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SCHOOL**

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THESIS

**VERIFICATION OF COASTAL LIGHTNING EVENT
TYPES USING SOUNDING DATA ALONG COASTAL
CALIFORNIA**

by

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June 2020

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**VERIFICATION OF COASTAL LIGHTNING EVENT TYPES USING
SOUNDING DATA ALONG COASTAL CALIFORNIA**

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY

from the

**NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

Predicting coastal lightning events in California is tough to do and has been an issue in the forecasting community for some time. In a 2018 study for the Naval Postgraduate School, Schlosberg found three characteristic event types using model analysis that could help to identify potential coastal lightning events. The problem with data from model analyses is that they have inherent biases in their diagnosis of convective parameters such as convective available potential energy (CAPE) because of low-level temperature and moisture uncertainties in gridded analyses. The work in this paper uses sounding data taken across coastal California to verify the findings of the three characteristic event types found in Schlosberg's 2018 study. The goal was to confirm the event type characteristics in the soundings as well as CAPE and convective inhibition (CIN) profiles for lightning events along coastal California from 2005 to 2011. This study verified the majority of Schlosberg's results across all event types. However, a difference in our results was that cold-core low events generally had larger CAPE values than jet-type events.

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LIST OF ACRONYMS AND ABBREVIATIONS

CAPE	Convective Available Potential Energy
CIN	Convective Inhibition
OAK	Oakland
SDO	San Diego
VBG	Vandenberg

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First and foremost, I would like to thank my advisor, Dr. John Peters, without whom I would not have been able to complete my thesis. Dr Peters was a great advisor and teacher. Secondly, I would like to thank my second reader, Dr. Wendall Nuss, for helping to review my thesis, for his teaching, and for helping me get the classes I needed to fulfill the requirement for my master's degree. Next, I would like to thank all my fellow classmates for their support, and the Thesis Processing Office for their help during this experience. Lastly, I would like to thank my family. They have always been there for me, supported me, and believed in me. Without their help and support I would not be where I am today.

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I. INTRODUCTION

California wildfires pose a substantial threat to society. These fires cause devastating damage to California's agricultural industry (an industry worth close to \$50 billion; CDFA 2018), the environment, and the residential population. Thirty-five percent of the largest 20 fires recorded over the last 87 years were ruled to have been the result of lightning (CAL FIRE 2018). If meteorologists can find a better way to forecast the chance of lightning in areas that are susceptible to the spark of a large forest fire, these fires might be prevented, or the damage from them minimized.

This thesis does not plan to solve that issue as a whole, but rather to take a step in the direction of expanding our understanding of weather events that can lead to coastal California lightning. Schlosberg (2018) began the first step by exploring coastal lightning events and categorizing them based upon their event type. Once the various event types had been determined, they used National Center for Environmental Prediction Global Forecast System atmospheric datasets for coastal lightning event dates from 2005–2011 to get composite vertical sounding profiles for each event type, and they explored wind profiles and convective available potential energy (CAPE)–related quantities. Their usage of gridded analysis was advantageous in that it allowed them to study the spatial distribution of atmospheric properties over a large number of cases. However, model analyses have inherent biases in their diagnosis of convective parameters such as CAPE because of low-level temperature and moisture uncertainties in gridded analyses. For instance, Peters et al. (2017) found that moisture errors contributed to CAPE uncertainties on the order of $1,000\text{--}2,000\text{ J kg}^{-1}$ in central plains convective events.

The motivation behind this work is to verify the results of Schlosberg's (2018) study using sounding data from Oakland, Vandenberg, and San Diego. Radiosonde observations have smaller moisture and temperature uncertainties than gridded analyses (e.g., Peters et al. 2017 and references therein), and have comparatively fine vertical resolution. Peters et al. found that model analysis tended to have larger errors in moisture content than radiosonde observations that would lead to relatively large errors in CAPE values. For a forecaster to be able to use these results, this paper seeks to validate

Schlosberg's findings by ensuring that model bias in moisture content is not giving incorrect results and CAPE values. Since it is known that model analysis have bias's that lead to large errors in moisture content and therefore CAPE values (Peters et al. 2017), it is necessary to validate Schlosberg's results using sounding analysis. The goal here is to use sounding data to verify the thermodynamic characteristics of the events studied by Schlosberg, such as the vertical distribution of CAPE. The event types that were found were warm-season, cold-core low, and jet-type. To summarize Schlosberg's preliminary findings, it was found that all event types favored anomalous steep mid-level lapse rates but each had their own synoptic scale set up and characteristics:

- The jet-type event was characterized by upper level quasi-geostrophic ascent related to a jet streak over the region that stimulated upward motion and gave rise to the storms that produced the lightning events. At the 850 hPa level the jet-type event had a strong low-level jet with a component of onshore flow. This set favored orographic lifting which aided the upper level forcing in initiating strong convection that lead to thunderstorms. In addition, the 850 hPa flow for jet-type events was parallel to the temperature gradient. The jet-type events also had a strong maximum in their surface-based CAPE than the other event types.
- The warm season events were characterized by a locally weak trough embedded within a large-scale ridge, along with southwesterly flow in the upper levels. When moving down to the lower levels there tends to be a weak offshore flow, and weak southerly moisture advection at the 700–850hPa levels. This warm season event type tends to have a strong inversion at the surface but substantial elevated CAPE. It also tends to have southerly flow from 800–600 hPa and a dry layer below the 750 hPa level.
- The cold-core low event is characterized by strong upper-level flow just south of the event center where the upper level trough is just south of the event location. As we look at the lower level flow we find that the cold-

core low event tends to have strong cold air advection to the west of the event and northwesterly flow parallel to the coast Schlosberg (2018), due to the topography of the California coast. This is indicative of frontal passage to the south of the event center. They found that this event type is characterized by surface-based CAPE, albeit the CAPE was not as strong as in Jet type events.

The hypothesis of this paper is that when using sounding data from 2005–2011 to verify these findings for coastal California over a 7-year time span of lightning events, it will confirm the conclusions of Schlosberg (2018) regarding the vertical distribution of CAPE. We are also adding higher resolution in the vertical, smaller uncertainty in measurements of moisture and CAPE. It is fully expected that the data will yield similar results in composite soundings as those made from model data by Schlosberg. The presence of steep mid-level lapse rates, surface-based CAPE in cold-core low and jet-type events, as well as elevated cape for warm-season events is expected.

It was found that the majority of Schlosberg's results were verified with sounding data from Oakland, Vandenberg AFB, and San Diego from 112, 108, and 92 soundings respectfully across all event types. The only thing that was found different in this paper is that the CAPE of Event Type 3's (cold-core low) were generally larger than that of Event Type 1's (jet-type event). It was even more defined that for all events taken into account only within 60 nautical miles of the sounding location, that the average Event Type 3 CAPE values were larger than the Event Type 1 mean CAPE values. That is the only difference we found from the results of Schlosberg.

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II. METHODS

The goal of this study was to determine if the results from Schlosberg's (2018) study were verifiable using actual sounding data from the event time frames they explored. In their paper they used the National Center for Environmental Information for their lightning data and the Global Forecast System one-degree resolution global analysis for their atmospheric data. They were looking at lightning strike events that occurred in coastal regions from 2005–2011. They found 487 such events with 199 jet-type events, 137 warm season events, and 151 cold-core low events. We used their results for the lightning event dates and locations in this paper.

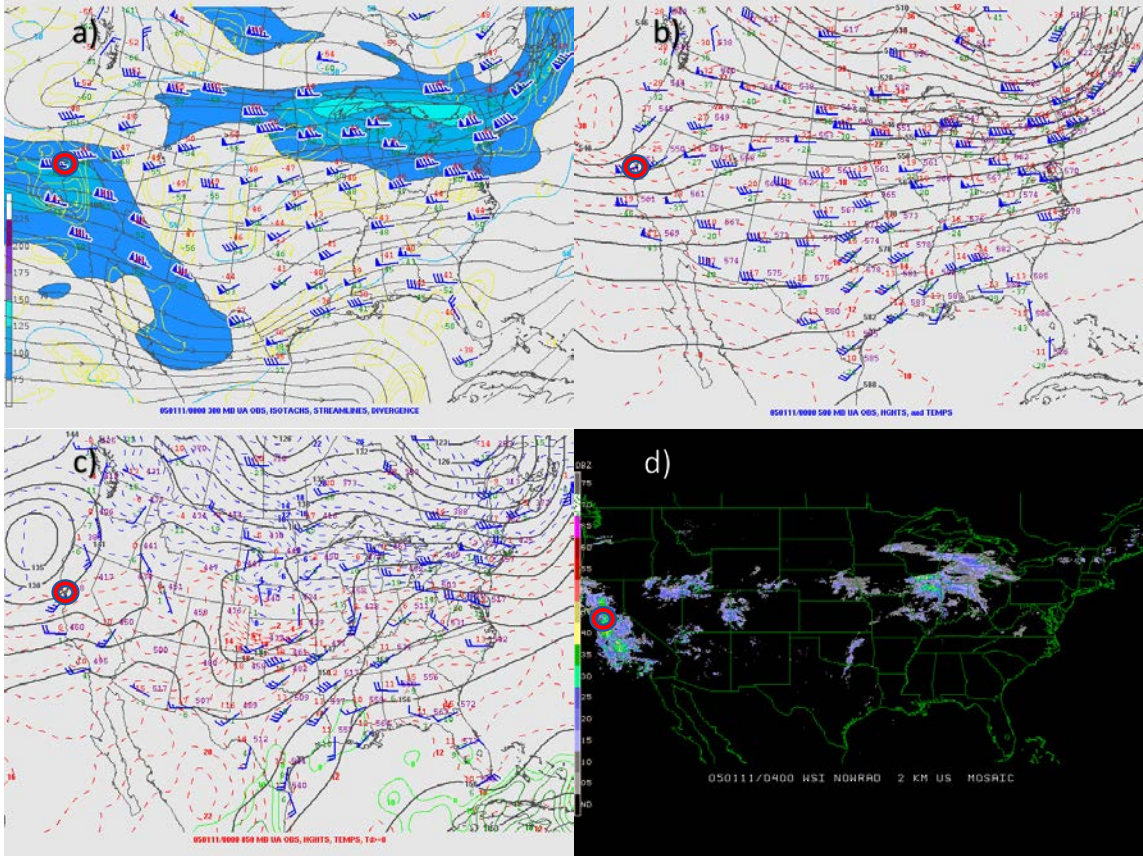
Using Schlosberg's lightning data locations, determined by the centroid of all lightning strikes per event, and associated event types, we narrowed down the events we would use in our data set to those that were within 60 and 100 nautical miles of the nearest balloon sounding location. We decided that we would use the sounding data from Oakland (OAK), Vandenberg AFB (VBG), and San Diego (SDO) California for the dates and locations from Schlosberg's paper. With these locations and the sounding data for these locations from the NOAA sounding data archive, we looked at each event type. For the purposes of this paper, the event types determined by Schlosberg correspond to the following:

1. Jet-type event: Event Type 1
2. Warm season event: Event Type 2
3. Cold-core low event: Event Type 3

This is important to note for further reference to images throughout this paper.

To familiarize the reader with the synoptic setup leading up to each event and a visualization of the satellite and radar imagery, I have provided examples from observations for each event type. Figure 1 is an example of an Event Type 1 that occurred over the Oakland area on January 11, 2005. Figure 2 is an example of an Event Type 2 that

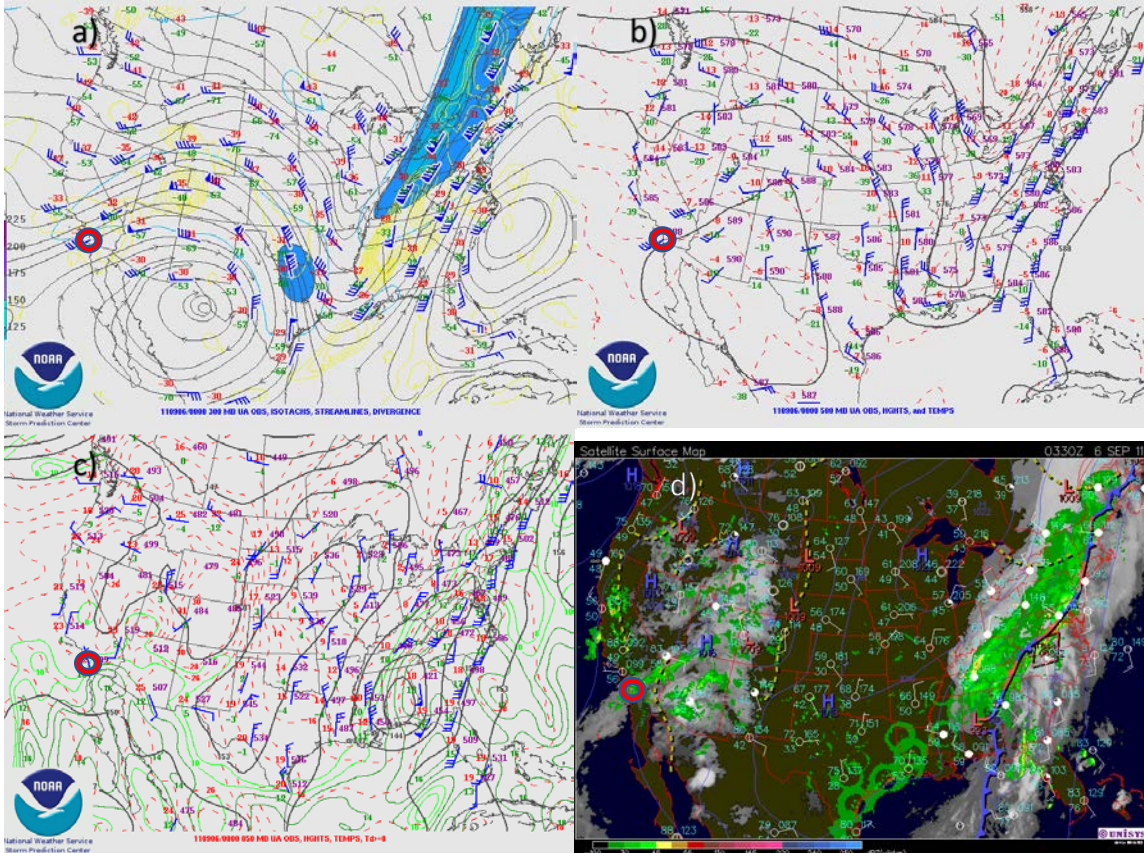
occurred over San Diego on September 6, 2011. Figure 3 is an example of an Event Type 3 that occurred over San Diego on April 21, 2007.



(a) 300mb obs, (b) 500mb obs, (c) 850mb obs, and (d) satellite and radar.

