storch and Navarra 1999). The lag-1 autocorrelation coefficient was calculated to be 0.3, which effectively increases the standard deviation to 71m (Wilkes 2006). Thus, the total random uncertainty is $\pm 71\text{m}$.

Appendix A2. Elevation-Time Analysis

Reap (1986) used lightning data from the Bureau of Land Management's western United States - from the Pacific coast to Wyoming – detection network for the summers of 1983 and 1984. He grouped all grid blocks with the same hour of maximum frequency of lightning and then calculated the average terrain height for each of the hour bins from the individual grid elevations. He plotted the hour of maximum lightning in Mountain Standard Time versus terrain elevation, beginning at 12 pm and ending at 9 am (Figure A32). Reap noticed that the hour of maximum lightning frequency occurs in the early to mid afternoon for higher elevations and in the evening to night for lower elevations. Reap's findings have a high confidence level due to the size of his dataset – over 2 million strikes in a 149 day period for the summers of 1983 and 1984.

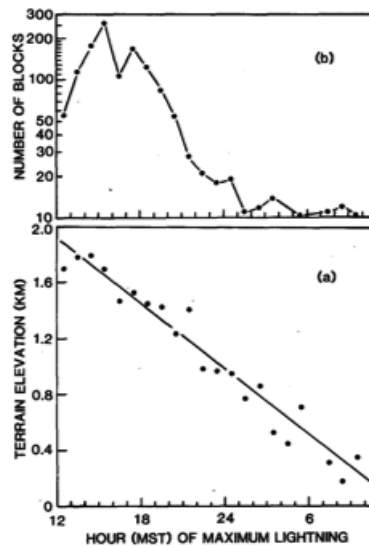


Figure A32. Plot of an analysis of strike elevation as a function of time of day for the western United States over 21 hours. Adapted from Reap (1986), Figure 6.

Similarly, we only took the summer (warm season) strikes from the Olympic Peninsula 1987-2009 data set for our calculation. Our data set is much smaller than Reap's so for each hour bin we included all spatial grids with lightning strikes during that hour rather than using only the spatial grids whose hour of maximum frequency is the selected hour. Also, our dataset has 54481 spatial grids and only 11482 strikes so most spatial grids experienced only one or two strikes; this made it impractical to find the hour of maximum lightning. Each grid with a lightning strike occurring in a particular hour was added to that hour's bin and that grid's average elevation was included in that hour's average elevation calculation. Hence, some grids were counted several times in different hours' average elevation calculations.

To reproduce Reap's calculation using our strike intensity definition, we calculated the strike intensity for each spatial grid for each hour with lightning activity. We weighted the elevation of each spatial grid by the strike intensity of that spatial grid for the selected hour. To find the average elevation of each hour bin we totaled the weighted elevations of all of the spatial grids in that hour bin and divided by the totaled strike intensities for that hour bin. The result was the average elevation for each hour, weighted by strike-intensity. Additionally, we only kept strikes with elevations greater than 350

m. We wanted to investigate strictly hour versus elevation patterns in the mountains - as in Reap's study - not storm direction patterns in the Hood Canal. A 350 m cutoff is right below the 400 m minimum and removes the majority of the strikes associated with the low elevation maximum. Like Reap, we plotted hour versus the weighted elevation from 12 pm to 9 am (Figure A33). There is a great deal of scatter, but we see the average elevation of lightning activity decrease as the day progresses from 12 pm.

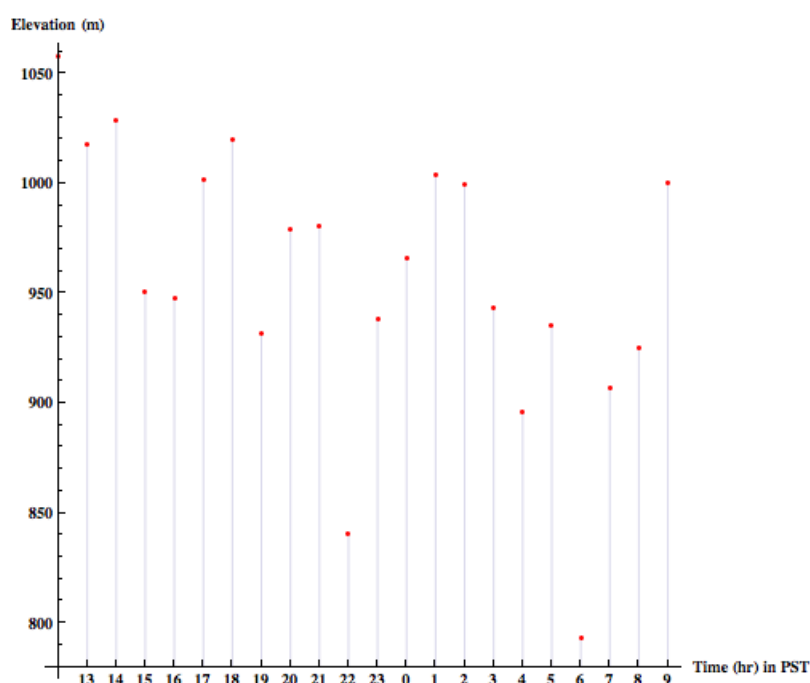


Figure A33. Plot of an analysis of the intensity weighted strike elevation as a function of time of day for the OP over 21 hours.

