Author response to Anonymous Referee 1 for "Brief Communication: An Electrifying Atmospheric River: Understanding the Thunderstorm Event in Santa Barbara County during March 2019" by Deanna Nash and Leila M.V. Carvalho.

Responses to reviewer comments are given in blue text. New or changed text is given in *italics* (***bold italics*** for emphasis where noted)

General Comments

This brief manuscript describes meteorological characteristics of an atmospheric river event from March 2019 that caused an unprecedented amount of lightning in Santa Barbara. The manuscript is clearly written, and the analysis is straightforward: brief but appropriate for publication as a brief communication. My biggest concern with the manuscript in its present form is that, while the exceptional nature of the amount of lightning is well described and detailed, the links between the meteorology and lightning itself are presumed and not very clearly described. The manuscript also restates the lightning results a bit more than necessary given the (very short) length of the Manuscript.

We thank the reviewer for the time taken to review this manuscript and all constructive feedback that helped improve the paper, specifically in regard to clarifying the links between the lightning and thermodynamics. Below we address the specific comments.

Specific Comments

L. 7-8, 41-43, and 70-71: This result (i.e., the average flash density for the region) is restated three times by the fourth page of the manuscript. Redundancies such as this example are not warranted in such a brief manuscript, and the text should be tightened up to remove them. The text of the abstract needs particular attention to ensure it conveys the most salient results of the manuscript: I suggest removing this peripheral detail in favor of an additional sentence at the end of the abstract that links the meteorology with the exceptional lightning.

We agree with the reviewer and have updated these sections to remove the redundancies. The final sentence of the abstract now states, *"Despite the negligible convective available potential energy (CAPE) during the peak of the thunderstorm near Santa Barbara, the lifting of layers with high water vapor content in the AR via warm conveyor belt and orographic forcing in a convectively unstable atmosphere resulted in the formation of hail and enhanced electrification."*

L. 111-112: It's rather difficult to see this synoptic feature (WCB) with such a zoomed-in domain.

We agree it was difficult to see the WCB in the previous version of the figure. We have zoomed out on the domain of Fig. S5, now Fig. S3, and have added contours of IVT to the maps for reference to the location of the AR in relation to the WCB (noted by RC2).

L. 147-150 and much of this entire section: Much of this text relays presumptions as conclusions. For example, 'The convective updraft in the lower troposphere was very important for the onset of electrification,...' this manuscript in no way proves what was or wasn't important for the onset of electrification (instead it presents the meteorology, documents that there was quite a lot of electrical activity, and requires inference between the two). This section needs revision to clarify what previous literature suggests are important factors for lots of lightning in storms, and how those factors relate to this particular storm. I was unable to read the citation Price 2013 from the manuscript, but found Pessi and Businger (2009) helpful in framing my review.

We agree that clarification was needed between what previous literature suggests are important factors in electrification and what the data implies about the electrification for this particular storm. We thank the reviewer for suggesting the reference Pessi and Businger (2009) which was added to this manuscript. The section on lightning conditions in the results has been edited extensively for these clarifications. Please see updated Section 3.4 Lightning Conditions.

L. 193-203: This summary paragraph could do a better job relating what was unusual about this atmospheric river (AR) event that potentially led it to produce so much lightning. ARs in particular are not terribly unusual for Santa Barbara (e.g. Rutz et al. 2014). In addition, the authors suggest that the 2.5km 0 degree C isotherm was a large factor in allowing hail to develop, but 2.5 km is not a particularly low freezing level for a midlatitude storm at this latitude (Cannon et al. 2017). More care and thought should be put toward this aspect of the manuscript; without this connection the main emphasis of the manuscript becomes a bit fuzzy. The dry air layer at 250 hPa is alluded to as a possible mechanism (and note there is another dry layer at 500 hPa).

According to Rutz et al. (2014), AR frequency in the Santa Barbara coastal region is approximately 6% of the time steps in ERA-Interim analyses (see Rutz et al. (2014) Fig 4a) between November 1988 to April 2011 (Nov-April only), meaning that an AR was identified at approximately 1,000 6-hour time steps or roughly 250 AR days out of 4,100. The global AR detection algorithm developed by Guan and Waliser (2015) used to identify previous AR days in our study shows similar agreement to the results of Rutz et al. (2014). We think that 6% of the time is a relatively infrequent occurrence for ARs, and Southern California has the lowest frequency of ARs compared to other regions along the west coast of North America (Harris and Carvalho, 2018; Guan and Waliser, 2015, among others) However, our manuscript shows that despite the AR having a relatively average IVT value for ARs that make landfall in Santa Barbara (around 400 kg m^{-1} s^{-1}; see Fig. S2b), when looking at the vertical profile of the horizontal water vapor flux at each pressure level, the AR that occurred on 5-6 March 2019 had a significantly above average water vapor flux content in the middle troposphere compared to the other 170 days and AR made landfall in Santa Barbara during the month of March (see Fig. 3c). To show what was unique and what was not for this particular AR, we have updated Fig. S3, now Fig. S2 to include distribution information of the characteristics of ARs in Santa Barbara, including 0°C Isotherm Height.

According to Cannon et al. (2017), the mean height of the 0°C isotherm was about 2,500 m for the 83 AR events in Central and Northern California (20°N to 60°N and 160°W to 110°W) during three winter seasons (October through March; 2014-2017). After calculating the height of the 0°C isotherm using MERRA2 and the methodology used in Cannon et al. (2017) and Harris Jr et al. (2000), we created a climatology of the 0°C isotherm for all days an AR made landfall in Santa Barbara (identified using the AR detection algorithm provided by Guan and Waliser (2015)) between 1980 and 2017 (n=1814), and found that the average height of the 0°C isotherm during these days was about 3500 m (Fig. S2d). Therefore, the 0°C isotherm during the 5 March AR was below average for the location and the period.

We do agree with the reviewer that the connection between the meteorological conditions and the lightning could be improved to demonstrate the reasons for the unusual lightning strikes. To properly address these issues we included new results regarding the profile of convective (potential) instability in the location of the highest lightning flash density (see new Fig. S4), identified by the profiles of Equivalent Potential Temperature (θ_E). We have also added the θ_E profile to Fig. 3 to indicate the importance of convective instability in Santa Barbara at the time of the peak of the event (see Fig. 3b). With this information we provided additional evidence that the deep moist atmosphere lifted via WCB and orographic forcing in a convectively unstable atmosphere with a low 0°C isotherm was highly conducive to hail formation and lightning, even under conditions of relatively low CAPE.

Author response to Anonymous Referee 2 for "Brief Communication: An Electrifying Atmospheric River: Understanding the Thunderstorm Event in Santa Barbara County during March 2019" by Deanna Nash and Leila M.V. Carvalho.

Responses to reviewer comments are given in blue text. New or changed text is given in *italics* (***bold italics*** for emphasis where noted)

General Comments

This brief communication is appropriate for publication in NHESS. It describes a topical event impacting southern California in March of 2019, and uses remote sensing and operational analysis data sources to better understand the behavior and evolution of this particular potentially hazardous atmospheric river event, which was unusual due to the frequency of lightning strikes.

We thank the reviewer for the time spent to review this manuscript and all constructive feedback that helped improve the paper. Please see responses to comments below.

Specific Comments

Section 1 – what is the purpose of including the information on the peak current – for example, is the strength also an outlier?

The information on the peak current was included since this was the first documented case of such an extreme number of lightning strikes occurring in this region; we believe it is important to include statistics of these lightning flashes for future comparisons. Since it is not important to the main message of this manuscript, we have removed it for brevity.

Also, there are several different numbers used for the flashes over Santa Barbara County in this and other sections (e.g. line 72), please clarify the areas over which these numbers are representing.

We made an effort to clarify the areas over which flash densities have occurred, for example, this line now reads, *"TRMM LIS-OTD records an area annual average of 9.15 flashes per day in the region surrounding southern California (20°N to 50°N and 140°W to 110°W), making the 14,416 lightning flashes in under 24 hours very extreme. In fact, even if this was the only lightning activity for 2019, it would represent about 1,500 times the climatological rate (Fig. 1d)."*

Section 2 – consider adding brief justifications for the data sources used. In particular, why GPM for precipitation and not any in situ gauges? How well does GPM estimate precipitation in this region?.

We have done some preliminary analysis into two additional different precipitation products, namely three in-situ gauges in the SB region from National Weather Service and radar data from NWS (see Figure 1 below - not included in manuscript). The plot below shows the precipitation accumulation for the duration of the storm for the different locations and data sources. The gauges and the radar seem to have similar values for precipitation, except in the last location, while GPM values fall above the gauge and radar measurements in all three locations. The authors have decided to switch the precipitation dataset to NOAA NEXRAD L3 precipitation accumulation estimates (which are similar the the rain gauges) for this manuscript. Since there was not a significant amount of precipitation during this particular event (less than 30 mm accumulated), and the main point of this article focuses on the lightning, we use NOAA NEXRAD L3 precipitation to show that there was in fact precipitation to support our conclusion that the hail identified by NOAA NEXRAD L3 was important for the electrification process.