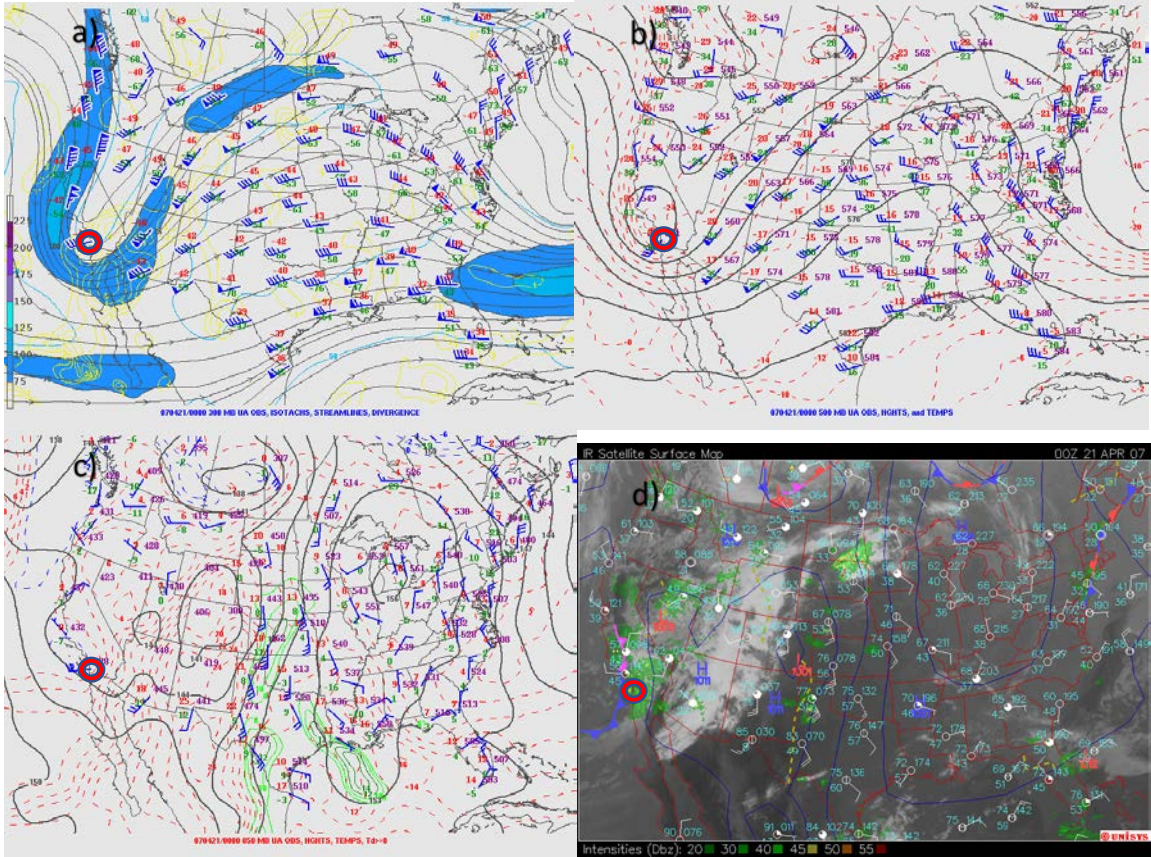
Images from UCAR (2005a, 2005c, 2005e, 2005g).

Figure 1. Jet-Type Event over Oakland 0000Z



(a) 300mb obs, (b) 500mb obs, (c) 850mb obs, and (d) satellite and radar
 Images from UCAR (2011a, 2011b, 2011d, 2005f).

Figure 2. Warm-Season Event over San Diego 0000Z



(a) 300mb obs, (b) 500mb obs, (c) 850mb obs, and (d) satellite and radar
 Images from UCAR (2007a, 2007b, 2007d, 2007f).

Figure 3. Cold-Core Low Event over San Diego 0000Z

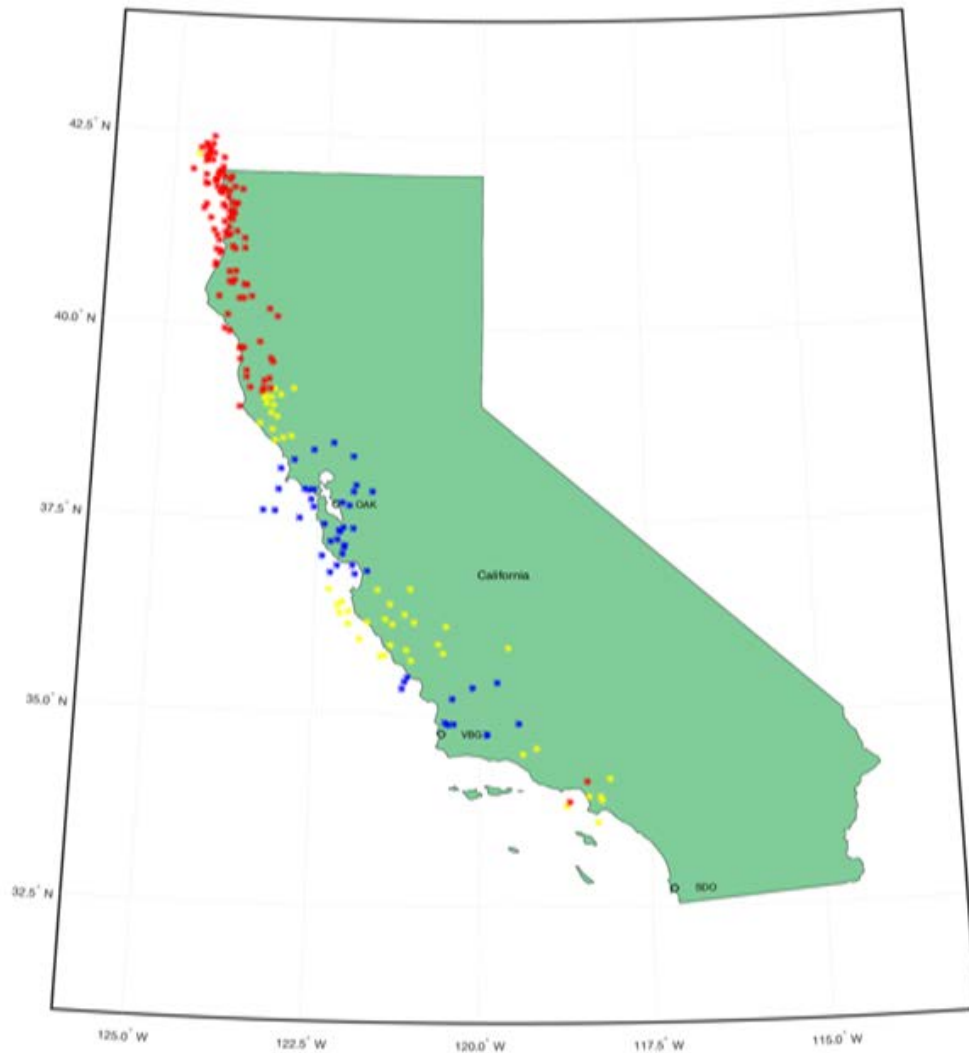
Each of these event types was explored through building composite soundings, CAPE, and CIN. The composite soundings were made by interpolating the temperature and mixing ratio onto a constant height grid for each individual event. Then the mixing ratio and temperature for all dates where events happened within one-hundred nautical miles of the closest sounding location were averaged at the same constant height grid for each event. Each sounding location had a separate composite sounding so that any differences due to the local climate of each area would be apparent in each sounding. We then proceeded to calculate CAPE and CIN for each sounding and then create a composite for each using a running average. We also calculated the standard deviation for the CAPE and CIN as well. Using this data, we compared to Schlosberg (2018) to determine the validity and applicability of their results.

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III. RESULTS

We will explore the results by event type in sequential order. To begin we will review the Event Type 1 events and its results. Next will be the results for the Event Type 2 events. Lastly, the results of the Event Type 3 events will be discussed.

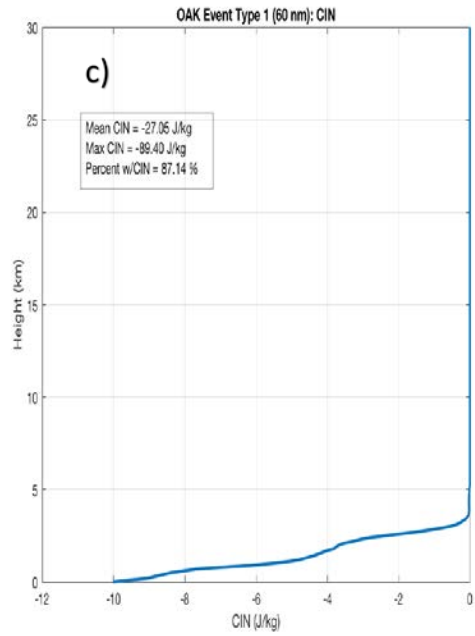
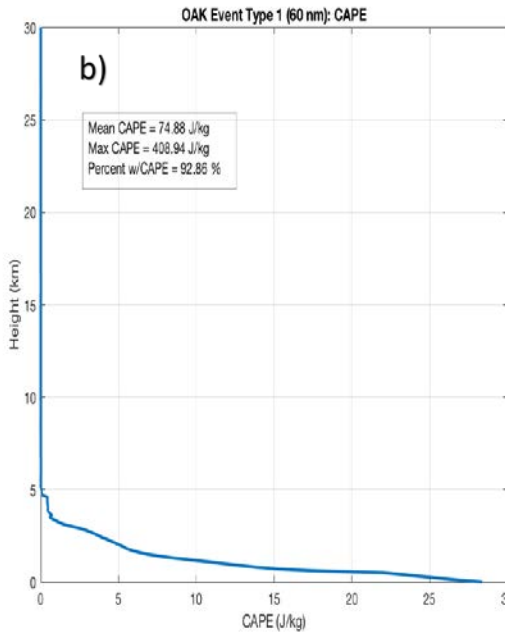
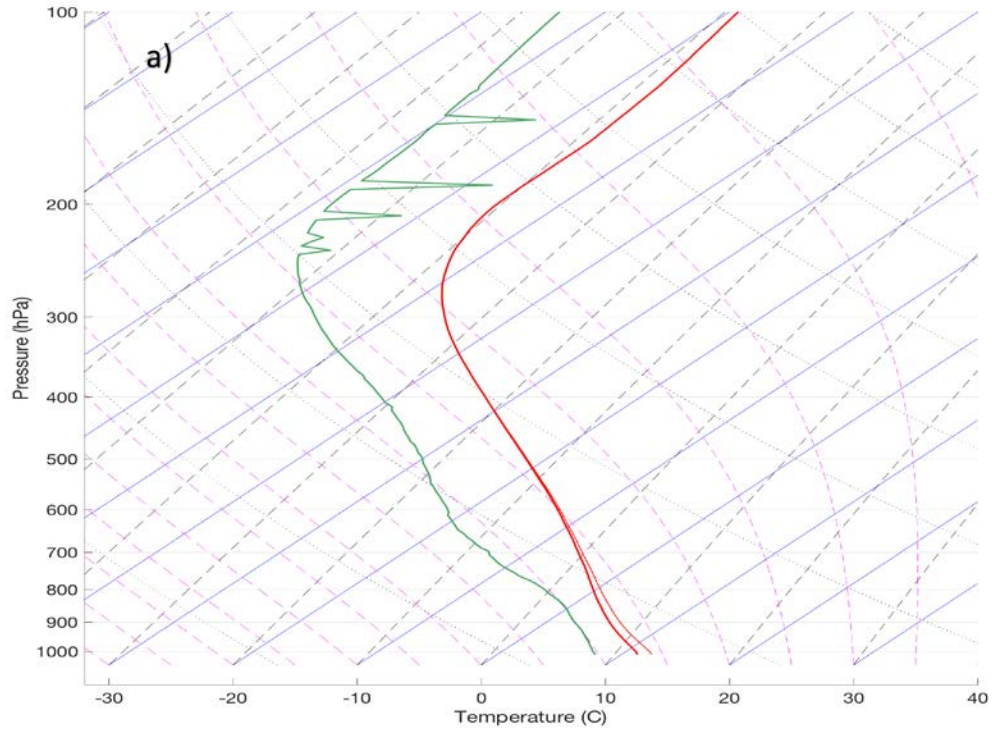
Let us first look at our data set, from the NOAA (2020) sounding archive, for our lightning strike event dates along coastal California for Event Type 1. In Figure 4 we can see the locations for all lightning strikes attributed to Event Type 1 synoptic scale set-ups for coastal California from 2005–2011. The red stars were data that was not used because they were farther than one-hundred nautical miles from any sounding location used in this paper. The yellow stars are lightning strike locations that occurred at or within one-hundred nautical miles but greater than sixty nautical miles of the closest sounding location. The blue stars are those that were at or less than sixty nautical miles from the closest sounding location. The black circles with their city abbreviations are the locations of the sounding sites. Please note that for further event types this will be the standard legend.



(Black) Sounding site location, (Blue) within 60 nautical miles of sounding site, (Yellow) within 100 nautical miles of sounding site, (Red) beyond 100 nautical miles of sounding location

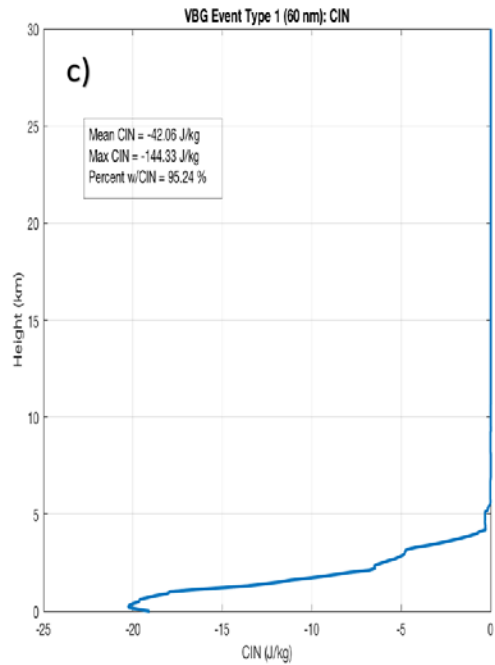
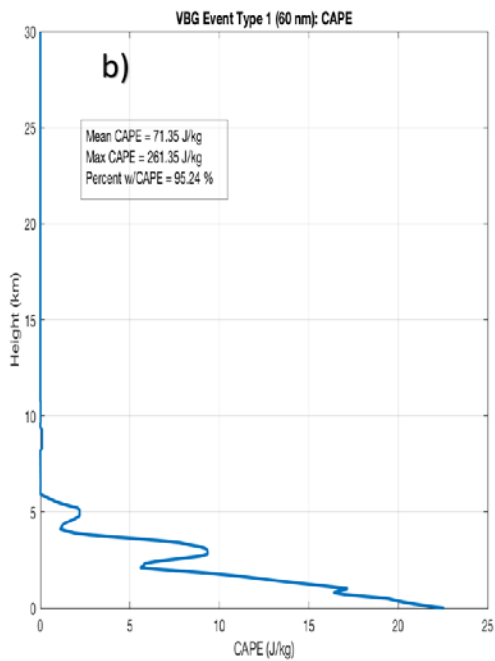
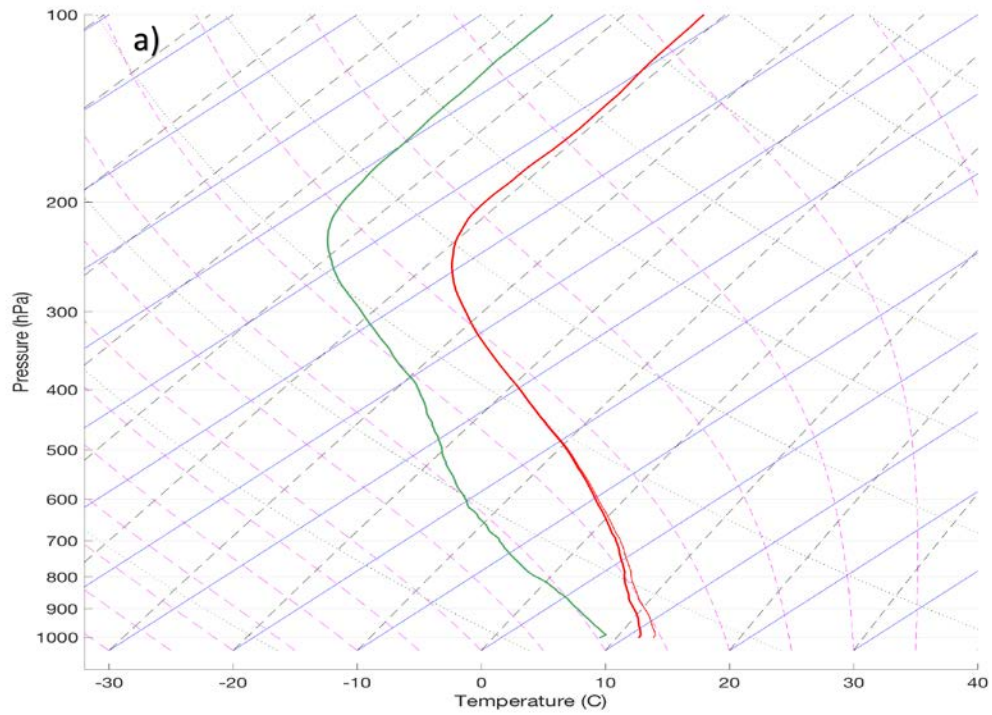
Figure 4. Locations of Lightning Strikes for Jet-Type Events (Event Type 1)

From the given data and event types composite soundings were made for events that occurred within one-hundred nautical miles or less of the sounding sites. Figure 5 (a) is for Oakland, which had 62 events such events. Figure 6 (a) is for Vandenberg AFB, which had 29 events within 100 nautical miles of the sounding site. Figure 7 (a) is for San Diego, which had 6 events within 100 nautical miles of the sounding location.