Reap overlays a linear fit on his lightning elevation time plot (Figure A32). We believe that including the data that he has omitted (for 10 and 11 am) would lead to a cyclic diurnal fit to the data points. The full 24 hour cycle of data is plotted for our data set in Figure A34. Our data has considerably higher scatter than Reap's due to our small sample size. However, the general downward

trend of elevations over time until 7 am - when the elevations start increasing due to increased convective instability - is still discernible. The peak elevation occurs at 2 pm and the minimum elevation occurs at 6 am. These times – an early morning minimum and an early afternoon maximum – are identical to those of our diurnal intensity distribution. This suggests temperature driven cyclic behavior.

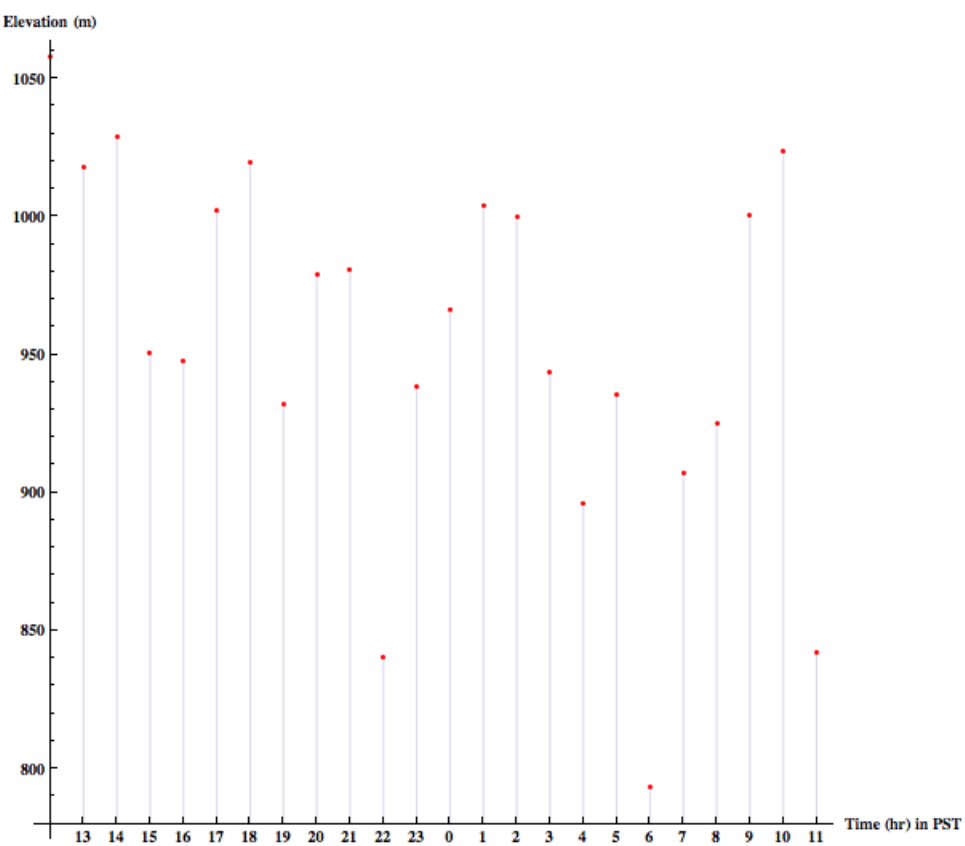


Figure A34. Plot of an analysis of the intensity weighted strike elevation as a function of time of day for the OP over 24 hours.

Additionally, like Reap, we attempted to plot the number of spatial grids in each hour bin. Reap had grid sizes of approximately 47 km x 47 km whereas our grids are approximately 0.5 km x 0.5 km. Due to the much greater number of strikes that one of Reap's grids can encompass, he has greater confidence in his hour of maximum lightning result. Figure A35 highlights the large variation in the number of spatial grids for each hour in our dataset. For hours like 2 pm – the peak, 10 pm – the nocturnal minimum and 8-9 am – the morning elevation increase, we can be more confident in our results. However, 13 hours have less than 100 spatial grids. Since the average elevation for each hour depends on the number of spatial grids in that hour, the large scatter in Figures A33 and A34 is directly due to the small spatial grid sample size for most hours. Unlike Reap, we did not find any trend in the number of spatial grids per hour.