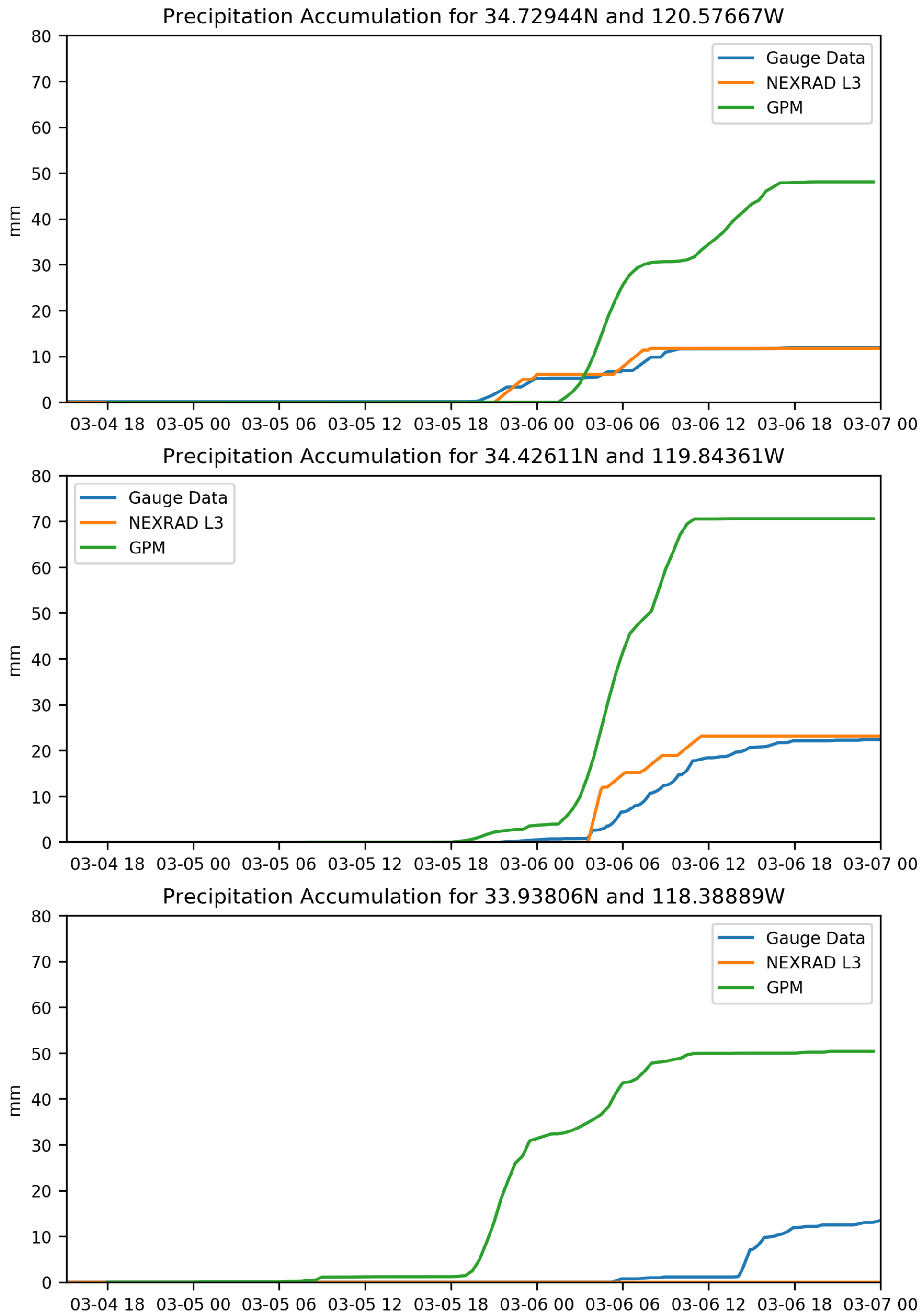

Figure 1. Precipitation accumulation (mm) over the duration of the storm period for 3 different locations near Santa Barbara for 3 different data sources, including NWS precipitation gauges (blue line), NOAA NEXRAD L3 precipitation estimates (orange line), and IMERG GPM (green line).

Please also discuss the implications of using the two different lightning data sources and uncertainties that might result from comparing between the two during different periods.

A few sentences have been added to the Data and Methods section describing how results could be impacted by two different lightning data sources. *"Comparing the two lightning sources has a certain level of uncertainty, due to the fact that TRMM LIS-OTD and ENGLN do not overlap temporally. However, because this event had significantly above average lightning flash rates compared to the climatology, the possible error introduced by comparing two different data sets does not impact the results."*

Section 2 - Consider moving some of the discussion on the lightning observations (e.g. after line 70) into the next section.

We have moved the discussion on the lightning observations to the lightning results section - now Section 3.4 Lightning Conditions

Fig 1b - I find the color scale a bit confusing. Consider a scale that goes up only to the maximum of what is in the domain and using a scale that doesn't have the black and brown colors as the highest accumulations.

Colormaps in Fig. 1 were updated to only go to the maximum, and black and brown were removed from the colormaps.

Line 73 - Consider adding "even" before "if"

We added "even" before "if" on line 73, so the sentence now reads, "In fact, *even* if this was the only lightning activity for 2019, it would represent about 1,500 times the climatological rate."

Line 117-118, where is this transport from AR to WCB shown?

The paragraph has been updated to say that both the WCB and AR can be seen in Figure S3. Fig. S3, which has been updated as per RC1's comment, has also been updated to show the location of the AR as contour lines in relation to the WCB.

Line 121 – Is this implying that the combination of the two was necessary for the updrafts, precipitation and hail formation? Perhaps state something more like "In this case, we observed an AR interacting with a WCB, along with updrafts and hail formation" (Please check on other statements of this nature too).

The wording on this statement and other statements like this have been updated to clarify that there is a connection rather than imply that one was necessary for the other.

Line 136 – why not just say saturated if the dew point is equal to the temperature?

The sentence has been updated to now says, "Between 800 hPa and 625 hPa, *parcels are saturated*, indicating the high moisture from the AR (Fig. 3a, b)."

Figure 3b – I am a little confused on the units. How was this calculated? How is water vapor incorporated?

The vertical profile of horizontal water vapor fluxes (m s-1) are the fluxes at each pressure level. At each pressure level, water vapor flux in the v direction is calculated by multiplying the v component wind and specific humidity (q) (same for u direction, but with u component wind). Then the magnitude is calculated by taking the square root of the v flux squared plus the u flux squared.

$$VT_u(m\,s^{-1}) = q(kg\,kg^{-1}) * u(m\,s^{-1}) \quad (1)$$

$$VT_v(m\,s^{-1}) = q(kg\,kg^{-1}) * v(m\,s^{-1}) \quad (2)$$

$$VT = \sqrt{VT_u^2 + VT_v^2} \quad (3)$$

Since specific humidity is unitless (kg kg^{-1}), it takes on the units of the wind component (m s^{-1}). Figure 8b in Guan and Waliser (2015) uses the mean vertical profiles of horizontal water vapor fluxes (m s^{-1}) to highlight the low-level nature of ARs across different regions. This figure allows us to show where the moisture of this particular AR is focused, as well as point out the above-average moisture levels compared to other landfalling ARs in the Santa Barbara region.

Section 3.3 - careful with tenses, some examples below in the technical corrections section. Also please make sure it is clear what processes you are hypothesizing played a role and what you can show played a role based on the data (e.g. paragraph lines 159-166)

We have updated the tenses using the examples in the technical corrections section. We have also clarified throughout section 3.3 the processes we are hypothesizing played a role in the electrification based on previous literature and where the connections are between that and what the data shows.

Section 4 - Could you explicitly quantify how unusual the lightning is (also in the abstract).

The conclusions section has been updated to quantify how unusual the lightning is, stating, *"In 30 hours between 5 March 12 UTC and 6 March 18 UTC, ENGLN detected 73,442 flashes of lightning with 119,363 combined in-cloud (IC) and cloud-to-ground (CG) pulses around Southern California (20°N to 50°N and 140°W to 110°W). Of those, 1,486 lightning pulses occurred over Santa Barbara County in the 24 hours following 6 March 2019 00 UTC, 533 of which were cloud-to-ground type. The lightning activity can be considered highly unusual in a region that observes, on average less than 23 flashes in the entire month of March."* We have also added a statement to the abstract that states, *"The Earth Networks Global Lightning Network (ENGLN) detected 14,416 lightning flashes in southern California (20°N to 50°N and 140°W to 110°W) in 24 hours, which is roughly 1500 times the climatological flash rate in this region."* Additionally, in our results, we state, *"TRMM LIS-OTD records an area annual average of 9.15 flashes per day in the region surrounding southern California (20°N to 50°N and 140°W to 110°W), making the 14,416 lightning flashes in under 24 hours very extreme. In fact, even if this was the only lightning activity for 2019, it would represent about 1,500 times the climatological rate (Fig. 1d) (Cecil, 2015)."*

It would be helpful to also explicitly quantify the distribution of freezing level – based on prior literature or the datasets you are using here, is this a much colder than normal vertical structure for an AR, or for this area, to make the case for this to be a potential reason behind the high number of lightning strikes?

A similar comment from RC1 was made. According to Cannon et al. (2017), the mean height of the 0°C isotherm was about 2,500 m for the 83 AR events in Central and Northern California (20°N to 60°N and 160°W to 110°W) during three winter seasons (October through March; 2014-2017). We have decided to calculate the height of the 0°C isotherm for AR events in Santa Barbara and add to the supplemental results (see new Fig. S2). After calculating the height of the 0°C isotherm using MERRA2 and the methodology used in Cannon et al. (2017) and Harris Jr et al. (2000), we created a climatology of the 0°C isotherm for all days an AR made landfall in Santa Barbara (identified using the AR detection algorithm provided by Guan and Waliser (2015)) between 1980 and 2017 (n=1814), and found that the average height of the 0°C isotherm during these days was about 3500 m (Fig. S2d). This puts the height of the 0°C isotherm for the thunderstorm event below the average.

Technical Corrections

Line 151 – I think "formed" should be "forming" or "allowing the formation of"

The sentence now reads, *"In the March 2019 storm, updrafts in the deep convective clouds, identified by overshooting cloud tops (Fig. S6), could have transported smaller droplets to above the freezing level, (below 700 hPa), potentially allowing for the formation of hail with a positive charge (Fig. 3c, 1b)."*

Line 152 – rephrase to something like "At the time closest to the peak of the event in Santa Barbara, dry air was entrained between 300 hPa and 200 hPa with winds reaching approximately 100 knots (Fig 3a)"

The sentence now reads, *"At the time closest to the peak of the event in Santa Barbara, dry air was entrained between 600 hPa and 400 hPa as well as in the upper-levels between 300 hPa and 200 hPa (Fig 3a), which could have enhanced downdrafts contributing in the formation of electrified hailstones."*

Line 160 – should be "warmer than its environment"

The sentence now reads, *"When the updrafted droplets and downdrafted hailstones collide, they can release latent heat, and potentially form graupel, a softer form of hail that is warmer than its environment."*

Line 174 – consider rephrasing to "The last peak of lightning frequency" or something like that

The sentence now reads, *"The last peak of lightning frequency occurred between 6 March 00 UTC and 06 UTC with approximately 3000 IC pulses and less than 1000 CG pulses centered at 34°N and 120°W (Fig. S7a)."*

Author response to Anonymous Referee 3 for "Brief Communication: An Electrifying Atmospheric River: Understanding the Thunderstorm Event in Santa Barbara County during March 2019" by Deanna Nash and Leila M.V. Carvalho.