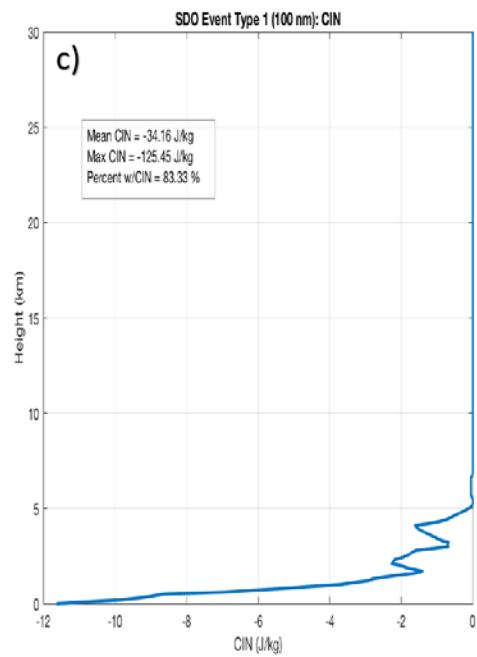
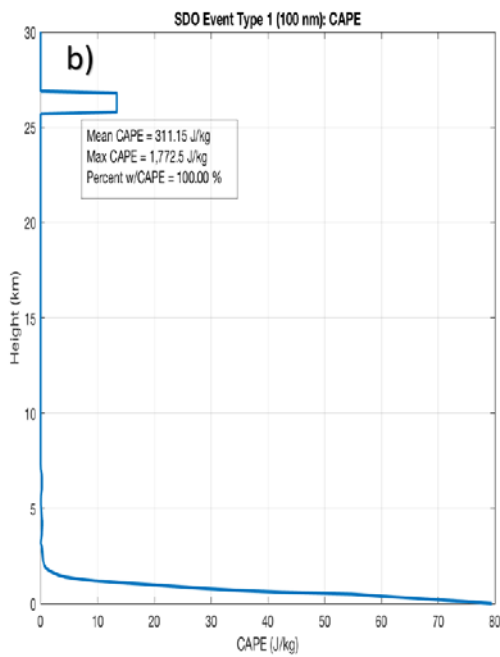
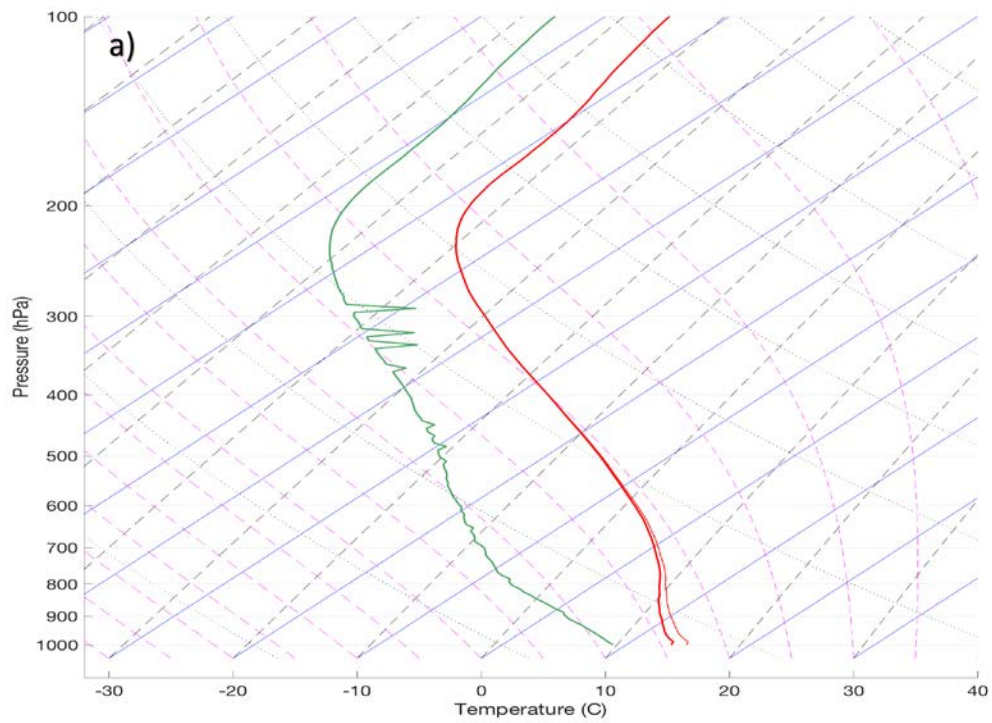
(a) composite sounding, (b) composite CAPE, (c) composite CIN

Figure 5. Event Type 1: Oakland



(a) composite sounding, (b) composite CAPE, (c) composite CIN

Figure 6. Event Type 1: Vandenberg

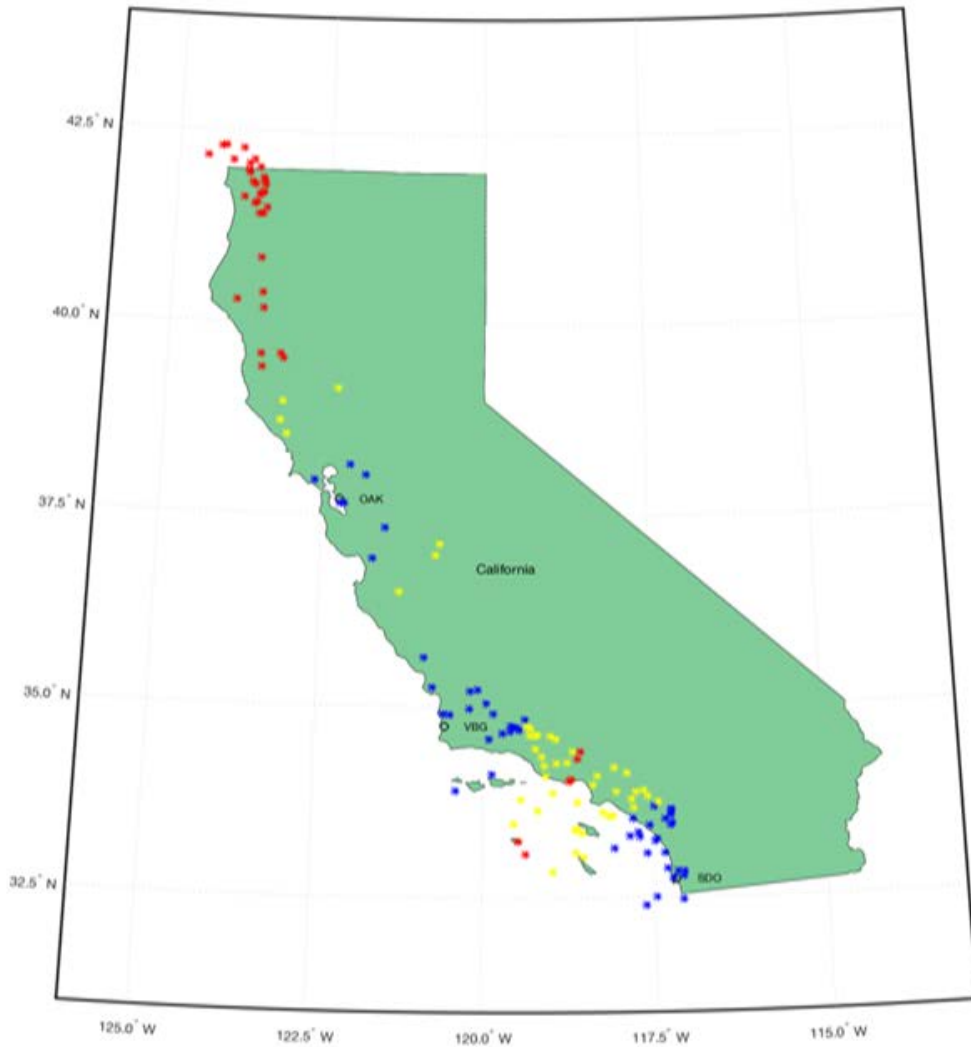


(a) composite sounding, (b) composite CAPE, (c) composite CIN

Figure 7. Event Type 1: San Diego

As you can see from all three composite soundings in Figures 5, 6, and 7 there appears to be surface-based CAPE in all three. To verify this the composite CAPE and CIN values were calculated and plotted. In Figure 5 (b), Figure 6 (b), and Figure 7 (b) you can see the composite CAPE values, percent of soundings with CAPE, max CAPE, and mean CAPE for the Oakland, Vandenberg AFB, and San Diego soundings respectively. In Figure 5 (c), Figure 6 (c), and Figure 7 (c) you can see the composite CIN values, percent of soundings with CIN, max CIN, and mean CIN for the Oakland, Vandenberg AFB, and San Diego soundings respectively. It is apparent from Figures 5, 6, and 7 (b) that the CAPE is maximized at the surface as hypothesized by Schlosberg (2018).

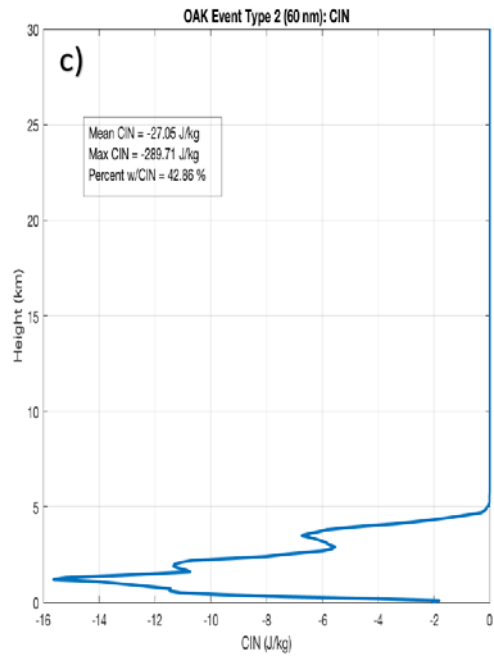
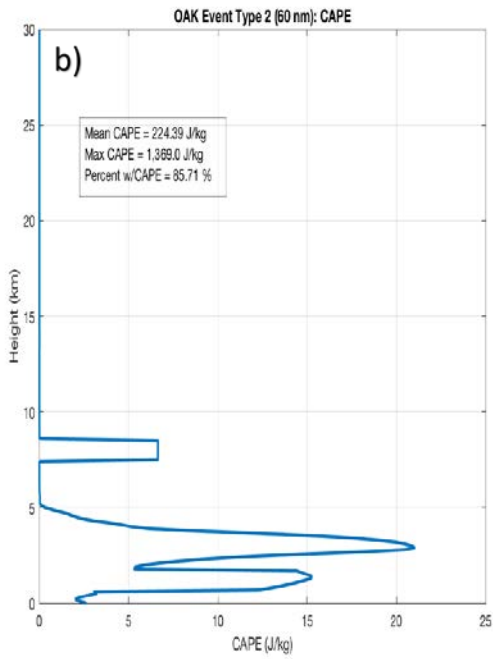
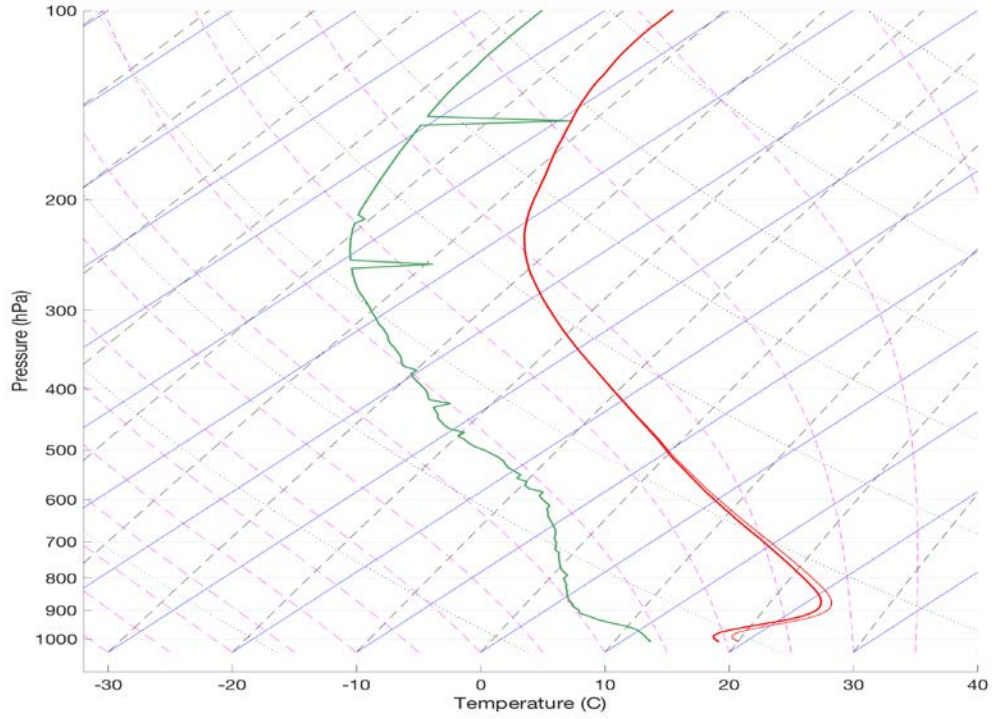
Next, we will look at our data set for lightning strikes along coastal California for Event Type 2. In Figure 8 we can see the locations for all lightning strikes attributed to Event Type 2 synoptic scale set-ups for coastal California from 2005–2011.



(Black) Sounding site location, (Blue) within 60 nautical miles of sounding site, (Yellow) within 100 nautical miles of sounding site, (Red) beyond 100 nautical miles of sounding location.