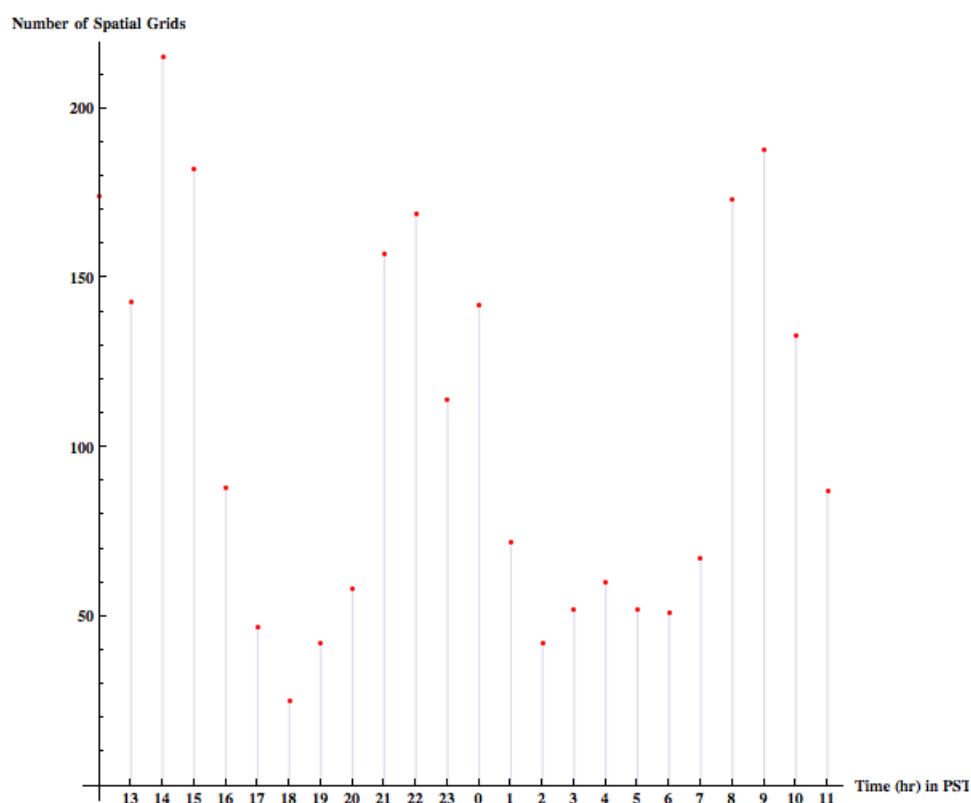


Figure A35. Plot of number of spacial grid points for each hour used in weighted average in Figure A34.

Our lightning elevation distribution analysis in the previous section suggests that the maximum lightning intensity is limited by cloud base height. We use this same cloud base data (**Appendix A1**) to demonstrate that the cloud base data follows a similar elevation time relationship as our lightning intensity data.

In our reproduction of Reap's calculation we found the average elevation for each hour by totaling the weighted elevations of all of the spatial grids in that hour bin and dividing by the totaled strike intensities for that hour. However, the Cougar Mountain and Bremerton cloud base data is not in a spatial grid format like the elevation data so calculating strike intensity was not possible. Instead, we weighted the cloud base heights with lightning strike-counts rather than strike-intensities. We grouped the lightning strikes by hour and found the total strike count for that hour. Next we took the calculated cloud base heights for each event hour and multiplied them by the total strike count for that hour. We totaled the weighted cloud base elevations for each hour bin and divided by the totaled strike counts for that hour bin. The result was the average cloud base elevation for each hour, weighted by strike count. We plotted hour versus weighted cloud base elevation for all hours starting at 12 pm – as in the Reap calculation (Figure A36).