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General Comments

The manuscript analyzes an AR event that occurred on March 2019. Despite having a relatively low amount of precipitation (77.6mm in 30h) it was extraordinary amount of lightning strikes in the region that stands out. The topic of this study is of interest to be published and the manuscripts is in general well written however I have a few structural issues that need to deal with before the manuscript is ready for publication.

We thank the reviewer for the time they took to review this paper and the constructive feedback that helped improve the paper, specifically with regard to the structure of the manuscript. Please see responses to comments below.

Specific Comments

I believe the entire Introduction section needs to be re-written. In the present form it's a mixture between introduction and results. Therefore, should have the following in mind when re-written the introduction: - What is an ARs; - Possible impacts and benefits (first paragraph should be in here); - Lightening brief introduction and precipitation measures and radar. - I would remove everything that is results from this specific event.

We have separated the introduction and results, and updated the introduction section to include a paragraph on the background of ARs and their relevance and impact to Southern California. We have also added a short background on lightning to the introduction.

Section 2. Parts of the introduction are already stated here. So, I would keep all the dataset and methodologies in this section and avoid repetition with the introduction.

Repetition with the introduction has been removed from the data and methods section and care has been taken to make sure this section is only dataset and methodologies and no results.

Section 3. I would include a new sub-section before sub-section "Extratropical Cyclone and AR Conditions". This new sub-section would be the description of the March 2019 event, with most of the information being taken what was already mentioned in the Introduction.

After restructuring the introduction (see above), we have moved the description of the March 2019 event to a new subsection in the results titled "March 2019 Event" to make sure the results are all in the results section.

Minor Comments

Figure 1. The color scales are a bit confusing.

A similar comment from RC2 was made. The colormaps in Fig. 1 were updated to only go to the maximum, and black and brown were removed from the colormaps.

How much do you trust in the vertical speed from reanalysis data?

We recognize that vertical velocity from reanalysis data is a calculated value. We found that the details provided from vertical velocity in the manuscript were not necessary to show updrafts and deep convection, so we removed vertical velocity from the manuscript and supplement. We have instead decided to focus on what the observed GOES-R infrared brightness temperature tells us, which is that there was an overshooting cloud top at approximately 4:30 UTC, indicating deep convection. We have updated Fig. S5 to highlight this information.

List of changes made for "Brief Communication: An Electrifying Atmospheric River: Understanding the Thunderstorm Event in Santa Barbara County during March 2019" by Deanna Nash and Leila M.V. Carvalho.

Figure updates

- Updated color bars on Fig. 1b, c, and d and changed precipitation data to NOAA NEXRAD L3 precipitation estimate for Fig. 1b.
- Added subplot c to Fig. 3 to show the equivalent potential temperature profile of the grid cell closest to Santa Barbara at the time closest to the peak of the storm.
- Fig. S2 removed since we decided to remove information on calculated vertical velocity and precipitation information was covered in Fig. 1b.
- Fig. S3 is now Fig. S2 and 3 additional subplots have been added showing the climatology of AR characteristics (IVT magnitude and direction and height of 0°C isotherm) from past ARs in Santa Barbara.
- Fig. S5 is now Fig. S3 and has a zoomed out domain as well as IVT contour lines to indicate the spatial extent and intensity of the AR.
- Fig. S4 has been updated to show skew(t) - log(p) and equivalent potential temperature profiles every 6 hours for the grid cell that has the highest lightning flash density. CAPE is shown in the plot that indicates the location of the highest lightning flash density.
- Fig. S6 has been renamed to Fig. S5 and a zoomed inset map has been added as well as locations of NOAA NEXRAD L3 hail.
- Fig. S7 is now Fig. S6. The colorbar for Fig. S6c, S6d, and S6e has been updated to match Fig. 1c and 1d.
- Fig. S8 is now Fig. S7
- Fig. S9 is now Fig. S8

Manuscript revisions

- **Abstract**: The abstract has been updated to show the most important results of this study.
- **Introduction**: The introduction has been restructured so that the description of the March 2019 event was moved to a new results section titled, "March 2019 Event". In addition, a brief description of ARs and lightning has been added to the introduction.
- **Data and Methods**: Revisions have been made to the Data and Methods section to only discuss data sources and methods used for the study.
- **Results,** *March 2019 Event*: This new section in the results was added to describe the precipitation and lightning that occurred during the March 2019 event.
- **Results,** *Extratropical Cyclone and AR Conditions*: This section was updated to only discuss the synoptic conditions associated with the March 2019 event.
- **Results,** *Thermodynamic Conditions*: This section has been renamed (previously "Precipitation and Hail) since the main focus of this section is to describe the thermodynamic characteristics of the March 2019 event. This section has been revised to clarify the unique thermodynamic conditions of this event, focusing on equivalent potential temperature and the significantly above average water vapor flux content in the middle troposphere provided by the AR.

- **Results,** *Lightning Conditions*: This section has been edited to clarify the difference between what previous literature suggests are important factors for electrification and what the data implies about electrification for this particular storm.
- **Conclusions**: This section has been updated to summarize the findings of this study, which are that we found that it is possible that these thousands of lightning flashes that occurred in under a few hours were related to an AR that was characterized by an unusual deep moist layer extending from low-to-mid troposphere in an environment with potential instability and low elevation freezing level.

References

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Brief Communication: An Electrifying Atmospheric River: Understanding the Thunderstorm Event in Santa Barbara County during March 2019

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Abstract. On 5 March 2019 12 UTC, an Atmospheric River (AR) made landfall in Santa Barbara, CA and lasted approximately 30 hours. This AR was one of many that occurred during the winter season in Santa Barbara. However, during this AR, a massive number of lightning pulses were detected by While ARs are typical winter storms in the area, the extraordinary amount of lightning strikes observed near coastal Santa Barbara made this event unique. The Earth Networks Global Lightning Network (ENGLN) near and off the coast of Santa Barbara, CA. In the 24 hours following 6 March 2019 00 UTC, detected 14,416 lightning flashes occurred around in southern California (140W to 110W and 20°N to 50°N). This far exceeded the climatological average number of lightning flashes recorded by the Lightning Imaging Sensor (LIS) and Optical Transient Detector (OTD) on the Tropical Rainfall Measuring Mission (TRMM). Between the years of 1995 and 2014, the TRMM LIS-OTD detected an average flash density of approximately 9.15 flashes per day in the same regionaround southern California. While the AR could be considered part of a typical winter storm in the area, the extraordinary amount of lightning strikes in the region was very anomalous. This combined thunderstorm and Atmospheric River event resulted in 36-hour precipitation totals in Santa Barbara to be approximately 77.6 mm, with a maximum rain rate of 16.5 mm hr^{-1}140°W to 110°W) in 24 hours, which is roughly 1500 times the climatological flash rate in this region. The AR related thunderstorm resulted in approximately 23.18 mm accumulated precipitation in 30 hours in Santa Barbara. This article describes the examines synoptic and mesoscale characteristics of features conducive to this electrifying AR event. , characterizing its uniqueness in the context of previous March events that made landfall in the region. We show that this AR was characterized by an unusual deep moist layer extending from low-to-mid troposphere in an environment with potential instability and low elevation freezing level. Despite the negligible convective available potential energy (CAPE) during the peak of the thunderstorm near Santa Barbara, the lifting of layers with high water vapor content in the AR via warm conveyor belt and orographic forcing in a convectively unstable atmosphere resulted in the formation of hail and enhanced electrification.

1 Introduction

Due to recent wildfire activity in Santa Barbara ~~county~~ County (e.g. Thomas Fire during December 2017, Whittier Fire during July 2017, and Sherpa Fire during June and July 2016) this region is at high risk for post-fire debris flow when 15 minutes of rainfall has an intensity greater than or equal to 24 mm hour^{-1} (USGS, 2019). These conditions were observed during the devastating Montecito debris flow on the 9 January 2018 that resulted in 23 deaths, 246 structures destroyed, and 167 damaged structures (Oakley et al., 2018). On 1 March 2019, the National Weather Service (NWS) in Oxnard, CA forecasted 2 storms to hit Santa Barbara County (1-2 March 2019 and 5-6 March 2019). ~~Approximately 17.5 mm of rain fell in Santa Barbara during the storm on 2 March 2019 based on Global Precipitation Measurement (GPM) precipitation (Huffman et al., 2019).~~ On 5 March 21 UTC, a mandatory evacuation order was ~~employed~~ issued for the Thomas, Whittier, and Sherpa fire burn areas due to the prediction of a subsequent severe storm and ~~the~~ flood potential that existed for low-lying areas given increased ground saturation from the storm on 2 March 2019, impacting about 3,000 residents. While no significant debris flows were triggered during this event, a combination of an Atmospheric River (AR) ~~event~~ and an extreme number of lightning strikes made this storm exceptional. Figure 1a shows a photo of lightning strikes at the Santa Barbara Harbor during the storm taken by Santa Barbara County Fire Department's Mike Eliason.