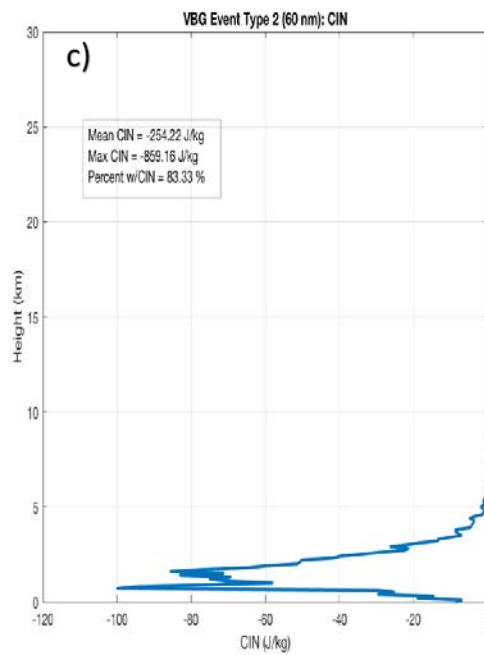
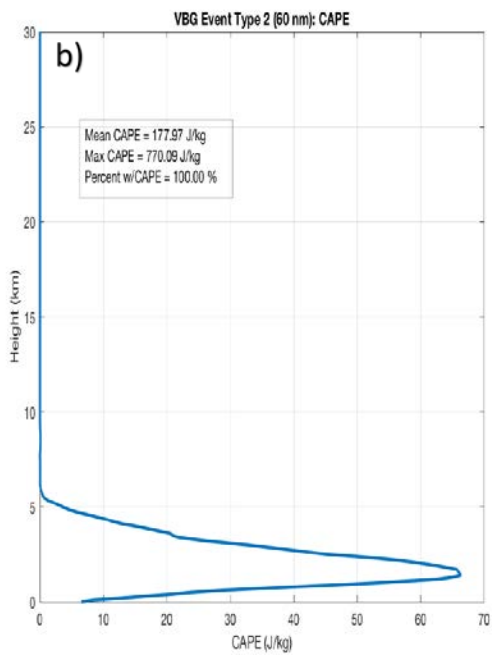
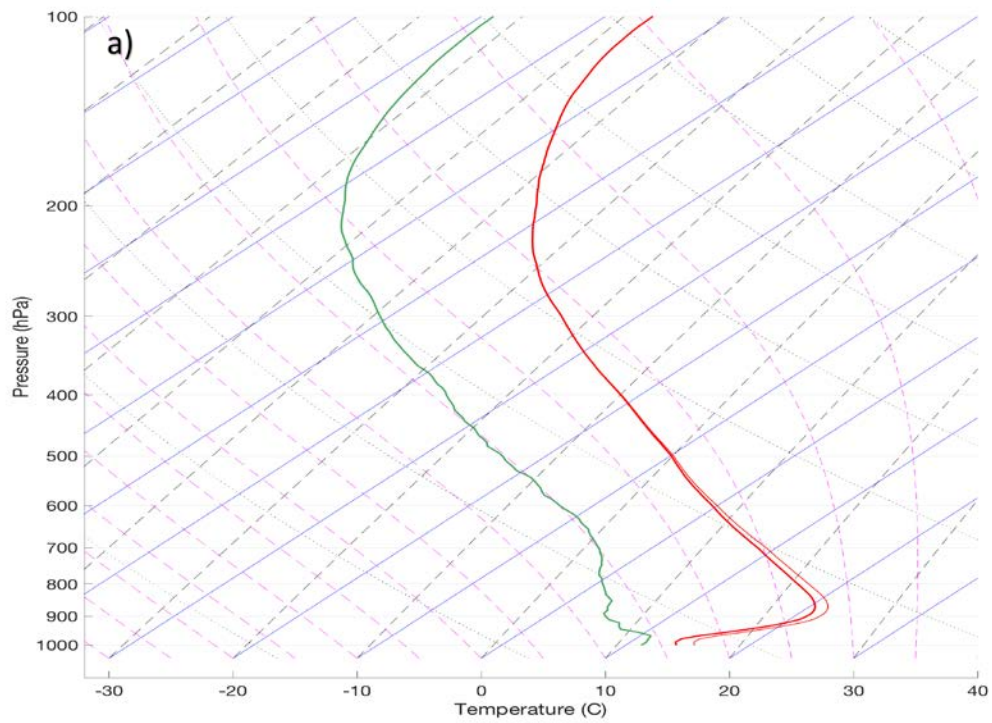
Figure 8. Locations of Lightning Strikes for Warm-Season Events (Event Type 2)

From the given data and event types composite soundings were made for events that occurred within one-hundred nautical miles or less of the sounding sites. Figure 9 (a) is for Oakland which had 14 events such events. Figure 10 (a) is for Vandenberg AFB which had 37 events within one-hundred nautical miles of the sounding site. Figure 11 (a) is for San Diego which had 46 events within 100 nautical miles of the sounding location.



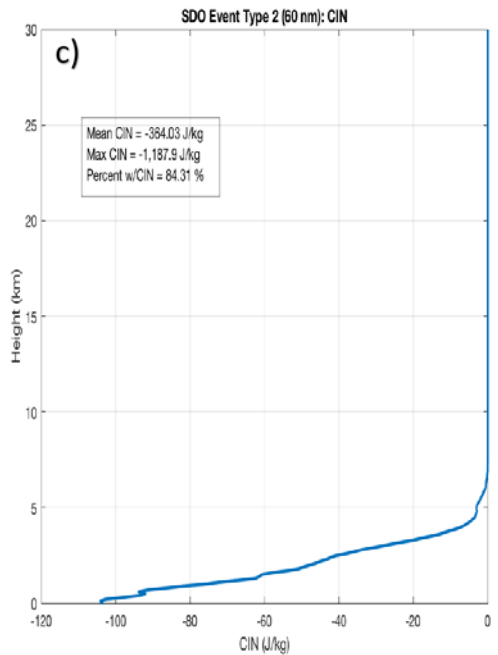
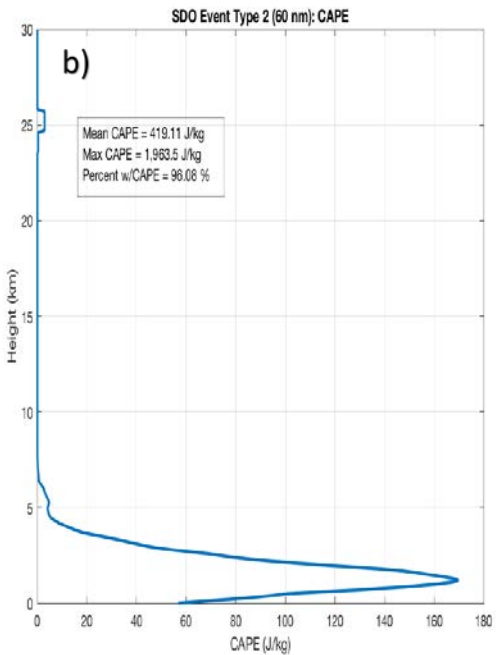
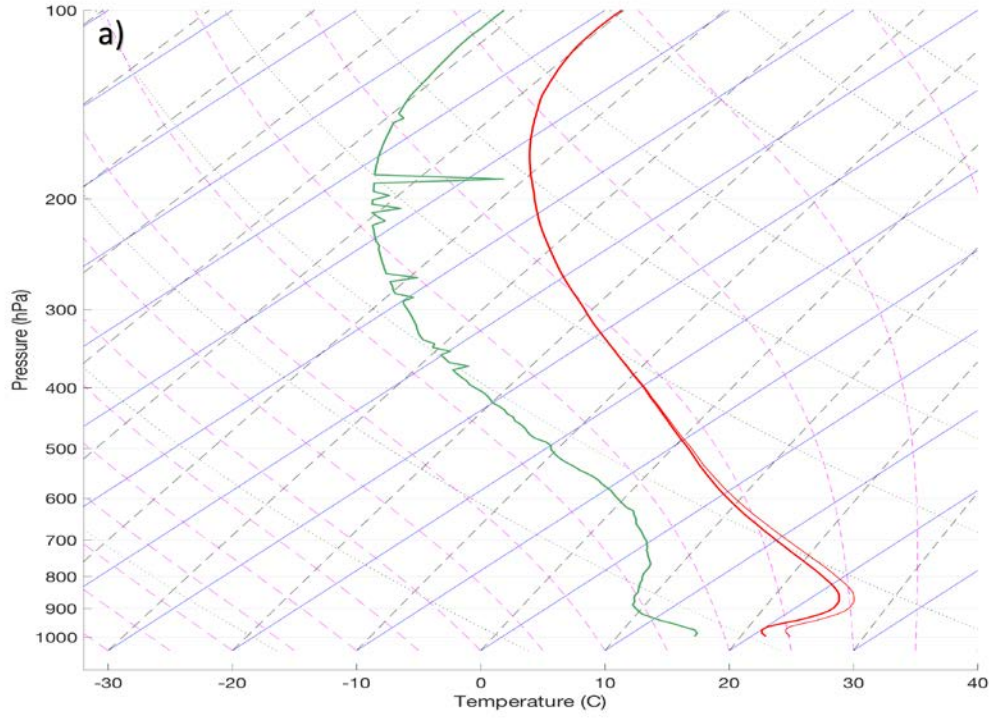
(a) composite sounding, (b) composite CAPE, (c) composite CIN

Figure 9. Event Type 2: Oakland



(a) composite sounding, (b) composite CAPE, (c) composite CIN

Figure 10. Event Type 2: Vandenberg

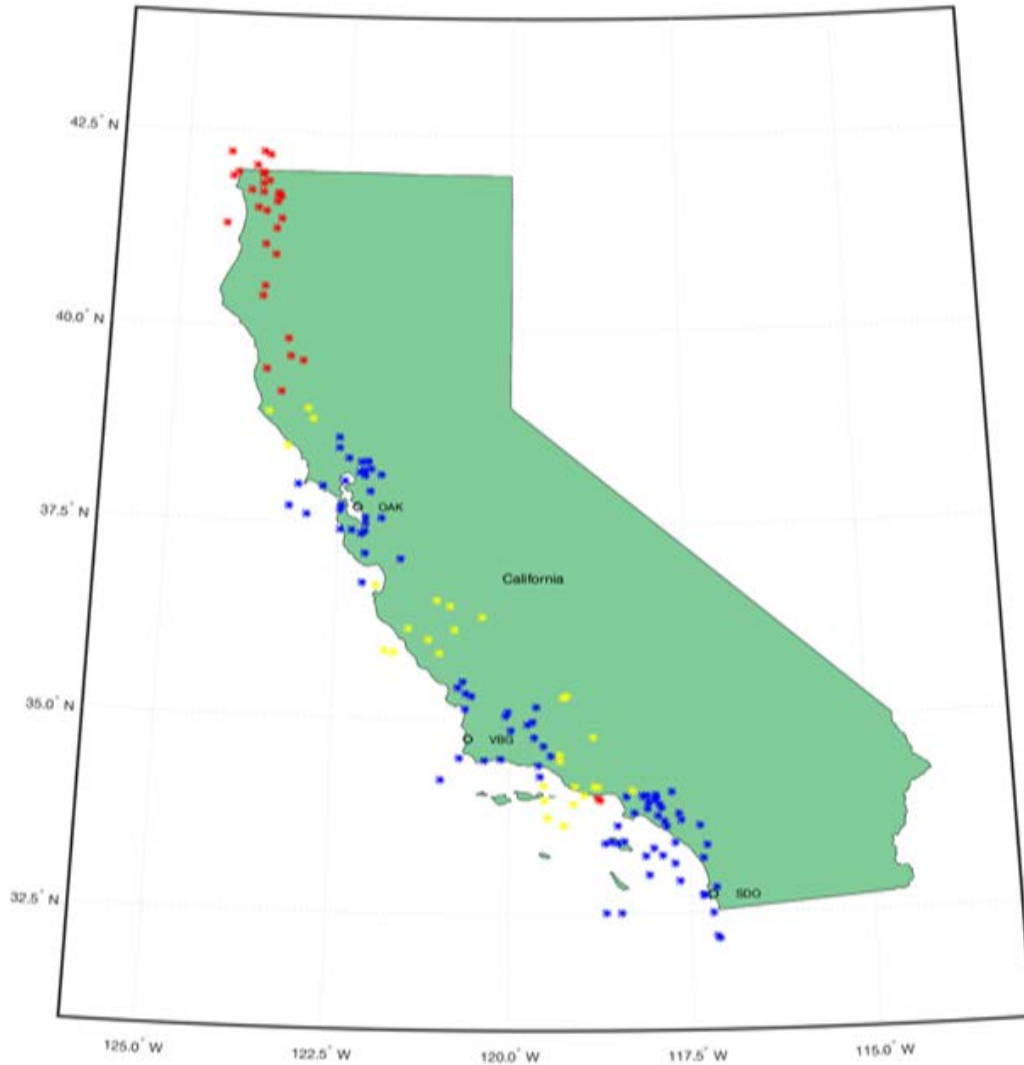


(a) composite sounding, (b) composite CAPE, (c) composite CIN

Figure 11. Event Type 2: San Diego

As you can see from all three composite soundings in Figure 9, 10, and 11, there appears to be elevated CAPE and a dryer level below 750 hPa in all three composites. To verify this the composite CAPE and CIN values were calculated and plotted. In Figure 9 (b), Figure 10 (b), and Figure 11 (b) you can see the composite CAPE values, percent of soundings with CAPE, max CAPE, and mean CAPE for the Oakland, Vandenberg AFB, and San Diego soundings respectively. In Figure 9 (c), Figure 10 (c), and Figure 11 (c) you can see the composite CIN values, percent of soundings with CIN, max CIN, and mean CIN for the Oakland, Vandenberg AFB, and San Diego soundings respectively. It is apparent from Figures 9, 10, and 11 (b) that the CAPE is maximized above the surface as hypothesized by Schlosberg (2018). Also in Figures 9, 10, and 11 (a), you can see the dry layer below 750 hPa that Schlosberg hypothesized as well.