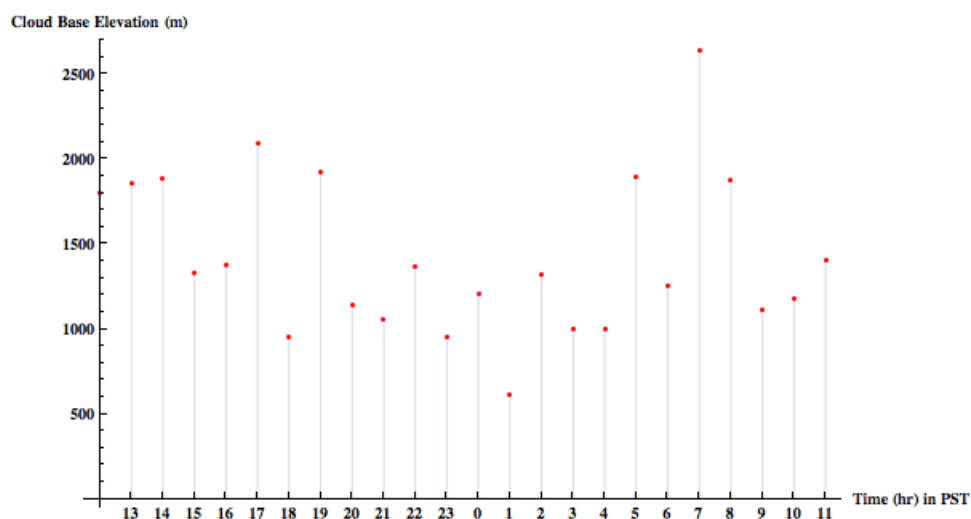


Figure A36. Plot of an analysis of the strike weighted cloud base elevation as a function of time of day for the OP over 24 hours.

The cloud base height at any given time is dependent on the difference between the air temperature and dew point temperature. It follows that the cloud base would increase and decrease along with the diurnal temperature cycle. As surface temperature increases in the morning due to solar heating we expect to see an increase in cloud base height leading to a peak in the early afternoon matching the daily high in surface temperature at that time. The cloud base should subsequently decrease throughout the rest of the day and night until the following morning. Figure A36 illustrates this pattern albeit with a large amount of scatter.

As in the Reap calculation, we grouped the number of spatial grids for each hour bin to see which hours we can have the most confidence in. Figure A37 shows that the number of spatial grids for each hour decreases with time after the early afternoon. Reap found the same pattern in his study (Figure A32). From Figure A37 we see that the hours with greatest confidence are from 1 pm to 4 pm – approximately our early afternoon peak. The high elevation values for early morning hours like 5 am and 7 am could be due to small sample size; both hours have less than 5 spatial grids in the calculation for average cloud base height. Altogether, the sample size for every hour bin is less than 25 spatial grids. The data set for our version of Reap's calculation contained 11482 strikes; the dataset for our time versus cloud base comparison only has 217 strikes. Consequently, it is not surprising that this distribution exhibits a great deal more scatter than the lightning intensity distribution. Taking into account the lack of confidence in the early morning values, a general picture of the diurnal pattern emerges. Cloud base height generally decreases with time after the early afternoon and increases in the early morning hours around 5 am due to increased convective instability.

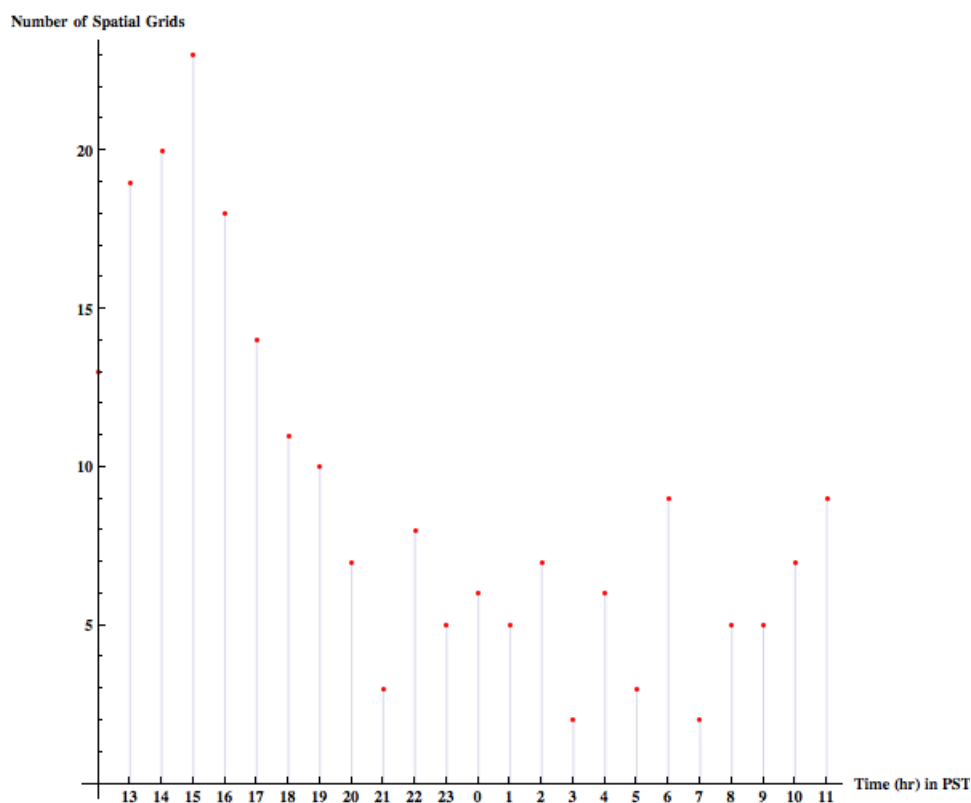


Figure A37. Plot of number of cloud base grid points for each hour used in weighted average in Figure A36.