~~On 5 March 2019 12 UTC, an AR made landfall on the Santa Barbara coast (34.5~~The term Atmospheric River (AR), describes a phenomenon that explains how baroclinic eddies transport large amounts of water vapor via relatively infrequent, long conduits of strong moisture transport across mid-latitudes and into polar regions (Newell et al., 1992; Zhu and Newell, 1994) . Many studies have focused on the regional impacts of ARs in western United States and have found that ARs bring large amounts of moisture to the west coast of North America and are related to precipitation extremes and flooding, particularly in the winter season (Harris and Carvalho, 2018; Dettinger, 2011; Guan et al., 2010, 2013; Ralph et al., 2006). Despite occurring less frequently than ARs in Northern California, the Southern California ARs have significant impact in the hydrological cycle of the region (Harris and Carvalho, 2018; Cannon et al., 2018; Oakley et al., 2018; Oakley and Redmond, 2014). Although ARs are often associated with extreme precipitation, flooding, and other hazardous events, they play critical role in replenishing reservoirs and underground water resources, particularly in dry areas of Southern California. Studies show that just a few AR events each year can contribute the majority of the precipitation and streamflow that regulates the state's water resources (Cannon et al., 2018; Gershunov et al., 2017; Ralph et al., 2019; Dettinger, 2013). Ralph et al. (2019) have developed a scale to characterize ARs based on intensity and duration, pointing out that ARs can result in a wide spectrum of conditions from beneficial to hazardous. As of now, no studies have examined the relationship between ARs and lightning.

Lightning usually occurs when the electric charges in a cloud separate and exceed the intensity that the air can sustain (Price, 2013). Charges usually build up in the mixed phase region of the clouds (0°~~N, 119.5~~C to -40°~~W) and lasted 30 hours. During the ARevent, between~~ C) when there are enough updrafts to lift particles above the freezing level (Price and Rind, 1993) . The correlation between cloud-top height and lightning rate is well documented and can be attributed to the deep vertical development of convective thunderstorms (Price and Rind, 1993; Pessi and Businger, 2009). Pessi and Businger (2009) documented that lightning activity can be associated with cold temperatures aloft or convection along cold fronts.

Although the thunderstorms on 5 March ~~12 UTC and 6 March 18 UTC, the total accumulated precipitation was approximately 77.6 mm in Santa Barbara (Fig. 1b), with the highest rain rate of 16.5 mm hour^{-1} at 6 March~~ 2019 ~~04:30 UTC based on GPM (Huffman et al., 2019). While this was not enough precipitation to initiate debris flow, instances of hail were identified by the National Oceanic and Atmospheric Administration (NOAA) Next Generation Radar Level 3 (NEXRAD L3) hail signature product (see Fig. 1b). The presence of hail indicates strong updrafts and a low freezing level, which are conditions that also favor the development of lightning in a storm (Pruppacher and Klett, 1997). During this AR event, Earth Networks Global Lightning Network (ENGLN) detected 73,442 flashes of lightning with 119, 363 combined in-cloud (IC) and cloud-to-ground (CG) pulses around Southern California (140W to 110W and 20N to 50N) (Earth Networks, 2019). Among these, 50,399 pulses occurred in the 24 hour period following 6 March 2019 00 UTC (Fig. 1c). There were 533 CG pulses and 953 IC pulses over Santa Barbara county on 6 March 2019. The strongest positive flash over Santa Barbara county was CG with a peak current of 127,212 amps located east of Cachuma Lake at 34.59N and 119.79W at 6 March 2019 05:48 UTC. At 6 March 2019 04:06 UTC, the strongest negative CG flash over Santa Barbara county occurred in Los Padres National Forest at 34.61N and 119.52W at a peak current of -223, 036 amps.~~

~~According to the Tropical Rainfall Measuring Mission Lightning Imaging Sensor and Optical Transient Detector (TRMM LIS-OTD) Lightning Climatology, there were, between 1995 and 2014, an average of 9.15 flashes per day in the region surrounding southern California (140W to 110W and 20N to 50N) (Fig. 1d) (Cecil, 2015). Based on the AR database of Guan and Waliser (2015), there were on average 10 AR days occurring between December and March each year in Santa Barbara, with a total of 742 ARs that made landfall in the grid cells closest to Santa Barbara. When compared to the TRMM LIS-OTD low resolution time series, between 1995 and 2014 there were approximately 350 landfalling AR events that coincided with lightning flashes, with the majority of events resulting in less than 60 flashes per day (Cecil, 2015). While there was minimal damage regarding the storm~~ caused minimal damage (e.g. small lightning fires, power outages), this event was meteorologically significant ~~, specifically~~ because of the exceptional number of lightning strikes in such a short period. This ~~paper describes the~~ study examines synoptic and mesoscale dynamics~~that caused the extreme number of lightning strikes to occur in a region that historically has seen little to no lightning. In addition, this paper explains the interaction of the AR that simultaneously occurred with the hail and lightning, resulting in precipitation~~, as well as the thermodynamic characteristics of this AR and investigates the uniqueness of this event compared to past March ARs that made landfall in Santa Barbara.

2 Data and Methods

Climate Forecast System version 2 (CFSv2) (Saha et al., 2014) operational analysis was used in this study to evaluate the synoptic and mesoscale meteorological conditions between 10°N and 50°N and 150°W to 110°W between the dates 4 March 2019 18 UTC and 6 March 2019 18 UTC. CFSv2 data at 0.5°x 0.5°horizontal resolution was obtained at 37 pressure levels between 1000 hPa and 1 hPa at a 6-hourly time scale. AR conditions are determined based on IVT (see appendix for calculation) exceeding 250 kg m^{-1} s^{-1} at a fixed geographical point. The AR event in this study refers to the time that the AR conditions occurred in Santa Barbara, i.e. at the grid cell centered on 34.5°N and 119.5°W. The duration of the AR event is

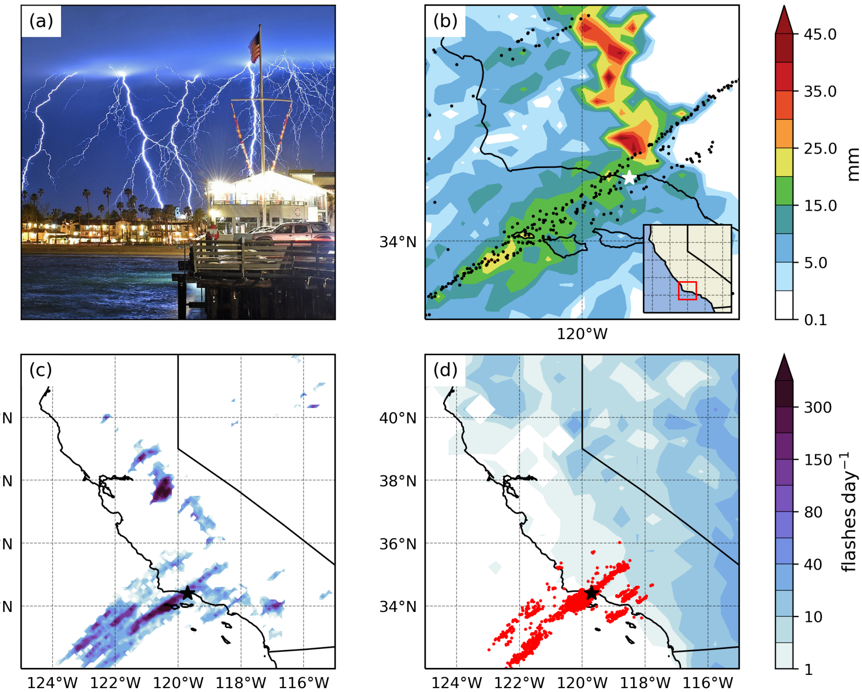

Figure 1. (a) Photo of lightning at the Santa Barbara Harbor in Santa Barbara, CA taken by Mike Eliason from the Santa Barbara County Fire Department during the storm at 6 March 2019 ~~04~~ 4 UTC. (b) ~~GPM~~ NOAA NEXRAD L3 precipitation ~~totals~~ accumulation (shaded; mm) and locations of NOAA NEXRAD L3 Hail Signatures (black points) between 5 March 2019 12 UTC and 6 March 2019 23:59 UTC. The location of Santa Barbara is indicated by the ~~gold~~ white star. (c) ENGLN lightning strike frequency (shaded; flashes day^{-1}) on 6 March 2019. The location of Santa Barbara is indicated by the ~~gold~~ black star. (d) Climatological annual mean lightning density (shaded; flashes day^{-1}) between 1995 and 2014 using TRMM LIS-OTD lightning climatology and lightning strike locations (red points) between ~~04~~ 4 and ~~05~~ 5 UTC on 6 March 2019 based on ENGLN. The location of Santa Barbara is indicated by the ~~gold~~ black star.

determined by the time (in hours) that the AR conditions are consecutively met. NASA's Modern Era Retrospective Reanalysis Version 2 (MERRA2) (Gelaro et al., 2017b; Bosilovich et al., 2015) and the global atmospheric river detection catalog that identifies atmospheric rivers on a global, 6-hourly basis were used to determine the anomalous characteristics of the March 2019 AR event compared to past ARs that made landfall in Santa Barbara. This AR detection algorithm was introduced in Guan and Waliser (2015) and refined in Guan et al. (2019). Here we analyzed ARs and their characteristics on a daily temporal scale at 0.5° by 0.625° spatial resolution between 1980 and 2018. The other calculated variables from CFSv2 are dew point (Td) and equivalent potential temperature (~~ϑ_e~~ θ_E), which are calculated based on Bolton (1980, eq. 11, 43).

Lightning flash data obtained from Earth Networks Global Lightning Network (ENGLN) (Earth Networks, 2019) was used to quantify the location and number of lightning strikes between 4 March 2019 ~~00~~ 0 UTC and 7 March 2019 ~~00~~ 0 UTC near southern California. The global lightning network, which includes more than 1,700 sensors, detects lightning flashes and provides various information about those flashes, including ~~the~~ latitude, longitude, amplitude of the lighting, duration of the flash, and the number of ~~IC and CG~~ in-cloud (IC) and cloud-to-ground (CG) lightning pulses within a given flash (Earth Networks, 2019). A lightning flash can be made up of one or more IC or CG lightning pulses, which connect regions of opposite polarity~~(+/-)~~. To put the extremity of this lightning event into climatological context, an annual lightning strike climatology from Tropical Rainfall Measuring Mission Lightning Imaging Sensor and Optical Transient Detector (TRMM LIS-OTD) (Cecil, 2015) was used at a horizontal resolution of 0.5° by 0.5° between 1995 and 2014 for the region surrounding southern California ~~. TRMM~~ (20°N to 50°N and 140°W to 110°W). Comparing the two lightning sources has a certain level of uncertainty, since TRMM LIS-OTD ~~records an area climatological average of 9.15 flashes per day in the region surrounding southern California, making the 14,416 lightning flashes in under 24 hours very extreme. In fact, if this was the only lightning activity for 2019, it would represent about 1,500 times the climatological rate~~and ENGLN do not overlap temporally. However, because this event had significantly above average lightning flash rates compared to the climatology, the possible error introduced by comparing two different data sets does not impact the results.