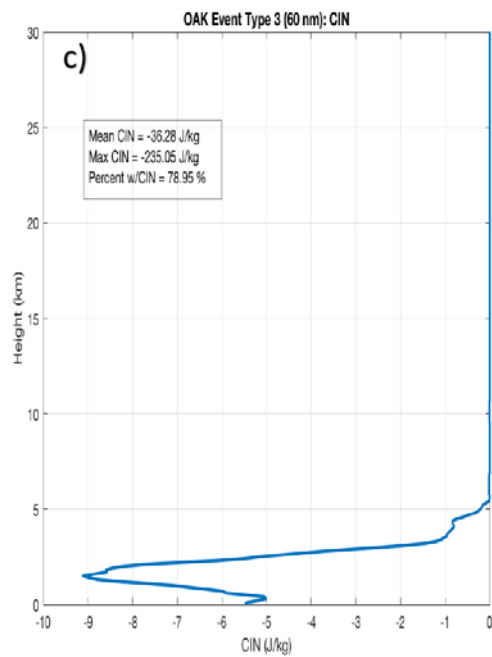
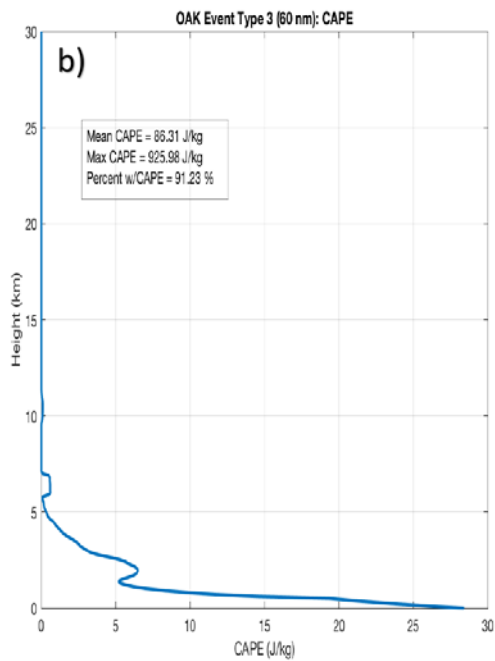
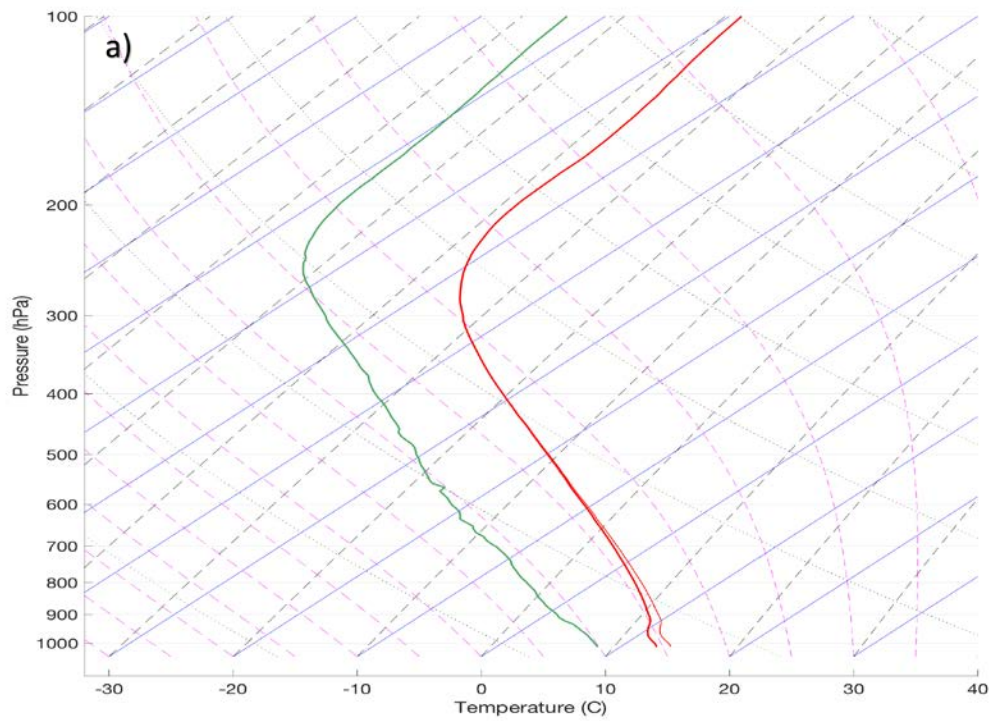
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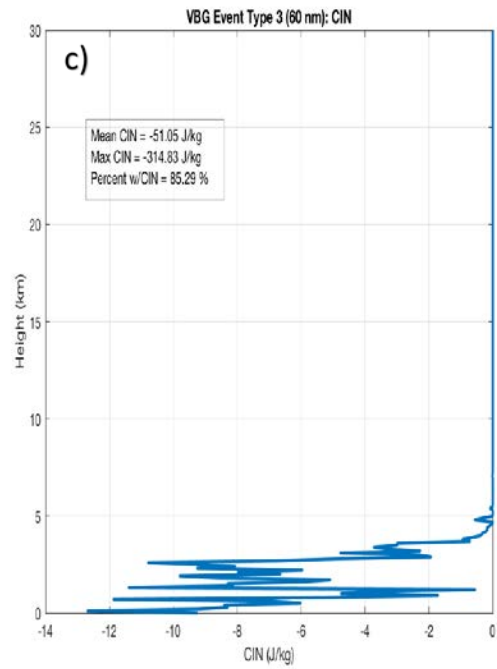
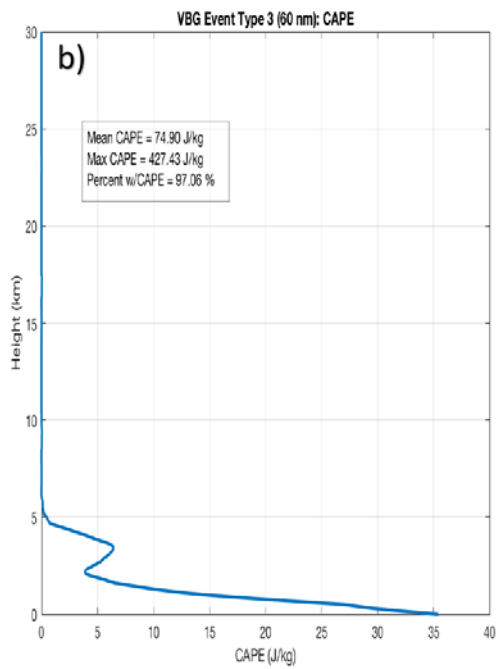
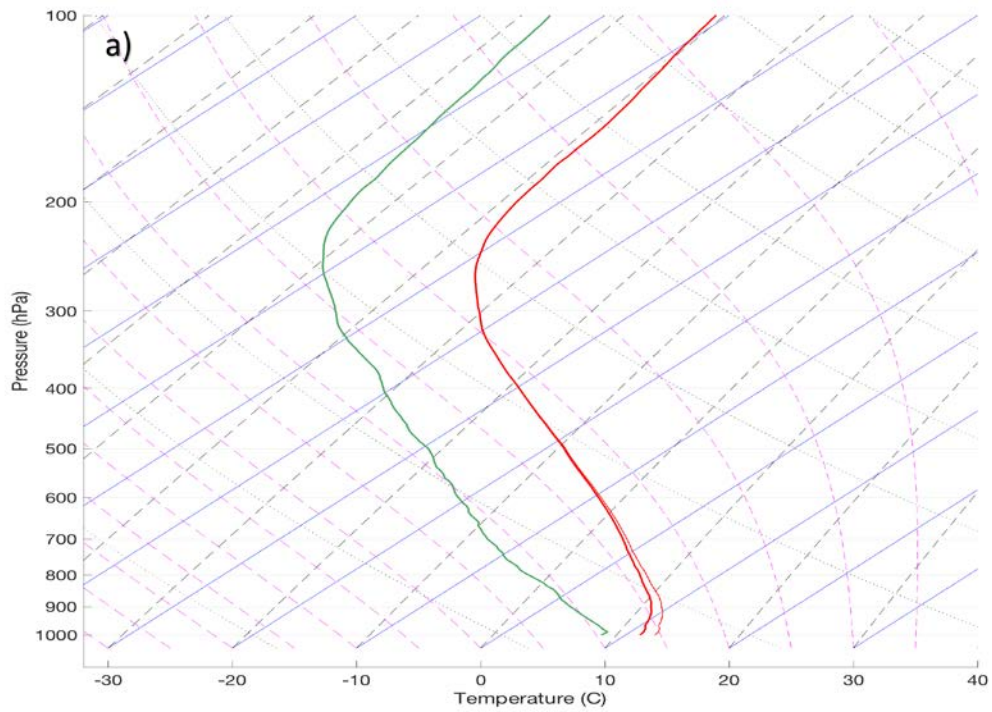
Figure 12. Locations of Lightning Strikes for Cold-Core Low Events (Event Type 3)

From the given data and event types composite soundings were made for events that occurred within one-hundred nautical miles or less of the sounding sites. Figure 13 (a) is for Oakland which had 36 events such events. Figure 14 (a) is for Vandenberg AFB which had 42 events within one-hundred nautical miles of the sounding site. Figure 15 (a) is for San Diego which had 40 events within one-hundred nautical miles of the sounding location.



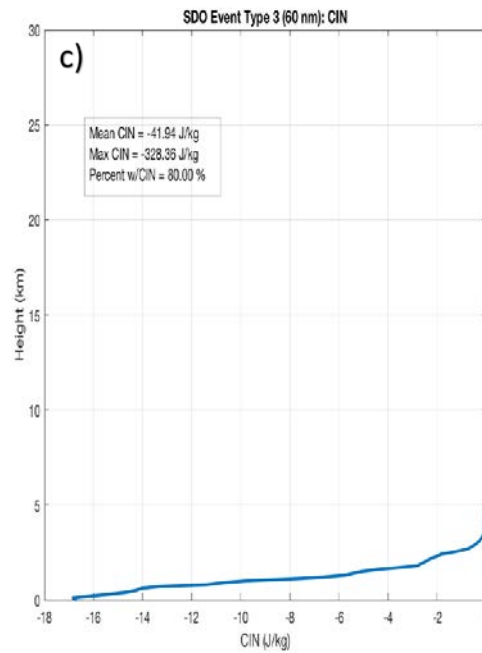
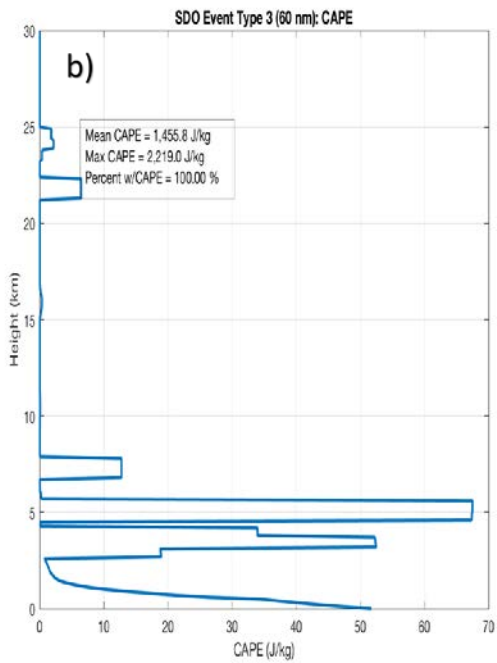
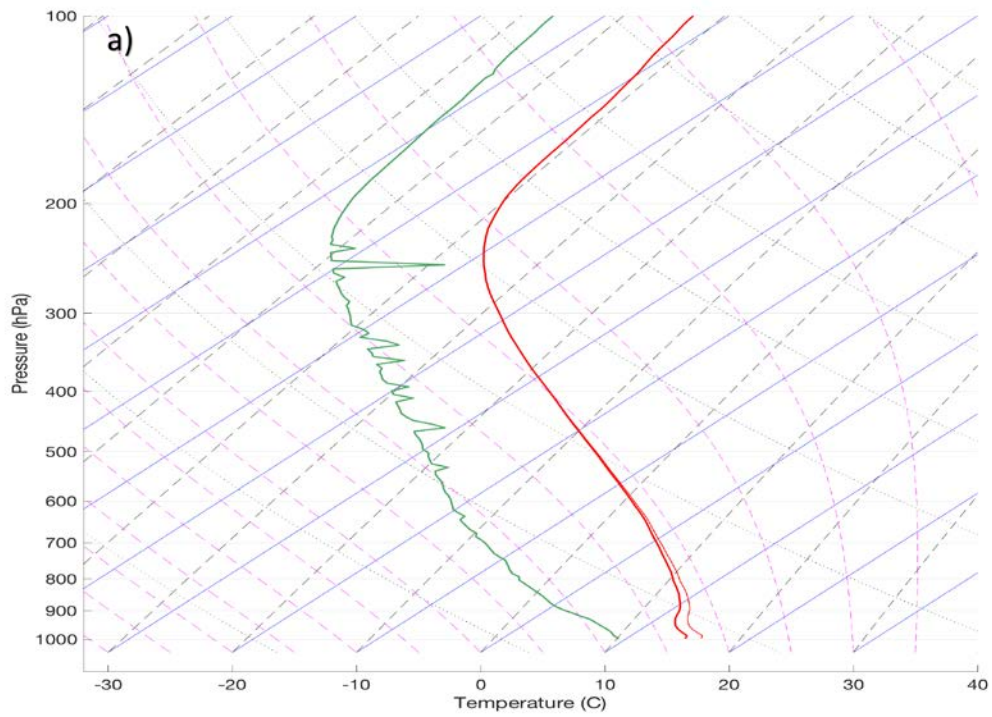
(a) composite sounding, (b) composite CAPE, (c) composite CIN

Figure 13. Event Type 3: Oakland



(a) composite sounding, (b) composite CAPE, (c) composite CIN

Figure 14. Event Type 3: Vandenberg



(a) composite sounding, (b) composite CAPE, (c) composite CIN

Figure 15. Event Type 3: San Diego

As you can see from all three composite soundings in Figures 13, 14, and 15, there appears to be surface-based CAPE in all three. To verify this the composite CAPE and CIN values were calculated and plotted. In Figure 13 (b), Figure 14 (b), and Figure 15 (b) you can see the composite CAPE values, percent of soundings with CAPE, max CAPE, and mean CAPE for the Oakland, Vandenberg AFB, and San Diego soundings respectively. In Figure 13 (c), Figure 14 (c), and Figure 15 (c) you can see the composite CIN values, percent of soundings with CIN, max CIN, and mean CIN for the Oakland, Vandenberg AFB, and San Diego soundings respectively. It is apparent from Figures 13, 14, and 15 (b) that the CAPE is maximized at the surface as hypothesized by Schlosberg (2018).

In the Appendix there are CAPE and CIN graphs for each event type for 60 nautical miles or less and 100 nautical miles or less with bars for plus or minus 1 standard deviation. In addition to the CAPE and CIN figures there are also the post storm synoptic observations in the appendix. All images in the appendix were not included in the main body of this paper as not to overwhelm the reader. However, if the reader is interested in those images please see the appendix.

To summarize what has been discussed previously, there is evidence of the following in our data above as hypothesized by Schlosberg (2018).