Since a significant majority of the strikes fall below the cloud base height of 1450m (Figure A21), the mean strike elevations at any time (Figure A34) should be expected to lie below the cloud base heights at corresponding times (Figure A36). This relationship is true with a few exceptions. Given the uncertainties in the values of both of these distributions, the exceptions at some hours are not surprising.

Appendix B1. Additional Criteria for Composite Analysis Group Membership

Since there were many more such events in the second group than those in the first group, events were chosen for the second group by ranking these events in order of the total number of strikes in the PNW. Members were chosen for the second group in order of this rank limited to the number chosen for the first group. The PNW activity lightning activity is typically characterized by multiple contiguous days of strikes. An additional criteria was imposed that there had to be a sequence of at least 5 days of strike activity centered about the peak day and not overlapping with another event sequence. the other members of either group. (All OP peak strike counts occurred within 1 day of the PNW peak day). These later criteria were imposed to significantly reduce the serial correlation that typically leads to inflated confidence estimates of composites for meteorological data when contiguous days are included in the composites (Storch and Navarra 1999).

There were 28 members in the first group that satisfied all of the criteria (Table B1). The case study event centered around September, 4th, 1995 is a member of group 1. The second group was formed by choosing the 28 members satisfying the criteria corresponding to the largest PNW events (Table B2). The case study event centered around July 11th, 2001 is a member of group 2. Both groups had enough members that the composites would be expected to conform to Gaussian statistics (Wilkes 2006). For the 28 members of group 1, all OP peak strike counts occurred within 1 day of the PNW peak day.

YEAR	MONTH	DAY	PNW LI	OP LI
1999	8	5	17032	1630
1995	9	4	12901	590
1998	7	3	10880	18
1994	7	24	7820	32
1998	6	22	6124	17
2004	8	17	5927	26
2004	5	22	4059	25
1997	7	5	3216	1264
1994	8	3	2959	243
1998	5	2	2284	72
1997	8	6	2157	832
2004	6	18	1944	20
2005	6	21	1660	199
1994	8	8	1384	11
2005	5	31	1349	12
2003	9	6	1279	16
1995	8	10	1269	44
2005	5	15	1171	20
1994	8	28	1129	177
2005	5	19	737	30
1997	9	1	685	10
2005	5	2	672	39
2002	6	14	670	17
2003	6	29	495	120
1997	9	12	300	14
1997	6	22	222	21
1997	8	27	168	13
2002	6	7	82	25