For precipitation, ~~data from NASA's Global Precipitation Measurement mission (GPM~~hourly precipitation data from National Oceanic and Atmospheric Administration's Next Generation Radar Level 3 (NOAA's NEXRAD L3) was used ~~at a 30-minute temporal resolution~~ between the dates ~~2~~ 4 March 2019 ~~00~~ 18 UTC and 6 March 2019 23:59 UTC at ~~a 0.1gridded resolution (Huffman et al., 2019)~~roughly 1 km resolution. To identify the approximate location, time, and diameter of hail, ~~National Oceanic and Atmospheric Administration's Next Generation Radar Level 3 (~~NOAA's NEXRAD L3 ~~)~~ hail signature product was used. ~~(NOAA National Weather Service (NWS) Radar Operations Center, 2019)~~. To identify cloud convection and cloud top height via cloud top temperature, the Cloud and Moisture Imagery (CMI) product from GOES-R (GOES-17) Advanced Baseline Imager Level 2 was obtained for 6 March between ~~03 UTC and 05~~ 3 UTC and 5 UTC at 5-minute temporal intervals and 10 km by 10 km spatial resolution (GOES-R Algorithm Working Group and GOES-R Series Program, 2017).

3 Results and Discussion

3.1 ~~Extratropical Cyclone and AR Conditions~~March 2019 Event

~~To understand why the lightning happened at such an extreme rate in a region that sees little to no lightning, the synoptic conditions for this event are described. Lightning usually occurs when the electric charges in a cloud separate and exceed the intensity that the air can sustain (Price, 2013). Charges usually build up in the mixed phase region of the clouds (~~An AR made landfall near Santa Barbara (34.5°N, 119.5°W) between 5 March 12 UTC and 6 March 18 UTC, resulting in total accumulated precipitation of approximately 23 mm around Santa Barbara according to NOAA NEXRAD L3 one-hour precipitation. While this was not enough precipitation to initiate debris flow, instances of hail were identified by the NOAA NEXRAD L3 hail signature product (see Fig. 1b). The presence of hail indicates strong updrafts and a low freezing level, which are conditions that also favor the development of lightning in a storm (Pruppacher and Klett, 1997). During this AR event, ENGLN detected 73,442 flashes of lightning with 119,363 combined IC and CG pulses around Southern California (140°W to 110°W and 20°N to 50°N) (Earth Networks, 2019). Among these, 14,416 flashes of lightning with 50,399 combined IC and CG pulses occurred in the 24 hour period following 6 March 0 UTC (Fig. 1c). TRMM LIS-OTD records an area annual average of 9.15 flashes per day in the region surrounding southern California (20°~~C to -40~~N to 50°~~C) when there are sufficient updrafts to lift particles above the freezing level (Price and Rind, 1993). The synoptic conditions of this event show that the cyclogenesis combined with the dynamical lift of the AR via the warm conveyor belt (WCB) provided enough updraft to aid in the electrification of the clouds.~~ N and 140°W to 110°W), making the 14,416 lightning flashes in under 24 hours very extreme. In fact, even if this was the only lightning activity for 2019, it would represent about 1,500 times the climatological rate (Fig. 1d) (Cecil, 2015). Based on the AR database of Guan et al. (2019), on average 10 AR days are observed between December and March each year in Santa Barbara, with a total of 742 AR days associated with ARs that made landfall in the grid cells closest to Santa Barbara between 1980 and 2019. When compared to the TRMM LIS-OTD low resolution time series, between 1995 and 2014 there were approximately 350 landfalling AR events that coincided with lightning flashes, with the majority of events resulting in less than 60 flashes per day (Cecil, 2015).

3.2 Extratropical Cyclone and AR Conditions

Following an extratropical cyclone that made landfall at 1 March ~~2019~~ 12 UTC, a deep mid-level (500 hPa) trough developed into a closed low system, forming a pool of cold air centered at approximately 32°N and 140°W by 4 March 18 UTC (Fig. 2a). The surface low-pressure was located directly below the 500 hPa closed low on 4 March 18 UTC (Fig. 2a). This mid-level closed low moved eastward and northward, until 6 March 12 UTC when it was no longer closed (Fig. 2h). According to Oakley and Redmond (2014), 41-50% of precipitation in Santa Barbara between October and March is associated with closed lows. The surface low-pressure deepened from 1005 hPa to approximately 996.36 hPa by the peak event time at 6 March 2019 ~~06 UTC, at which~~ 6 UTC; at this point it was centered around 38°N and 126°W, west of northern California (Fig. 2g). At the peak time of the event, 6 March ~~06~~ 6 UTC, the jet streak exit region was located at 35°N and 122°W, directly northwest of Santa Barbara (Fig. S1g). ~~Vertical velocity peaked in Santa Barbara on 6 March 06 UTC with a value of 0.35 m s^{-1} indicating strong upward motion (Fig. S2g). Off the coast at 34N and 121.5W, vertical velocity reached 0.9 m s^{-1} at 6 March 06 UTC (Fig. S2g).~~ Pessi and Businger (2009) showed that most of the storms that have lightning activity over the North Pacific Ocean are associated with similar synoptic conditions as those observed during the storm in March 2019.

These synoptic conditions provided the dynamical mechanisms necessary for subtropical moisture to be transported via an AR, shown as the area of IVT greater than 250 kg m^{-1} s^{-1} (Fig. 2). This AR made landfall at approximately 5 March 12 UTC on the west coast near Santa Barbara and lasted approximately 30 hours (Fig. 2d-i). ~~For the duration of the event , the AR had an average IVT value of 395~~ The peak IVT value for this event within the AR was 1034 kg m^{-1} s^{-1} ~~with a maximum value of 735 kg m^{-1} s^{-1})in~~ at 5 March 12 UTC (Fig 2d). In the grid cell closest to Santa Barbara (34.5°N and 119.5°W) the AR had a peak IVT value of 446 kg m^{-1} s^{-1} on 6 March 6 UTC (Fig. ~~S3~~S2a). Based on the duration (30 hours) and maximum instantaneous IVT intensity of the AR (~~735~~ 446 kg m^{-1} s^{-1}), this event is categorized at AR-CAT ~~2~~ 1 according to Ralph et al. (2019), indicating that this AR was most likely beneficial ~~with a possibility of being hazardous. Most thunderstorms are associated with high values of Convective Available Potential Energy (CAPE), which measures the amount of energy available for convection. While this storm had values of surface-based CAPE up to 1000 J kg^{-1} as it made its way across the Pacific~~

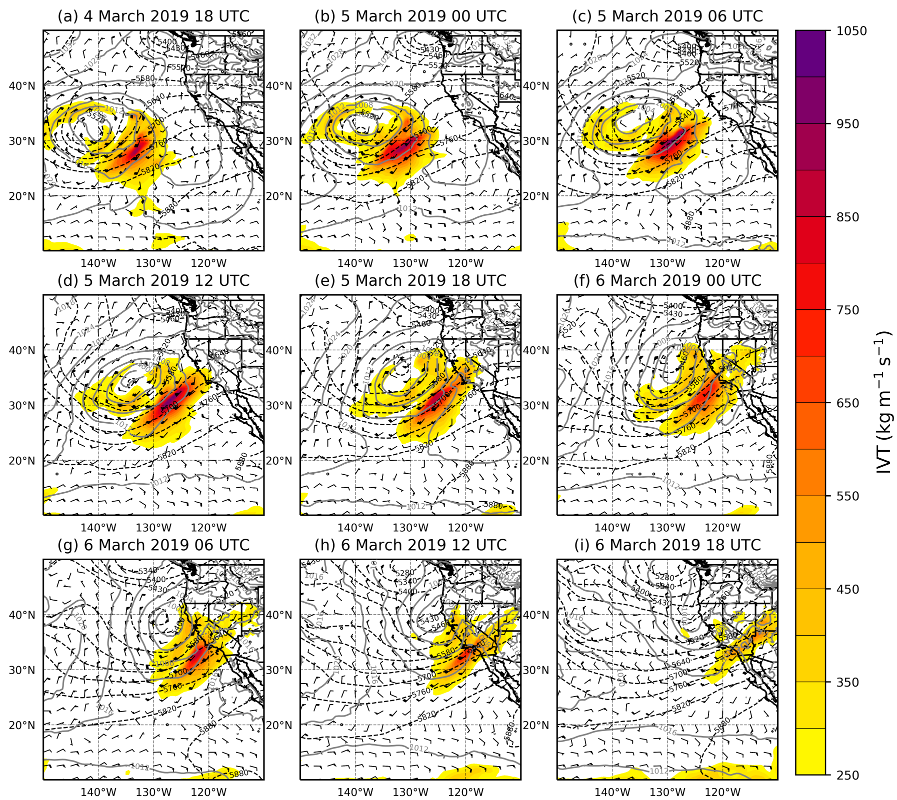

Figure 2. CFSv2 data showing IVT (shaded; kg m^{-1} s^{-1}), 850 hPa wind (barbs; knots), Mean sea level pressure (grey contours; hPa), and 500 hPa geopotential height (black dashed contours; m) at 6-hourly time steps between 4 March 2019 18 UTC and 6 March 2019 18 UTC. The time step closest to the peak of the event is shown in figure (g) at 6 March 2019 ~~06~~ 6 UTC in the bottom left corner.