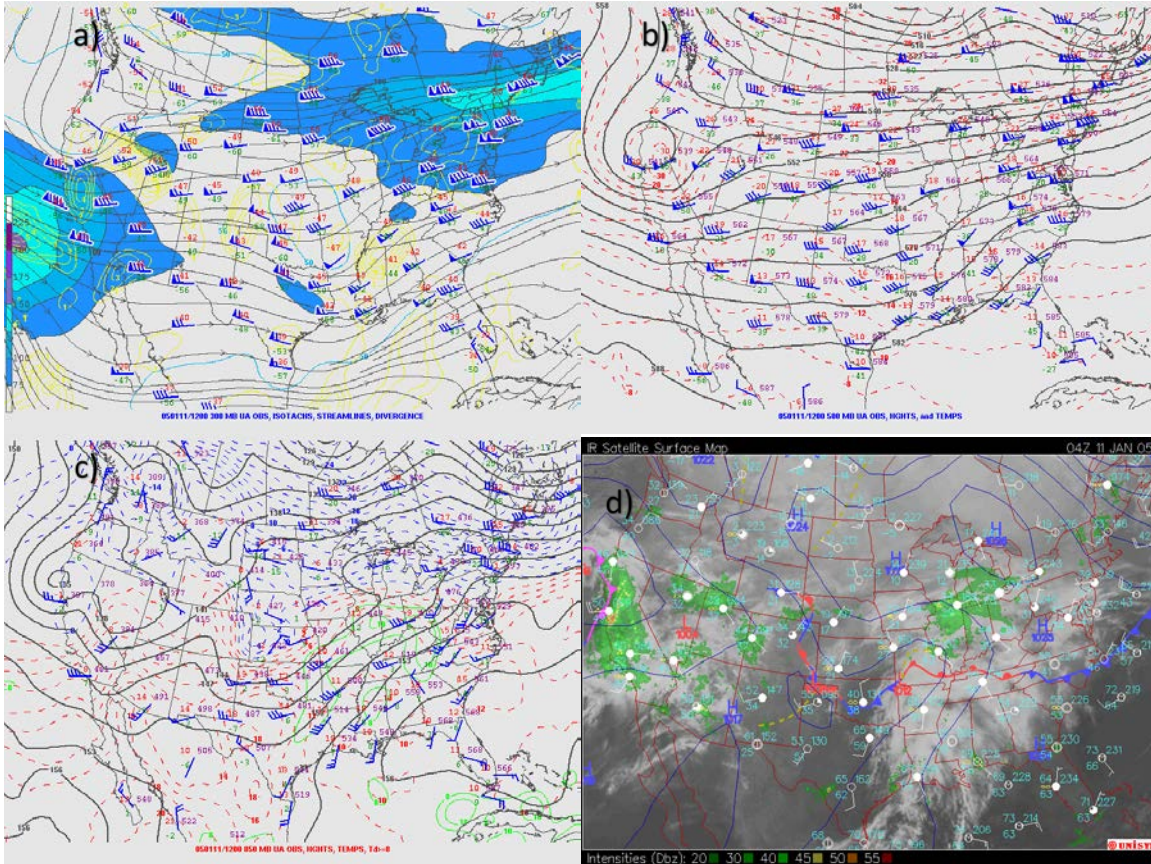
- All event types have a favored anomalously steep mid-level lapse rate.
- Event Types 1 and 3 (jet-type and cold-core low events) do appear to have been the products of surface-based CAPE and have their maximum average CAPE located at the surface.
- Event Type 2's (warm season events) were found to have had elevated-based CAPE with the maximum average CAPE located above the surface at all three locations. Also, there is a distinct dry layer below 750 hPa in all composite soundings.

Therefore, the majority of the results of Schlosberg have been verified with sounding data from Oakland, Vandenberg AFB, and San Diego from 112, 108, and 92 soundings respectfully across all event types. The only thing that we found different in this

paper is that the CAPE of the Event Type 3's (cold-core low) were generally larger than the Event Type 1's (jet-type event). This result was seen even more clearly for all events taken into account only within 60 nautical miles. For all of these events within 60 nautical miles, the average Event Type 3 CAPE values were larger than the Event Type 1 mean CAPE values. This is the only difference we found from the results of Schlosberg.

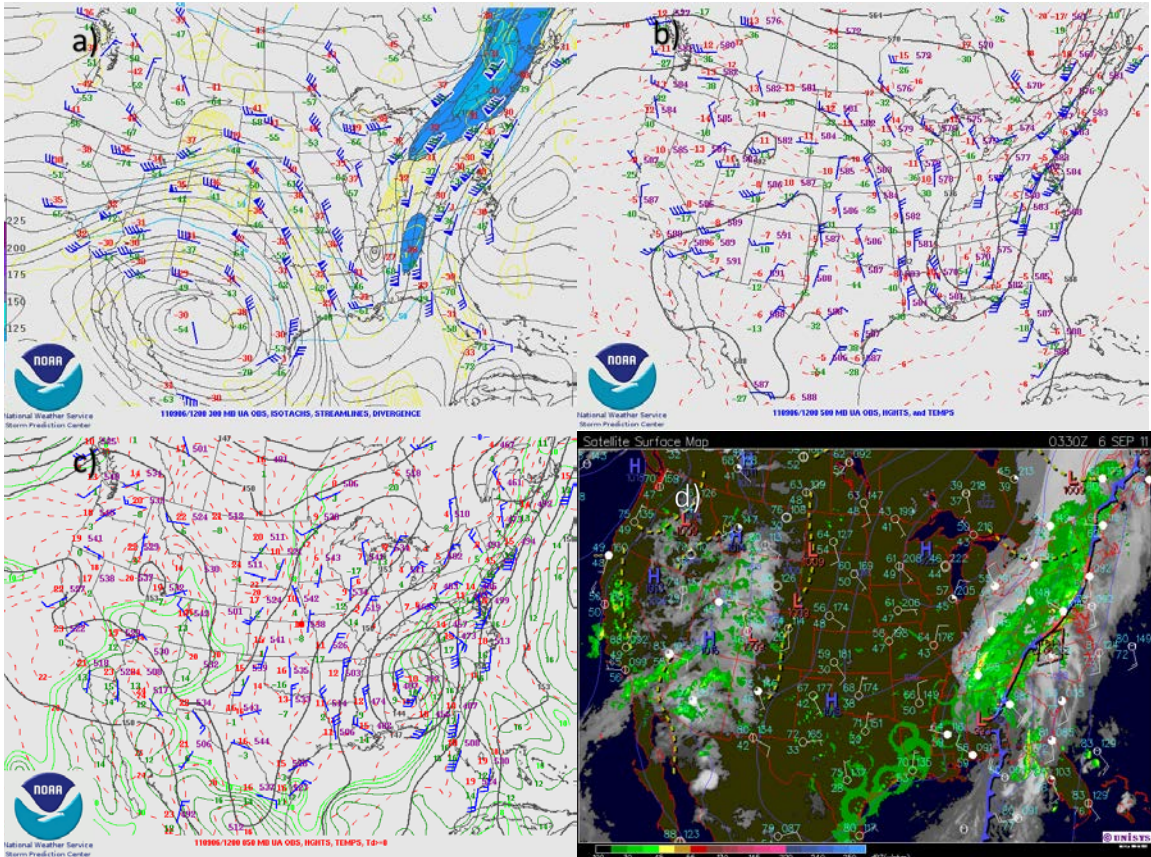
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APPENDIX. SYNOPTIC IMAGES FOR EVENT TYPES AND CORRESPONDING CAPE AND CIN GRAPHS



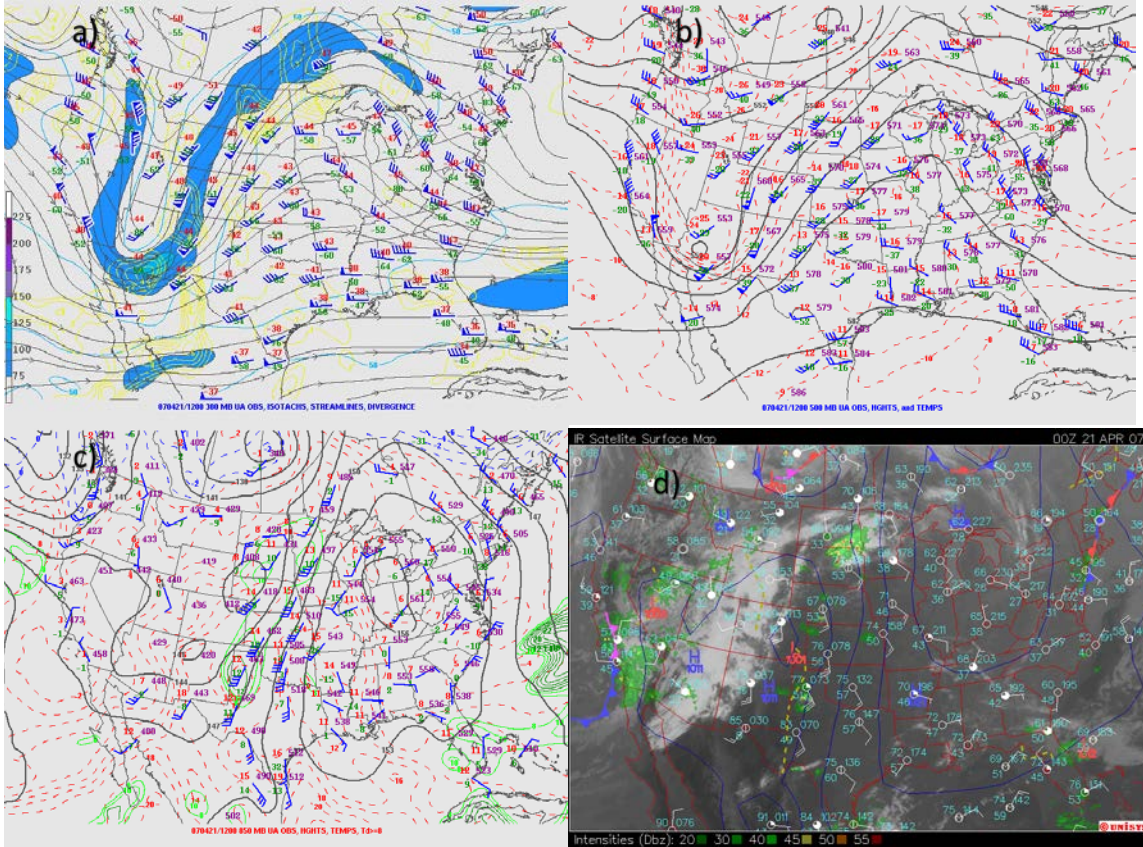
(a) 300mb obs, (b) 500mb obs, (c) 850mb obs, and (d) satellite and radar at 0400Z
Images from UCAR (2005b, 2005d, 2005f, 2005h).

Figure 16. Post-Jet-Type Event over Oakland 1200Z



(a) 300mb obs, (b) 500mb obs, (c) 850mb obs, and (d) satellite and radar at 0330Z
 Images from UCAR (2011a, 2011c, 2011e, 2011g).

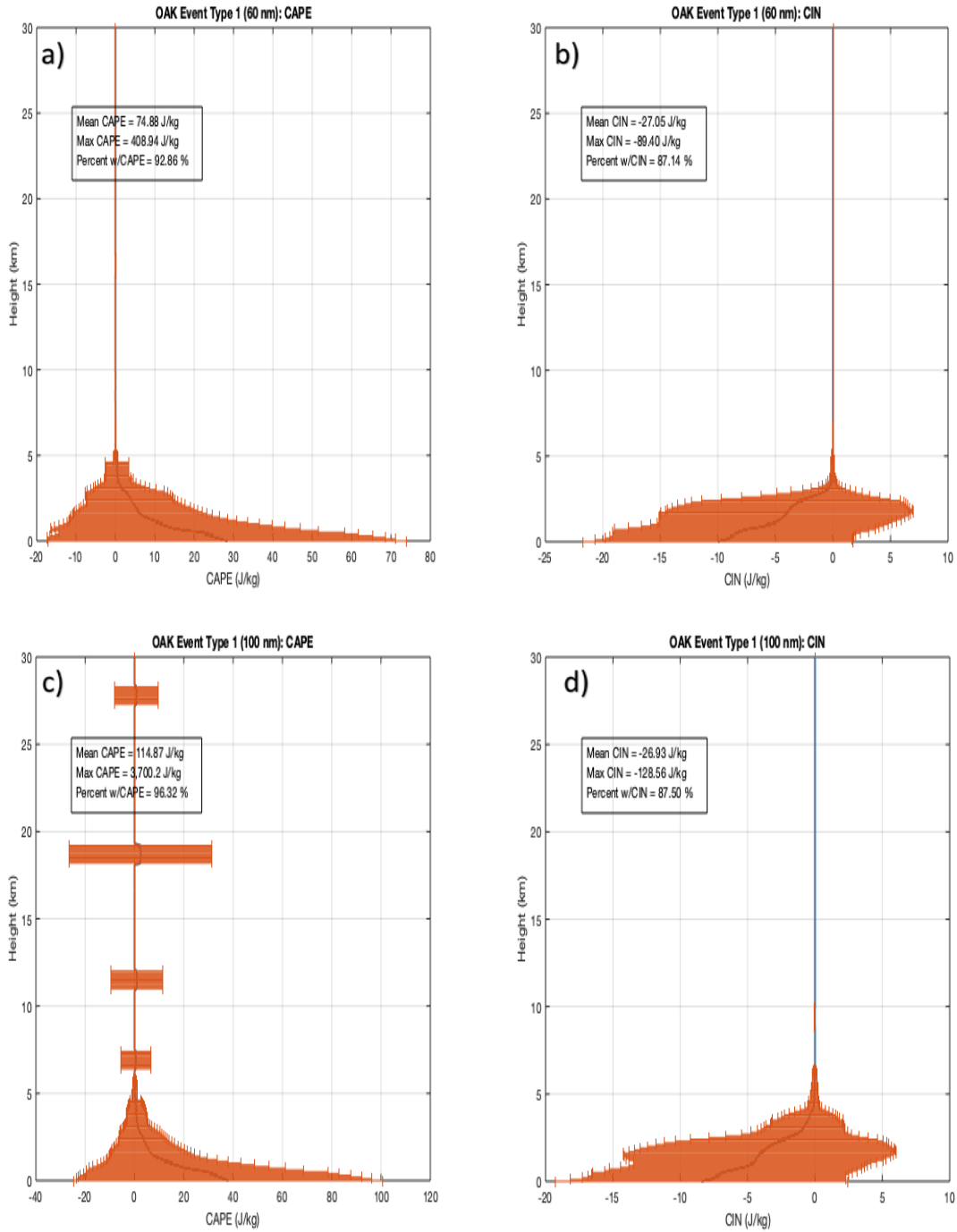
Figure 17. Post-Warm-Season Event over San Diego 1200Z



(a) 300mb obs, (b) 500mb obs, (c) 850mb obs, and (d) satellite and radar at 0600Z

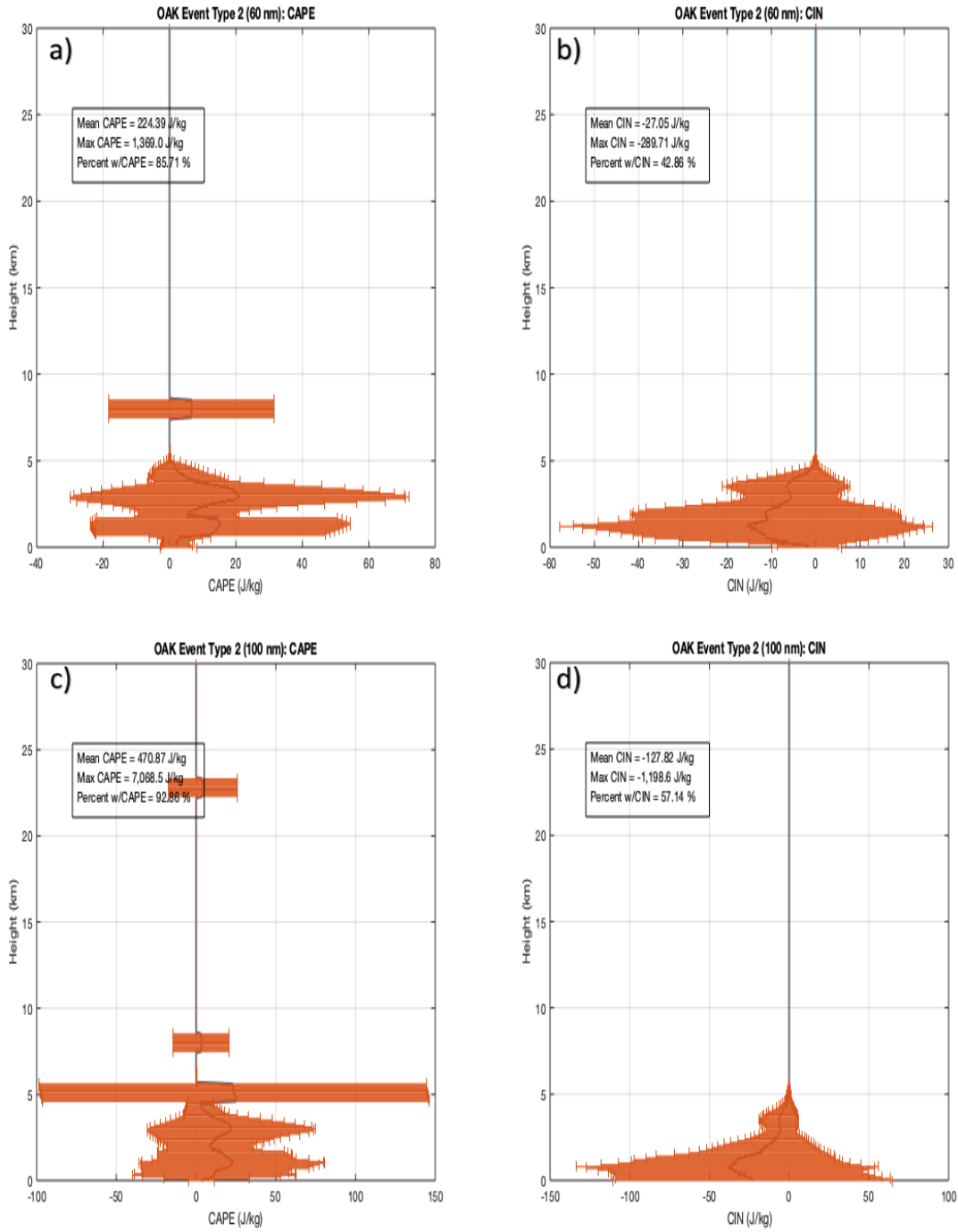
Images from UCAR (2007a, 2007c, 2007e, 2007g).