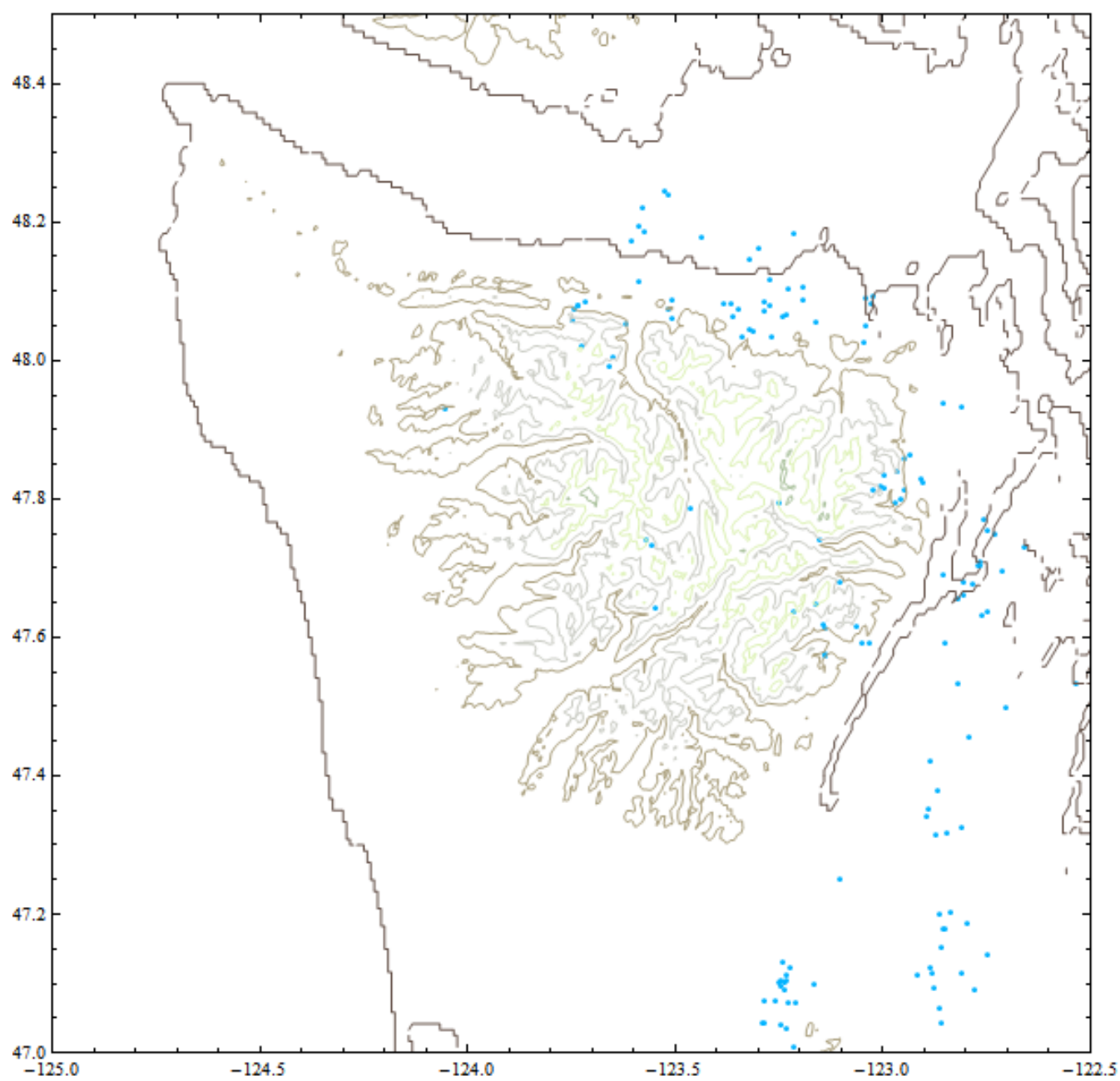
Table B1. Peak day dates (GMT) and strike counts for the PNW and OP for 28 separate events which had 10 or more strike counts on the OP.

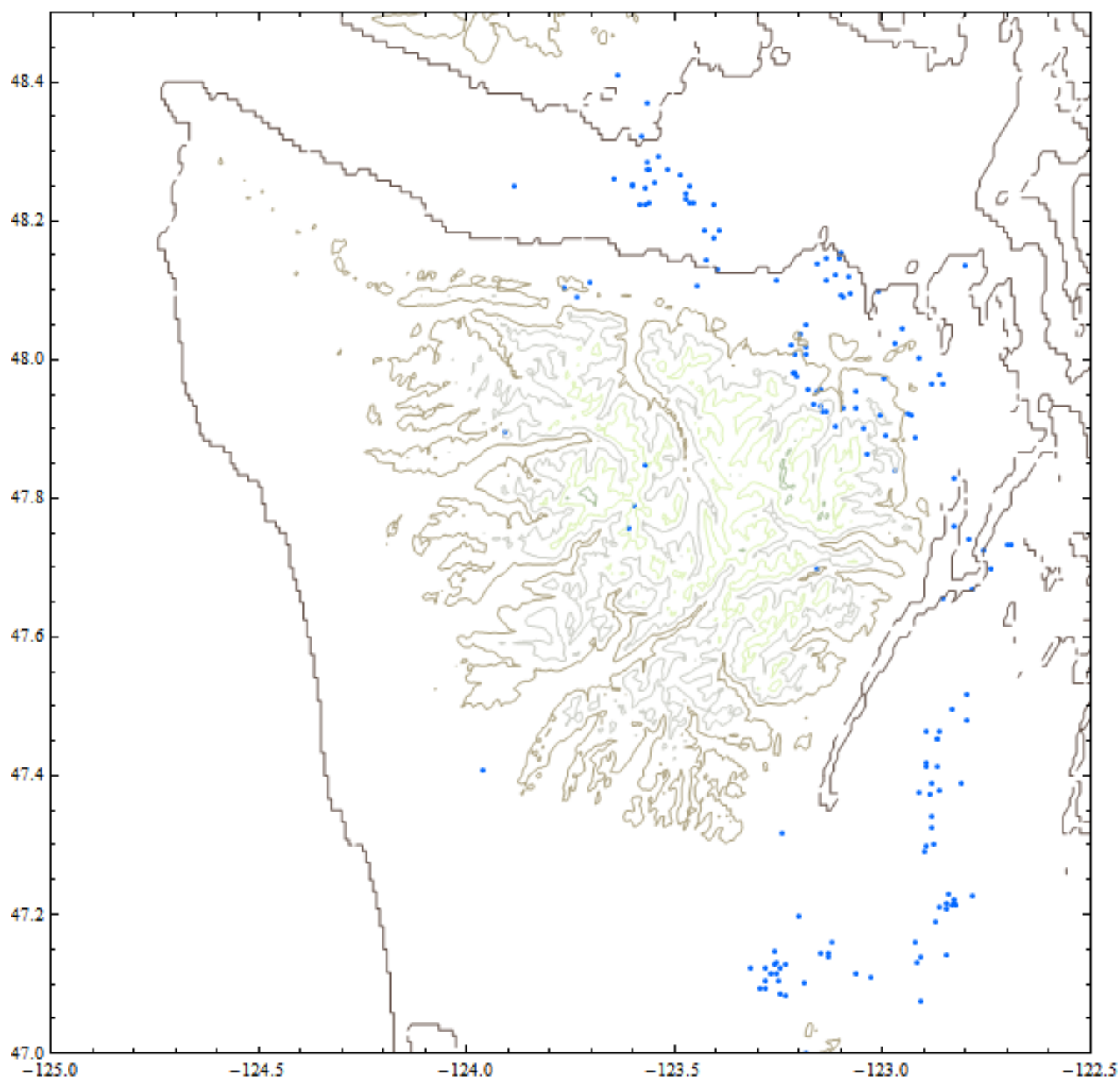
YEAR	MONTH	DAY	PNW LI	OP LI
2003	5	30	14298	1
2003	8	5	14256	0
2004	7	19	13705	0
1996	8	14	13468	0
2003	7	24	13318	0
2004	6	29	13070	0
1998	7	10	11737	0
2001	7	11	10039	0
1995	7	29	9979	1
1997	6	11	9157	0
1998	7	30	9127	0
1996	7	30	8949	0
2003	8	22	8772	0
2001	9	15	8484	0
1996	8	27	8351	0
2002	7	14	7841	0
2003	6	19	7534	0
1998	6	12	7318	0
1999	8	13	7310	0
1998	4	23	7215	0
2003	5	25	6731	0
2005	7	22	6631	0
1997	5	31	6130	0
1994	9	28	6065	0
2001	8	9	6055	0
1995	7	19	5946	0
1998	9	7	5911	0
2005	4	27	5868	0