~~Ocean toward the west coast of California, at the time closest to the peak of the event, there was little to no CAPE in Santa Barbara (10 J kg^{-1}) where lightning occurred (Fig. S4). However, like the extreme precipitation events in Cannon et al. (2018), additional dynamical forcing can develop convection even when CAPE is low.~~ to the Santa Barbara area. This particular AR had IVT direction and magnitude characteristics similar to past ARs that made landfall in the Santa Barbara area (Fig. S2b, S2c).

Equivalent potential temperature at 850 hPa (~~ϑ_e~~ θ_E) (Fig. ~~S5~~S3) identifies the formation of the warm conveyor belt (WCB), or the ascending air within the warm sector of the extratropical cyclone and the overlap of the AR between 5 March 12 UTC and 6 March 12 UTC (Browning, 1986; Dettinger et al., 2015). At 6 March ~~06~~ 6 UTC (Fig. ~~S5g~~S3g), the cold front lies along the densely packed isotherms between the coast of California and 32°N and 124°W, and the warm front is located parallel to the coast of California. This placed the region of warm air advection and the WCB in the southern region of the domain between the two fronts where ~~ϑ_e~~ θ_E is around 320 K. Water vapor in the AR, which can be sourced from intense vapor transport out of the tropics as well midlatitude convergence of water vapor along the path of the AR, was transported via winds into the

WCB (Fig. S3) (Dettinger et al., 2015). The uplift of the moisture from the AR most likely occurred due to orographic uplift from interaction with complex topography as well as dynamic uplift from the WCB (Fig. ~~S2, S5~~S3). It has been suggested that WCBs and ARs can form on their own without direct connection to each other (Dettinger et al., 2015; Dacre et al., 2019). In ~~our case, the combination of the AR with the WCBresulted in updrafts as well precipitation~~ this case, we observed an AR interacting with a WCB, along with updrafts and hail formation. The synoptic conditions of this event show that the cyclogenesis combined with the dynamical lift of the AR in a convectively unstable environment provided enough updraft to potentially aid in the electrification of the clouds via hail formation.

3.3 ~~Precipitation and Hail~~Thermodynamic Conditions

Wind in the skew(t) - log(p) diagram at 34.5°N 119.5°W (Fig. 3a) for the time closest to the peak of the event (6 March ~~06~~ 6 UTC) indicates strong warm air advection below 800 hPa. This strong veering profile near the surface with increasing wind speeds with height intensifies the mesocyclone and maintains the storm. ~~At the surface, although~~ Most thunderstorms are associated with high values of Convective Available Potential Energy (CAPE)~~was low~~ , which measures the amount of energy available for convection. While this storm had values of surface-based CAPE up to 1000 J kg^{-1} as it made its way across the Pacific Ocean toward the west coast of California, there was little to no CAPE in Santa Barbara (10 J kg^{-1}) ~~, the~~ where lightning occurred at 6 March 6 UTC (Fig. 3a, S4). However, like the extreme precipitation events in Cannon et al. (2018), additional dynamical forcing can develop convection even when CAPE is low. Although CAPE was low near Santa Barbara, the proximity of temperature and dew point profiles in the lower troposphere place the Lifting Condensation Level (LCL) very close to the surface (Fig. 3a). ~~These factors combined with the vertical velocity of 0.35 m s^{-1} (Fig. S2g) in Santa Barbara resulted in precipitation. At the time closest to the peak of the event (6 March 06 UTC), a band of precipitation parallel to the cold front is associated with the AR (Fig. S2g). In the Santa Barbara region, GPM measured peak rain rate values at about 16.5 mm hour^{-1}, with the 36-hour rain totals of about 77.6 mm (Fig. 1b). GOES-17 Cloud and Moisture Imagery Brightness Temperature (Fig. S6) indicates vigorous convection via cold cloud temperatures that decrease to approximately -71C near Santa Barbara. These temperatures indicate a very strong updraft where they occur, which would result in hail formation when water droplets in the region of the updraft are carried above the freezing level (Wallace and Hobbs, 2006; Pruppacher and Klett, 1997).~~

Between 800 hPa and 625 hPa, parcels are ~~extremely moist (the dew point is equal to the temperature)~~saturated, indicating the high moisture ~~from~~ content of the AR (Fig. 3a, ~~b). Precipitation resulted from the moisture from the AR being lifted via the WCB~~ c). The equivalent potential temperature profile (Fig. 3b) shows decreasing θ_E with increasing height, indicating convective instability at the surface as well as in the midlevels between 800 and 600 hPa. A close inspection of the θ_E profile at the location of the highest lightning flash density (Fig. ~~S2, S5) . Figure 3b shows the vertical profile of~~ S4) indicates convective instability at nearly every 6-hour time step for the duration of the storm. The horizontal water vapor flux (m s^{-1}) calculated at each pressure level on 6 March ~~06~~ 6 UTC at 34.5°N, 119.5°W, ~~showing~~ (Fig. 3c) indicates that the water vapor flux peaked at 0.17 m s^{-1} between 700 and 800 hPa. Similar results were found when using MERRA2, although with a slightly lower water vapor flux that occurred around 650 hPa (Fig. 3c). Compared to the climatological vertical profile of water vapor flux from the past ~~170~~ March AR events in Santa Barbara, the AR on 6 March 2019 was extremely moist ~~and peaked at an altitude closer~~

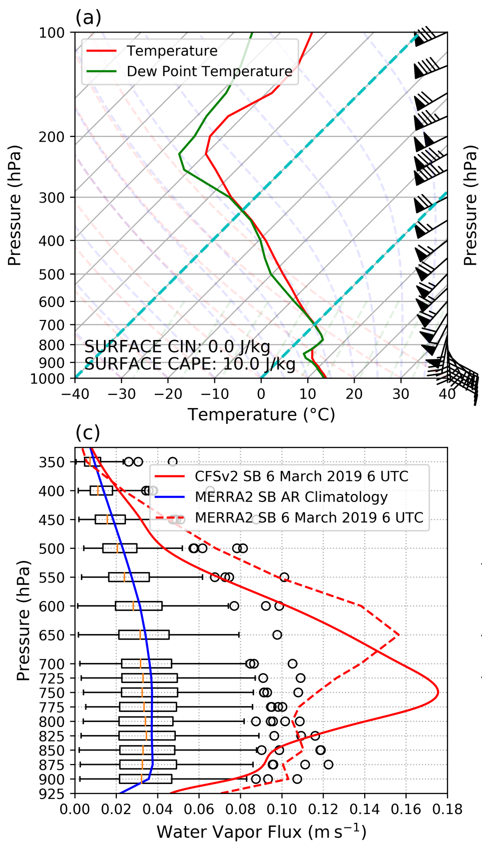

Figure 3. (a) Skew(t) - log(p) vertical profile of CFSv2 temperature (red line) and dew point (green line) at 34.5°N and 119.5°W at 6 March 2019 ~~06~~ 6 UTC. CFSv2 winds (knots; barbs) are indicated on the right side of the figure for each vertical level. ~~The thermodynamic profile~~ Surface values of ~~the parcel is indicated by the solid black line.~~ CAPE ~~is indicated as the red shaded region~~ and Convective Inhibition (CIN) ~~is indicated by~~ are shown in the ~~blue shaded region~~bottom left corner. (b) CFSv2 Equivalent Potential Temperature θ_E (blue line; K) at 34.5°N and 119.5°W at 6 March 2019 6 UTC. (c) Climatological vertical profile of horizontal water vapor flux (m s^{-1}) based on MERRA2 at 34.5°N, 119.375°W for all days when AR conditions are met during the month of March between 1980 and 2015 (i.e. IVT >= 250 kg m^{-1} s^{-1}) at this location (blue line and box and whisker plots show the distribution of the 170 events), and vertical profile of horizontal water vapor flux (m s^{-1}) based on CFSv2 (red solid line) and MERRA2 (red dashed line) at the same location at 6 March 2019 ~~06~~ 6 UTC. (~~c~~d) CFSv2 winds (knots, barbs) at vertical levels (km above mean sea level) at 34.5°N and 119.5°W at 6-hour intervals from 4 March 2019 18 UTC to 6 March 2019 18 UTC. The temperature (°C) is indicated by the color of the barb. Red barbs mean the temperature was greater than 0°C and blue barbs mean the temperature was less than 0°C. The height of the 0°C isotherm is indicated by the black dashed line.

~~to the surface.~~ with maximum moisture peaking at a higher than average pressure level (Fig. 3c). The height (km above mean sea level) of the 0°C isotherm at 34.5°N, 119.5°W (Fig. ~~3c) is located between~~ 3d) is around 2.5 km ~~and 4 km~~ above mean sea level ~~for the duration~~ during the peak of the storm, which is ~~roughly below 700 hPa. Therefore, the moisture that was being~~

~~transported in via the AR was lifted by strong updrafts in a~~ below the average height of the 0°C isotherm during past AR events in Santa Barbara (Fig. 2d). The lifting of moist layers in these thermodynamic conditions either orographically or by the WCB resulted in conditionally unstable air and strong updrafts below freezing level ~~environment~~ (Fig. ~~3b,~~ 3c~~) which~~ , 3d). GOES-17 Cloud and Moisture Imagery Brightness Temperature (Fig. S5) indicates vigorous convection via cold cloud temperatures that decrease to approximately -71°C near Santa Barbara at the time closest to the peak of the event. These cold top temperatures indicate a very strong updraft, which would result in hail formation when water droplets in the region of the updraft are carried above the freezing level (Wallace and Hobbs, 2006; Pruppacher and Klett, 1997). The lifting of the moist layers as well as the convective updrafts contributed to the formation of hail with an average size of 13.5 mm, which is co-located with cold cloud top temperatures (Fig. ~~1b)due to the low freezing level (Fig. 3c). When compared to the hail locations from NOAA's NEXRAD L3 hail signatures, the location of the hail is co-located with the cold cloud top temperature~~S5), indicating the importance of deep convective updrafts for the development of the thunderstorms.