Figure 18. Cold-Core Low Event over San Diego 1200Z



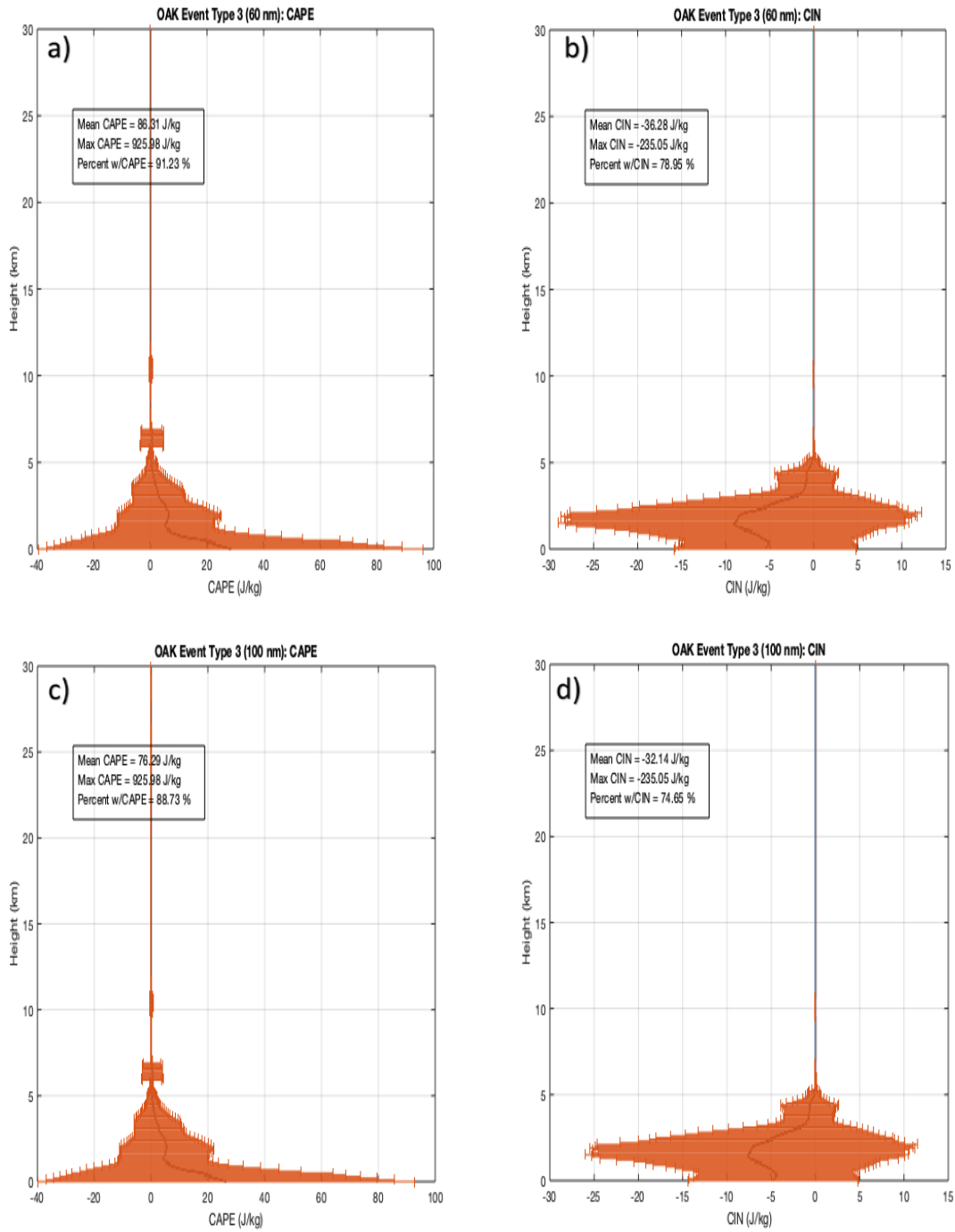
(a) CAPE w/ +/- 1 standard deviation 60 nautical miles, (b) CAPE w/ +/- 1 standard deviation 60 nautical miles, (c) CAPE w/ +/- 1 standard deviation 100 nautical miles, (d) CIN w/ +/- 1 standard deviation 100 nautical miles

Figure 19. Event Type 1: Oakland



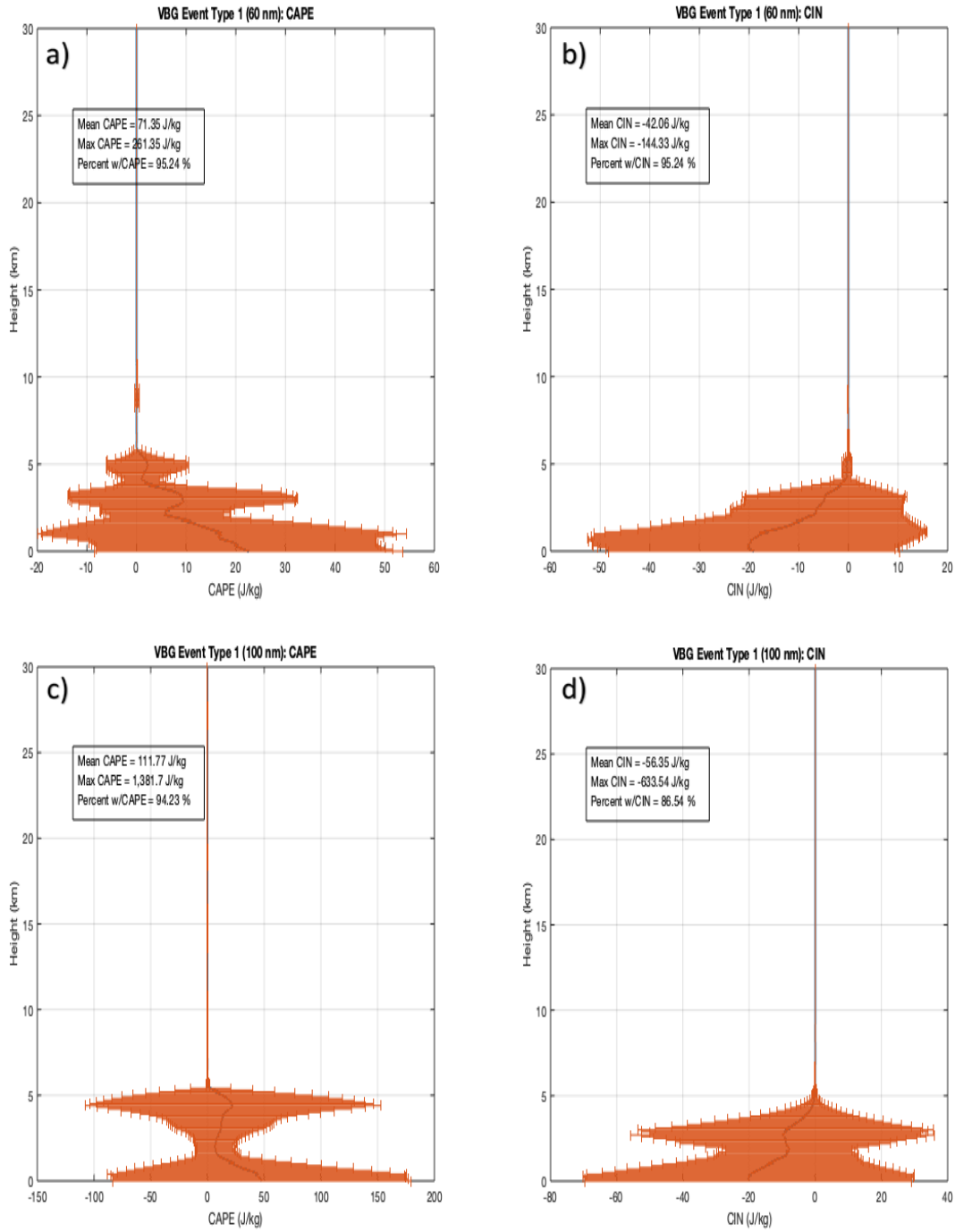
(a) CAPE w/ +/- 1 standard deviation 60 nautical miles, (b) CAPE w/ +/- 1 standard deviation 60 nautical miles, (c) CAPE w/ +/- 1 standard deviation 100 nautical miles, (d) CIN w/ +/- 1 standard deviation 100 nautical miles

Figure 20. Event Type 2: Oakland



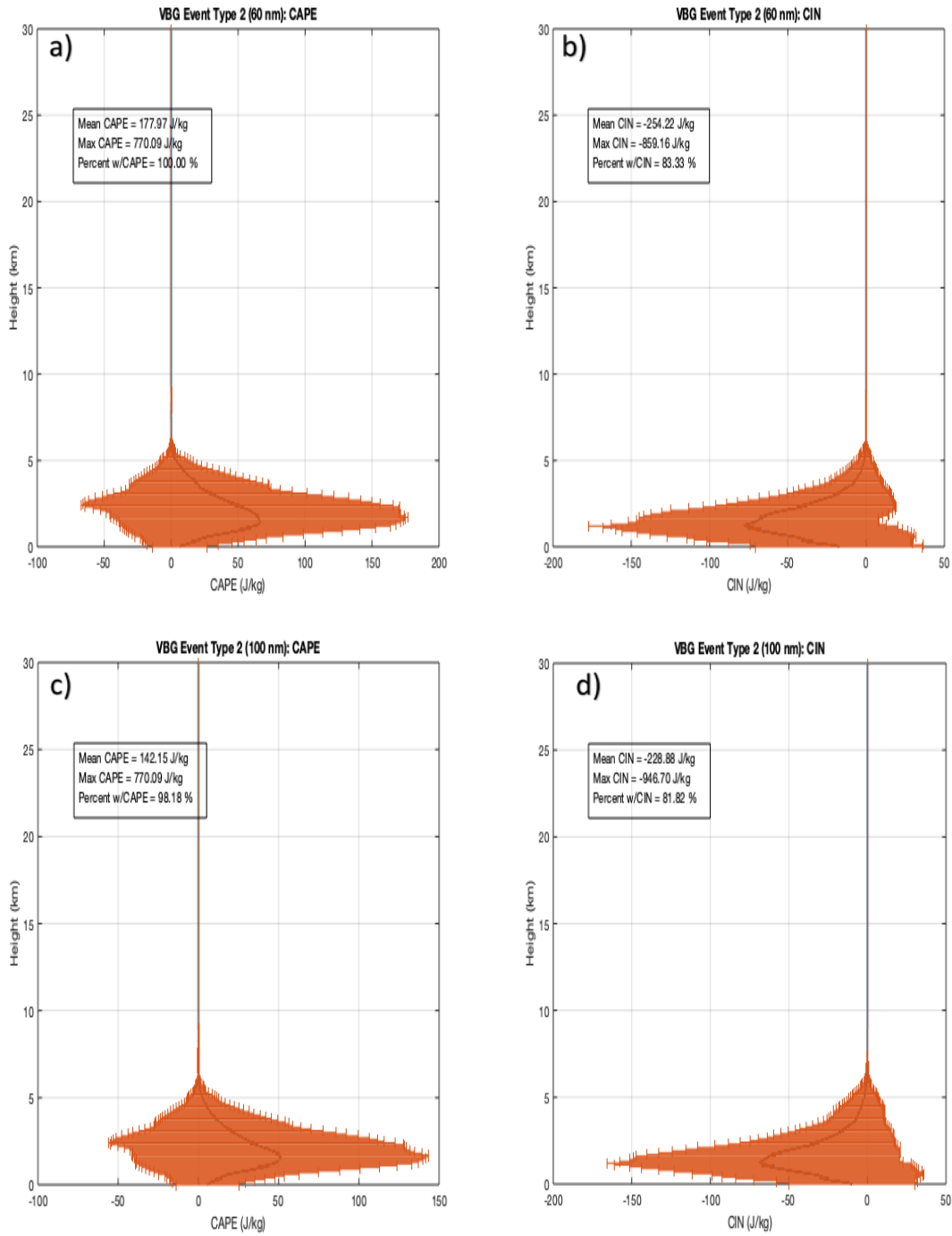
(a) CAPE w/ +/- 1 standard deviation 60 nautical miles, (b) CAPE w/ +/- 1 standard deviation 60 nautical miles, (c) CAPE w/ +/- 1 standard deviation 100 nautical miles, (d) CIN w/ +/- 1 standard deviation 100 nautical miles