Table B2. Peak day dates (GMT) and strike counts for the PNW and OP for top 28 separate PNW events which had 1 or less strike counts on the OP.

Appendix C1. Thunderstorm Cell Motion

The motion of the active thunderstorm cell at the peak hour was determined from the displacement of an isolated cluster of activity in a time interval of 15 minutes. In Figure C2c, illustrating the strike locations from 22:00 to 22:15 we chose the cluster of strikes at the southeast corner of the OP – since this cluster is near the plotted 700 mb wind vector in Figure C2a. Figure C2d illustrates the location of strikes from 22:15 to 22:30. The cluster of strikes in the southeast corner is interpreted as coming from the same active cell 15 minutes later. The center of these two clusters was estimated to have been displaced $.05^{\circ}\text{N}$ and $.02^{\circ}\text{W}$. From this displacement, a velocity of the thunderstorm cell is calculated to be 7m/s to the NNW. This suggests that the 700mb wind of approximately 9m/s to the NNW (Figure C2a) represents the thunderstorm cell velocity reasonably well.

**c**



d

Figures C2c&C2d. Strike locations on the OP in two successive 15 minute time intervals near the time of peak activity. Plots for (c) 22:00 – 22:15 time interval, (d) 22:15 – 22:30 time interval.

Appendix C2. Fire Starts and Strike Locations

Fire start locations for both the August 17, 2008 and September 6, 2003 **Storm Direction** case studies provide an indirect method of estimating the accuracy of lightning strike locations used for this study. In the former case, the lightning strikes in the northeast portion of Olympic National Park (ONP) in the vicinity of Blue Mountain (Figure C23) started numerous fires. These fires were mostly confined to small areas (typically one tree) and were flown over and located by Todd Rankin and Larry Nickey, ONP Fire Management. The location of these fire starts are plotted in Figure C23c along with the subset of lightning strikes in Figure C23 from this area. Since the fire start observations were made after they occurred, it is impossible to definitely associate the individual strikes with individual fire starts. However the distance between strikes and the nearest fire start occur at distances up to about 5km – an order of magnitude larger than the published estimated median accuracy of the strike location. The three western most fire starts are so distinctly separated from the cluster of lightning strikes as to also suggest that the strikes that started these fires may not have even been detected.