3.4 Lightning Conditions

~~The convective~~ Convective updraft in the lower troposphere ~~was very~~ are considered important for the ~~onset of electrification, or the~~ build-up of regions with positive and negative net charges in the mixed-phase region of the cloud (0°C to -40°C), ~~which results in~~ playing a role in the onset of lightning and thunder ~~(Price and Rind, 1993; Price, 2013). Updrafts via convection transported smaller droplets to above the freezing level, located below 700 hPa, giving them a positive charge and formed hail (Fig. 3c, 1b) (Doswell, 2001; Price and Rind, 1993). Figure 3a shows the skew(t) - log(p) plot at Santa Barbara at the time closest to the peak of the event (6 March 06 UTC) and indicates entrainment of dry air between 300 hPa and 200 hPa with fast winds of approximately 100 knots. This upper-level intrusion of dry, cold air via the larger scale extratropical cyclone's cold front possibly resulted in cold, descending air into the mixed phase~~ (Price and Rind, 1993; Price, 2013; Pessi and Businger, 2009) . Enhanced updrafts increase electrification and lightning rates because they transport droplets to below freezing levels increasing ice mass (Pessi and Businger, 2009). Downdrafts into the mixed-phase region of the ~~thunderstorm that negatively charged particles (Fig. 3a) (Price and Rind, 1993; Price, 2013). While clouds that have high lightning activity are usually associated with maximum updrafts (> 10 $m\ s^{-1}$), very little updraft was required to carry the particles to the mixed-phase region of this thunderstorm cloud because the freezing level was low (about 2.5 km above mean sea level) (Price, 2013).~~

cloud may aid in pushing hailstones downward and are important mechanisms for electrification of the storm (Price and Rind, 1993; Price, 2013). When the updrafted droplets ~~from the AR and WCB and the downdrafted hailstones collided and released~~ and downdrafted hailstones collide, they can release latent heat, ~~they would have potentially formed~~ and potentially form graupel, a softer form of hail that is warmer than ~~their~~ its environment (Price and Rind, 1993; Doswell, 2001). ~~The particles become positively charged when ascending or negatively charged when descendingwhen they collide with graupel~~Particles in the mixed phase region of the cloud can collide with graupel and acquire positive charges when ascending (negative when descending). Over time, this ~~changed~~ process changes the storm cloud microphysics and electrical charges resulting in a negatively charged base and a positively charged top (Doswell, 2001; Price, 2013). ~~In-cloud (IC)lightning pulses transport charges between the positively charged region of the thunderstorm and the negatively charged region of the~~

thunderstorm while cloud-to-ground (CG)lightning pulses transport negative charges from the lower to middle region of the thunderstorm to the ground (Price, 2013)

In the March 2019 storm, updrafts in the deep convective clouds, identified by overshooting cloud tops (Fig. S5), could have transported smaller droplets to above the freezing level, (below 700 hPa), potentially allowing for the formation of hail with a positive charge (Fig. 3a, 3d, 1b, S5). At the time closest to the peak of the event in Santa Barbara, dry air was entrained between 600 hPa and 400 hPa as well as in the upper-levels between 300 hPa and 200 hPa (Fig 3a), which could have enhanced downdrafts contributing in the formation of electrified hailstones.

According to Price and Rind (1993), the proportion of IC to CG in-cloud (IC) to cloud-to-ground (CG) lightning pulses in thunderstorms is well correlated with the thickness of the cloud region between 0°C and the top of the cloud. Therefore, as the thickness of the thunderstorm cloud increases, the ratio of IC to CG also increases. Here we use cloud-top height from GOES-R (GOES-17) Advanced Baseline Imager Level 2 (Fig. S8S7) and the height of the 0°C isotherm (Fig. S9S8) as a proxy for cloud thickness. Figure S7a S6a shows the number of IC pulses and CG pulses at every 15 minutes between 4 March 00 0 UTC and 7 March 00 0 UTC in the region of the extratropical cyclone. Between 4 March 00 0 UTC and 12 UTC, there are between 2000 and 3000 CG pulses and about 1000 to 2000 IC pulses centered around 26°N and 136°W. The second peak in lightning occurs at approximately 5 March 12 UTC with almost 4000 CG pulses and 3000 IC pulses centered around 30°N and 128°W (Fig. S7aS6a). The last peak of lightning frequency occurred between 6 March 00 UTC and 06 0 UTC and 6 UTC with approximately 3000 IC pulses and less than 1000 CG pulses centered at 34°N and 120°W (Fig. S7aS6a). The cloud top height near the lightning throughout the event is between 9,000 m and 10,000 m (Fig. S8S7). However, the 0°C isotherm near the lightning grows drops closer to the ground as time passes, indicating that the cloud thickness increases as the event progresses (Fig. S9S8). The height of the IC pulses are below 5000 m before 5 March 12 UTC and between 7500 and 10000 m after 5 March 18 UTC (Fig. S7bS6b). The increased IC pulse height (Fig. S7b) can be accounted for because of S6b) could be explained by the increased cloud thickness between the height of 0°C isotherm and the cloud top in the later half of the storm (after 5 March 18 UTC), similar to the findings of Price and Rind (1993). This shows that the increased moisture from the AR being lifted via the WCB and orographic uplift and the decreased freezing level from the large-scale cold front were critical in generating the conditions necessary for the exceptional amount of lightning that occurred.

4 Conclusions

On the coast of the Santa Barbara, CAregion, an extratropical cyclone and an AR made landfall at 5 March 2019 12 UTC. The AR intensified until its peak at 6 March 2019 06 6 UTC, resulting in precipitation via uplift from the WCB . There were cold and orographic forcing. This event was associated with cold top clouds and vigorous convection that reached its peak at 6 March 2019 04 UTC. According to GPM, precipitation in the Santa Barbara region reached its peak at approximately 04:30 UTC on 6 March 2019 at a rate of 16.5 mm hr^{-1}. The event total accumulated precipitation in the Santa Barbara regionwas 77.6 mm4 UTC. While the accumulated rainfall seen during this storm (about 23 mm) are not uncommon in winter storms associated with ARs making landfall in Southern California, this system exhibited extraordinary lightning activity for the region. In 30 hours between 5 March 12 UTC and 6 March 18 UTC, ENGLN detected 73,442 flashes of lightning with 119,363 combined in-cloud (IC) and cloud-to-ground (CG) IC and CG pulses around Southern California (20°N to 50°N and 140°W to 110°W). Of those, 1,486 lightning pulses occurred over Santa Barbara County in the 24 hours following 6 March 2019 00 0 UTC, 533 of which were cloud-to-ground type.

It is highly unusual that lightning would occur in this region , let alone the sheer number of lightning strikes that have occurred. A co-occurring AR likely made the lightning event doubly unusual because of the heat and moisture the AR provides. This storm was The lightning activity can be considered highly unusual in a region that observes, on average less than 23 lightning flashes in the entire month of March. Although the system evolved as a typical winter storm for the region of Santa Barbara, made unusual by associated with a cutoff low, it was exceptional due to the high water vapor content provided by the AR. This system developed in a cool environment due to the , particularly at mid-levels of the atmosphere. The AR developed in an troposphere cooler than average for an AR, as indicated by the low elevation of the 0°C isotherm being close to the surface (approximately (about 2.5 km above mean sea level)with a great available moisture content from maximum IVT and event duration typical of AR category 2 (mean IVT = 395 kg m^{-1} s^{-1}, maximum IVT = 735 kg m^{-1} s^{-1}, duration = 30 hours). The unique combination of the cold environment with . The AR provided higher than average horizontal water vapor flux between 800 and 600 hPa compared to other March landfalling ARs in Santa Barbara. Unlike most thunderstorms in the tropics, this event was not characterized by significant CAPE when the storm approaches the coast. However, thermodynamic profiles indicated layers with potential instability near the surface and in the mid-troposphere throughout the life cycle of the thunderstorms. The uplift of saturated parcels in a convectively unstable atmosphere from the WCB and further by the orographic forcing resulted in enhanced updrafts. These updrafts transported droplets in a cold environment and high moisture availability provided the from the AR, providing the ingredients to form hail. Dry air entrainment from the cold front at about 250 hPa enhanced downdrafts and the WCB that lifted the AR generated updrafts at 850 hPa. The combination of updrafts and downdrafts formed hailand helped to change the charge of the clouds to produce lightning Downdrafts enhanced by entrainment between 600 hPa and 400 hPA may have contributed to the downward transport hail, helping to transform the charge distribution in the clouds enhancing lightning activity. Understanding the dynamics of this storm provides the theoretical basis for future, systematic investigation of the relationship between ARs and unusual lightning scenarios in other regions. It also is critical to understand these processes in populated areas such as Santa Barbara, where lightning can significantly increase hazards during extreme rainfall events.

Code and data availability. The code for this analysis can be found at https://github.com/dlnash/arthunderstorm2019. May et al. (2008 - 2017) was used for the development of some of the figures. CFSv2 data (Saha et al., 2014, https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/climate-forecast-system-version2-cfsv2), TRMM LIS-OTD lightning climatology (Cecil, 2015, https://ghrc.nsstc.nasa.gov/uso/ds_details/collections/loCv2.3.2015.html), GOES-R data (GOES-R Algorithm Working Group and GOES-R Series Program, 2017, https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C01502), MERRA-2 data (Global Modeling and Assimilation Office (GMAO), 2015; Gelaro et al., 2017a, https://disc.gsfc.nasa.gov/datasets/M2I6NPANA_V5.12.4/summary?keywords=MERRA2), and NOAA NEXRAD

L3 data (NOAA National Weather Service (NWS) Radar Operations Center, 2019, https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00708) are all freely available online. The global AR database based on MERRA-2 and the detection algorithm from Guan and Waliser (2015) used to identify AR events between 1980 and 2019 are freely available at https://ucla.box.com/ARcatalog. The lightning data used for this study was freely provided by Earth Networks (Earth Networks, 2019).