Figure 21. Event Type 3: Oakland



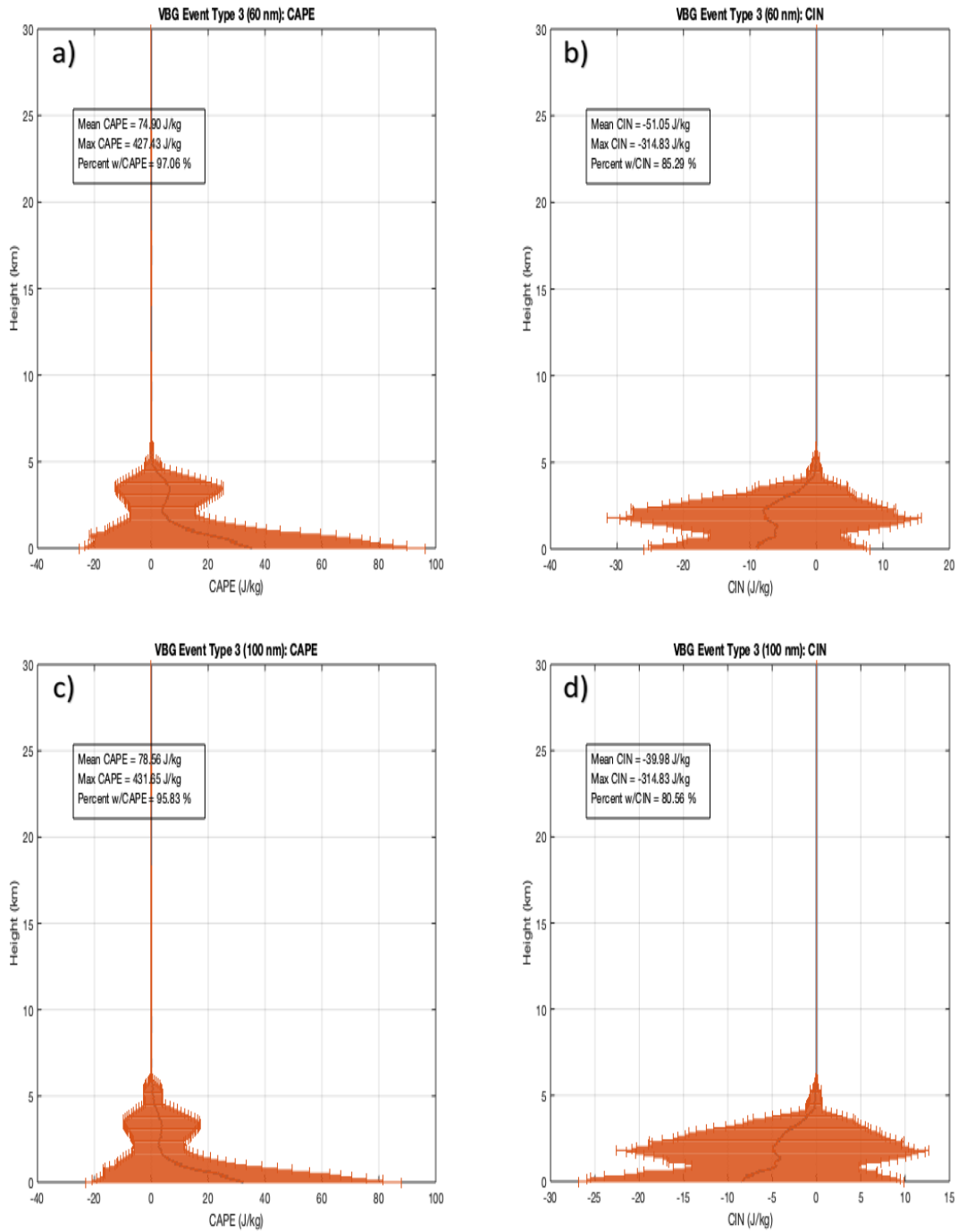
(a) CAPE w/ +/- 1 standard deviation 60 nautical miles, (b) CAPE w/ +/- 1 standard deviation 60 nautical miles, (c) CAPE w/ +/- 1 standard deviation 100 nautical miles, (d) CIN w/ +/- 1 standard deviation 100 nautical miles

Figure 22. Event Type 1: Vandenberg



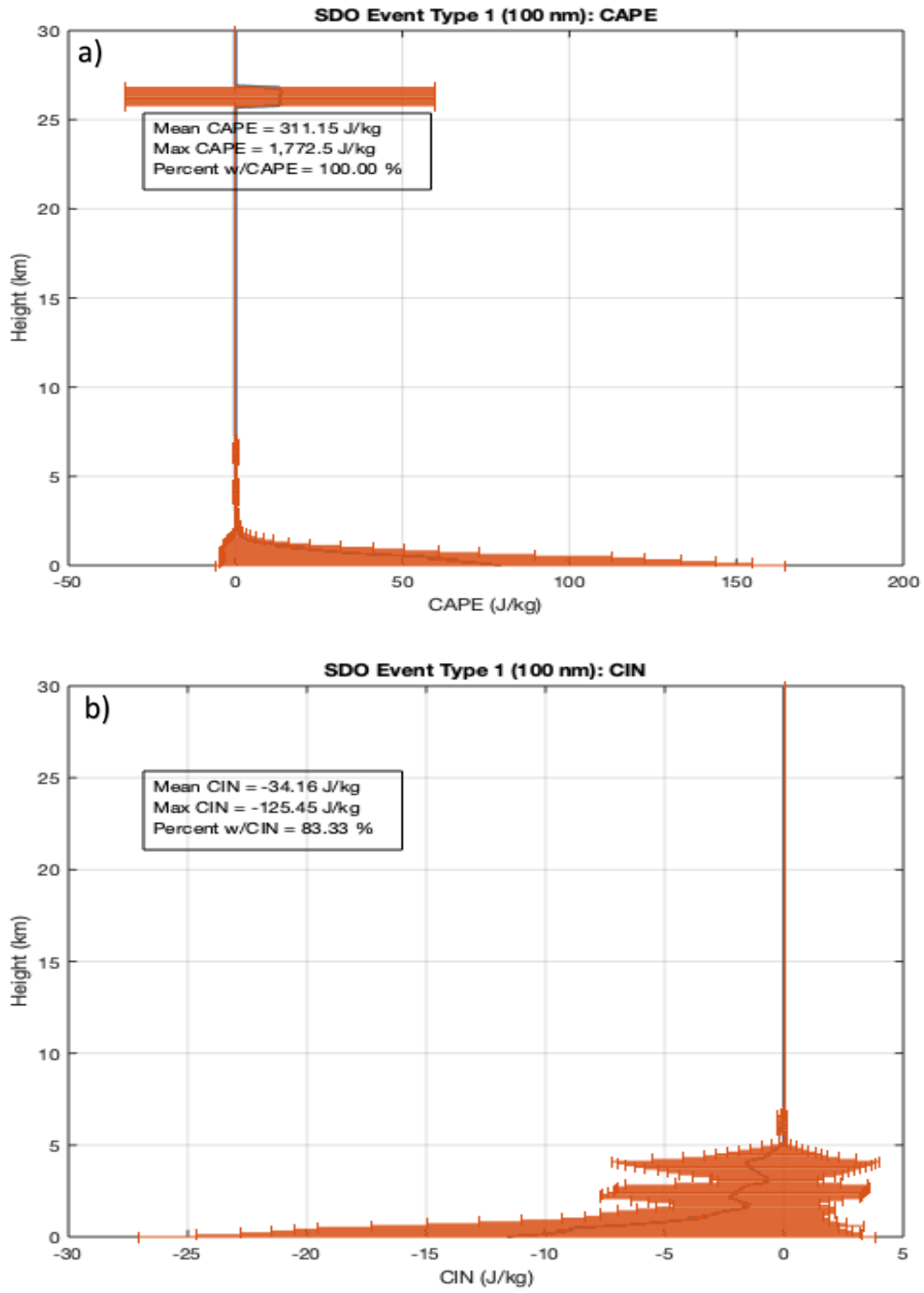
(a) CAPE w/ +/- 1 standard deviation 60 nautical miles, (b) CAPE w/ +/- 1 standard deviation 60 nautical miles, (c) CAPE w/ +/- 1 standard deviation 100 nautical miles, (d) CIN w/ +/- 1 standard deviation 100 nautical miles

Figure 23. Event Type 2: Vandenberg



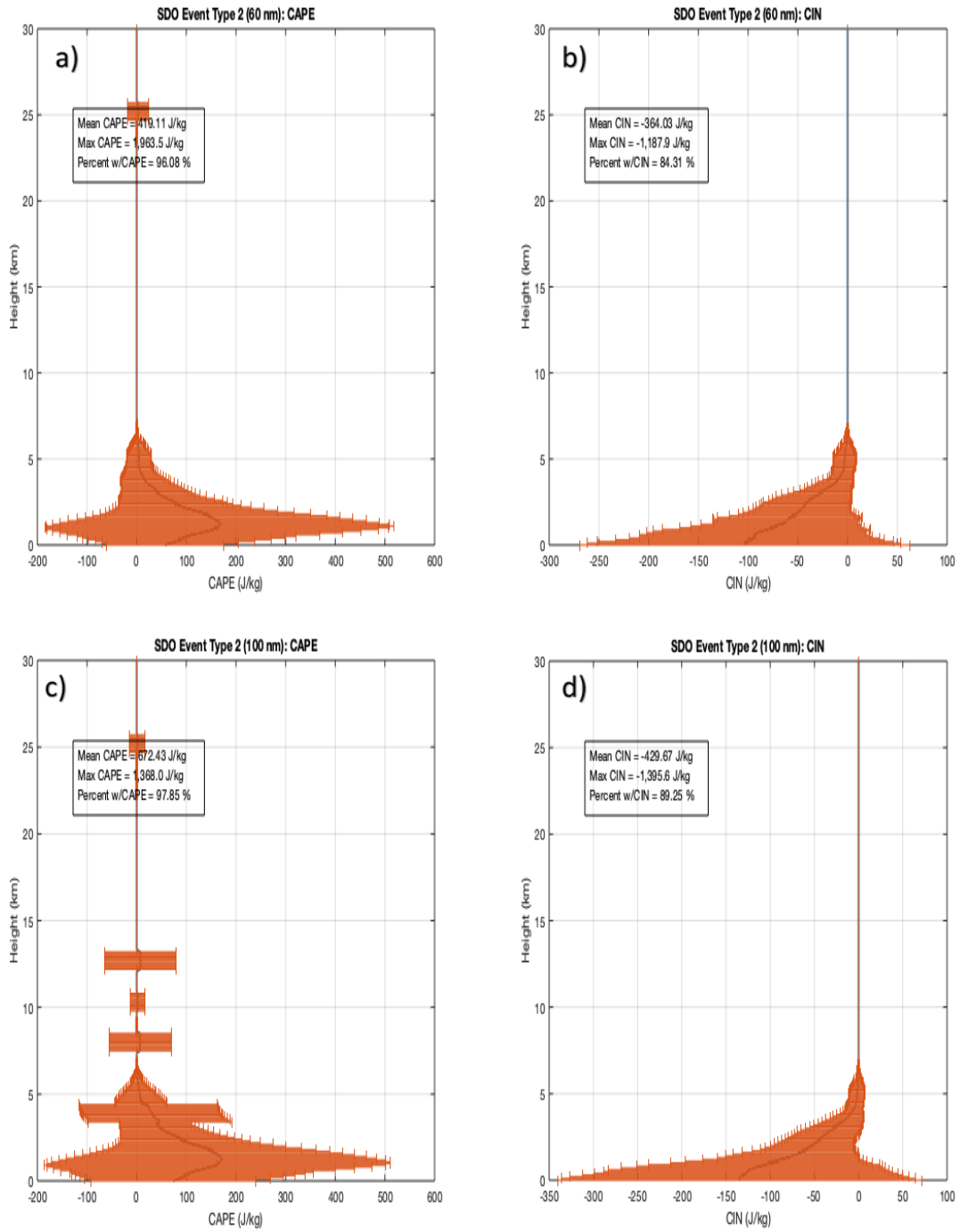
(a) CAPE w/ +/- 1 standard deviation 60 nautical miles, (b) CAPE w/ +/- 1 standard deviation 60 nautical miles, (c) CAPE w/ +/- 1 standard deviation 100 nautical miles, (d) CIN w/ +/- 1 standard deviation 100 nautical miles

Figure 24. Event Type 3: Vandenberg



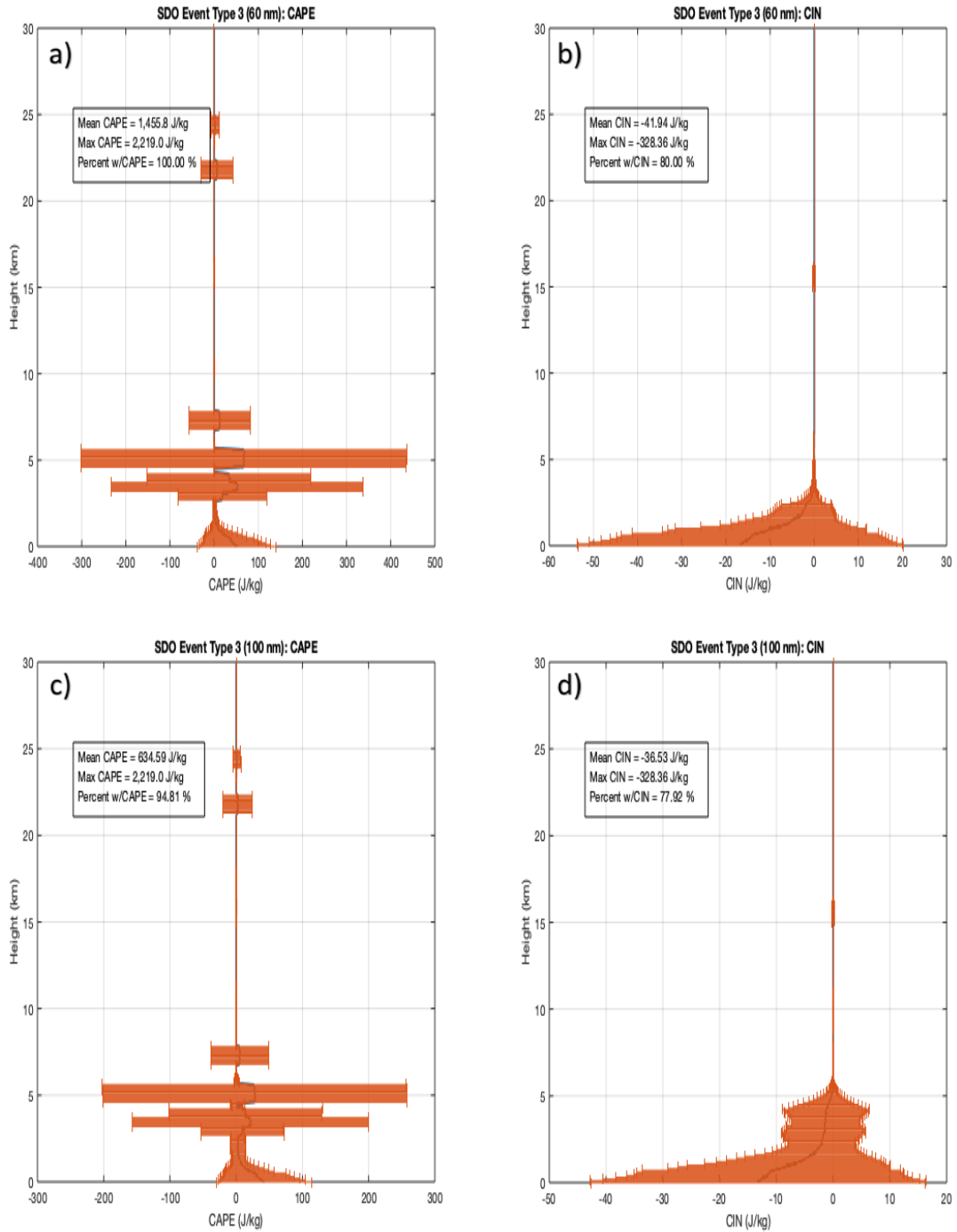
(a) CAPE w/ +/- 1 standard deviation 100 nautical miles, (b) CIN w/ +/- 1 standard deviation 100 nautical miles.

Figure 25. Event Type 1: San Diego



(a) CAPE w/ +/- 1 standard deviation 60 nautical miles, (b) CAPE w/ +/- 1 standard deviation 60 nautical miles, (c) CAPE w/ +/- 1 standard deviation 100 nautical miles, (d) CIN w/ +/- 1 standard deviation 100 nautical miles.

Figure 26. Event Type 2: San Diego



(a) CAPE w/ +/- 1 standard deviation 60 nautical miles, (b) CAPE w/ +/- 1 standard deviation 60 nautical miles, (c) CAPE w/ +/- 1 standard deviation 100 nautical miles, (d) CIN w/ +/- 1 standard deviation 100 nautical miles.

Figure 27. Event Type 3: San Diego

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