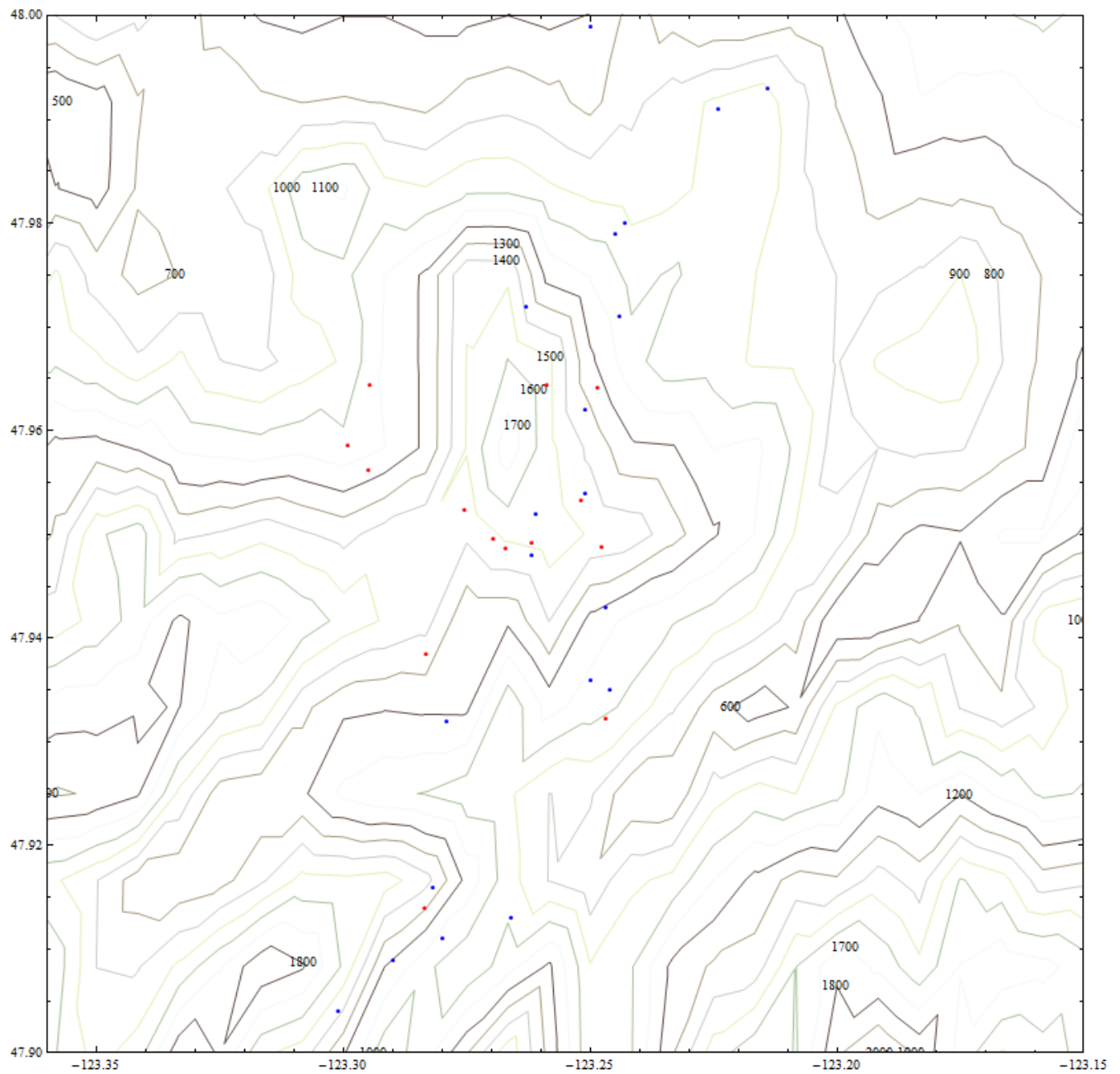


Figure C23c. Lightning strikes (blue dots) and fire starts (red dots) in the vicinity of Blue Mountain for the August 17th, 2008 case study. Elevation contours in meters are also shown.

The data for the September 6 event is less complicated in that there was only one fire start was thought to have initiated the Griff Peak Fire. This occurred near the summit at 48.003°N, 123.495°W. The strike that was detected closest to this location is approximately 5km away.

This data raises questions about the location accuracy of the detected strike locations and possibly the strike detection efficiency. Published estimates of these quantities assume rather idealized models of both the nature of the cloud to ground strike characteristics as well as the characteristics of the atmospheric and terrestrial environment (Rakov and Uman 2003). The steep vertical gradients of the Olympic Mountains is an example of the significant departures from these idealized assumptions. We know of no published “ground truthing” studies of either the strike location accuracy or the detector efficiencies in this kind of mountain environment.

The possibility that the location error is too low for mountainous regions would imply that the error bars for the elevation distributions should be increased to account for this location error. (See the method section of the elevation distribution section above).

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