Appendix A: Calculation of IVT

Integrated water vapor transport (IVT), a variable widely used for the detection and identification of ARs (e.g. (Guan and Waliser, 2015; Ralph et al., 2019; Dettinger et al., 2015)) is derived from specific humidity and wind fields at 17 pressure levels between 1,000 and 300 hPa inclusive from the CFSv2 operational analysis. IVT is calculated in the zonal (x) and meridional (y) direction using the following equations:

$$IVT_x = -\frac{1}{g}\int_{1000}^{300} uq\,dp \tag{A1}$$

$$IVT_y = -\frac{1}{g}\int_{1000}^{300} vq\,dp \tag{A2}$$

where g is the gravitational acceleration, u is zonal wind, v is meridional wind, q is specific humidity, p is pressure, and the column integration is between pressure levels 1000 and 300 hPa inclusive.

Author contributions. LC conceptualized this article and participated in the interpretation of the data. DN participated in data collection, analysis, interpretation, and drafting of the article. All authors participated in the revision and final version of the article.

Competing interests. The authors declare that they have no conflict of interest.

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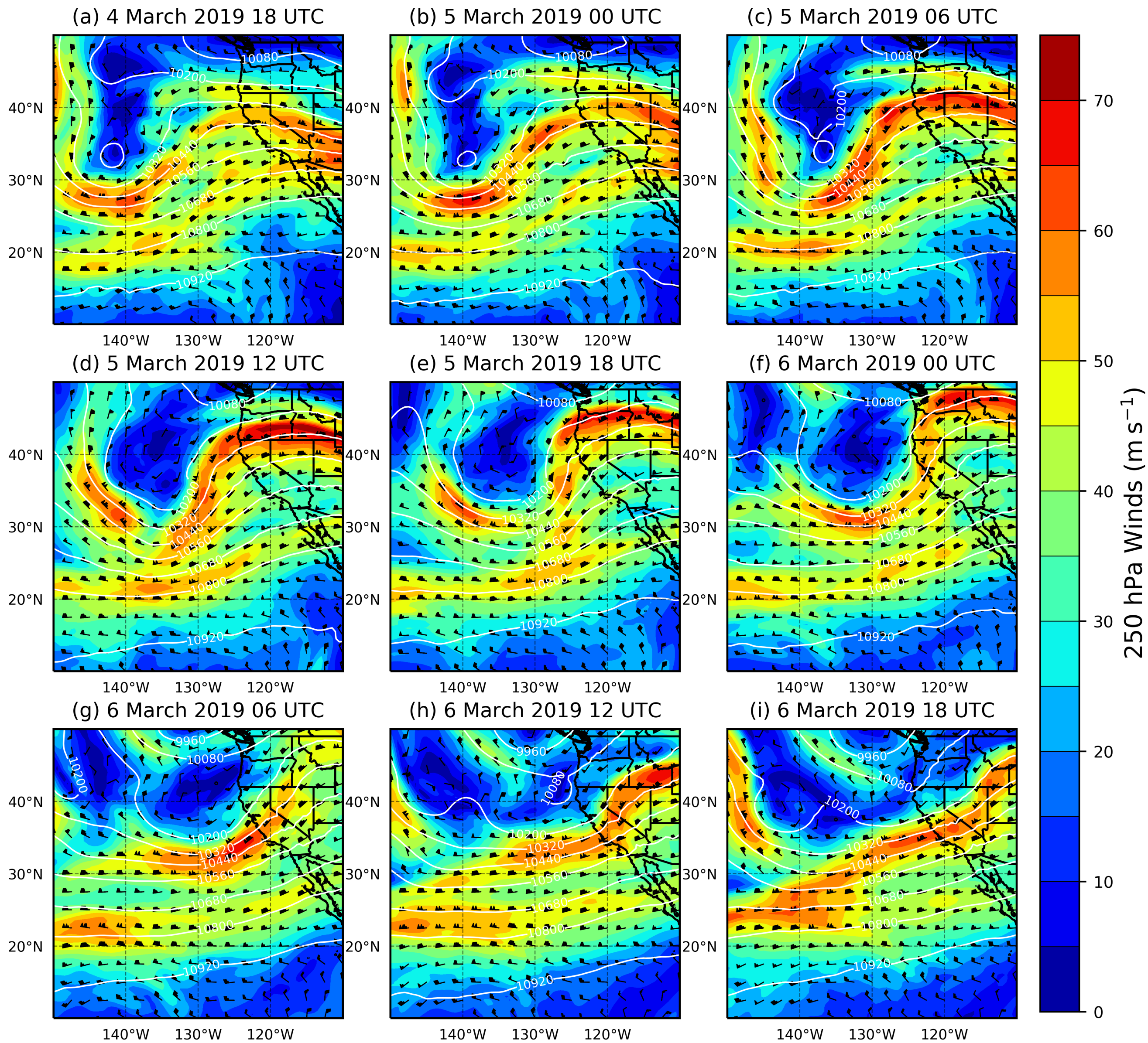
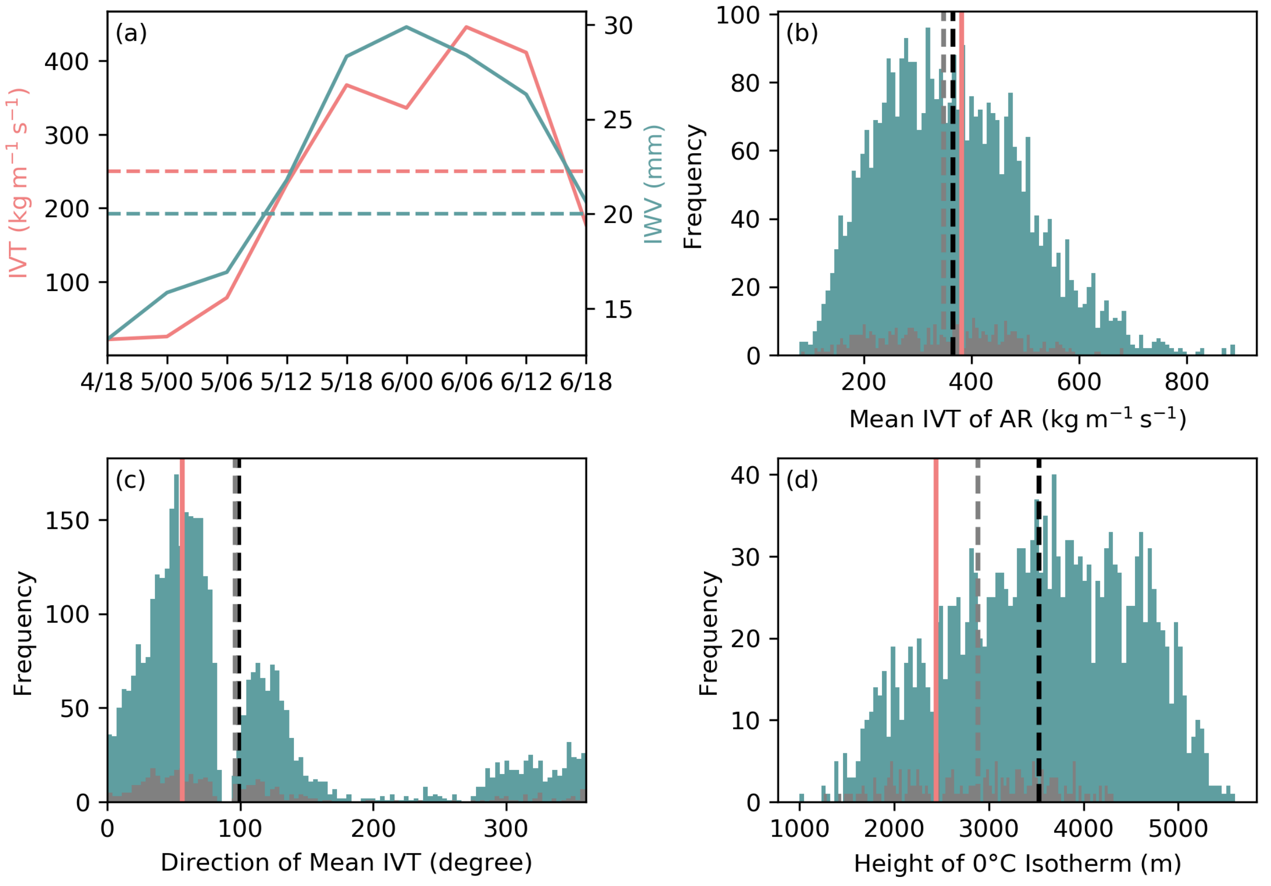


Figure S1. CFSv2 250 hPa winds (barbs, knots), 250 hPa wind magnitude (shaded; m s^{-1}) and 250 hPa geopotential height (white contours; m) at 6-hourly timesteps between 4 March 2019 18 UTC and 6 March 2019 18 UTC.



~~CFSv2 IVT (red line; kg m^{-1} s^{-1}) and IWV (blue line; mm) at the grid cell closest to Santa Barbara (34.5°N, 119.5°W) at each 6-hour time step between 4 March 2019 18 UTC and 6 March 2019 18 UTC. The minimum thresholds for the location to be considered part of an AR event are indicated by the dotted lines.~~

Figure S2. CFSv2 IVT (red line; kg m^{-1} s^{-1}) and IWV (blue line; mm) at the grid cell closest to Santa Barbara (34.5°N, 119.5°W) at each 6-hour time step between 4 March 2019 18 UTC and 6 March 2019 18 UTC. The minimum thresholds for the location to be considered part of an AR event are indicated by the dotted lines. (b) Mean IVT of the AR objects that made landfall in Santa Barbara in all the months (blue lines) and only March (grey lines) between January 1980 and May 2019 based on the AR Catalog from Guan and Waliser (2015). The mean IVT for the AR Event on March 5 is shown by the red solid line. The means of the distributions are shown in the dotted line. (c) Same as (b) but for direction of mean IVT propagation (azimuth is 0° if IVT is directed to the north). (d) Same as (b) but for the height of the 0°C Isotherm (m) interpolated from MERRA2 temperature and geopotential height

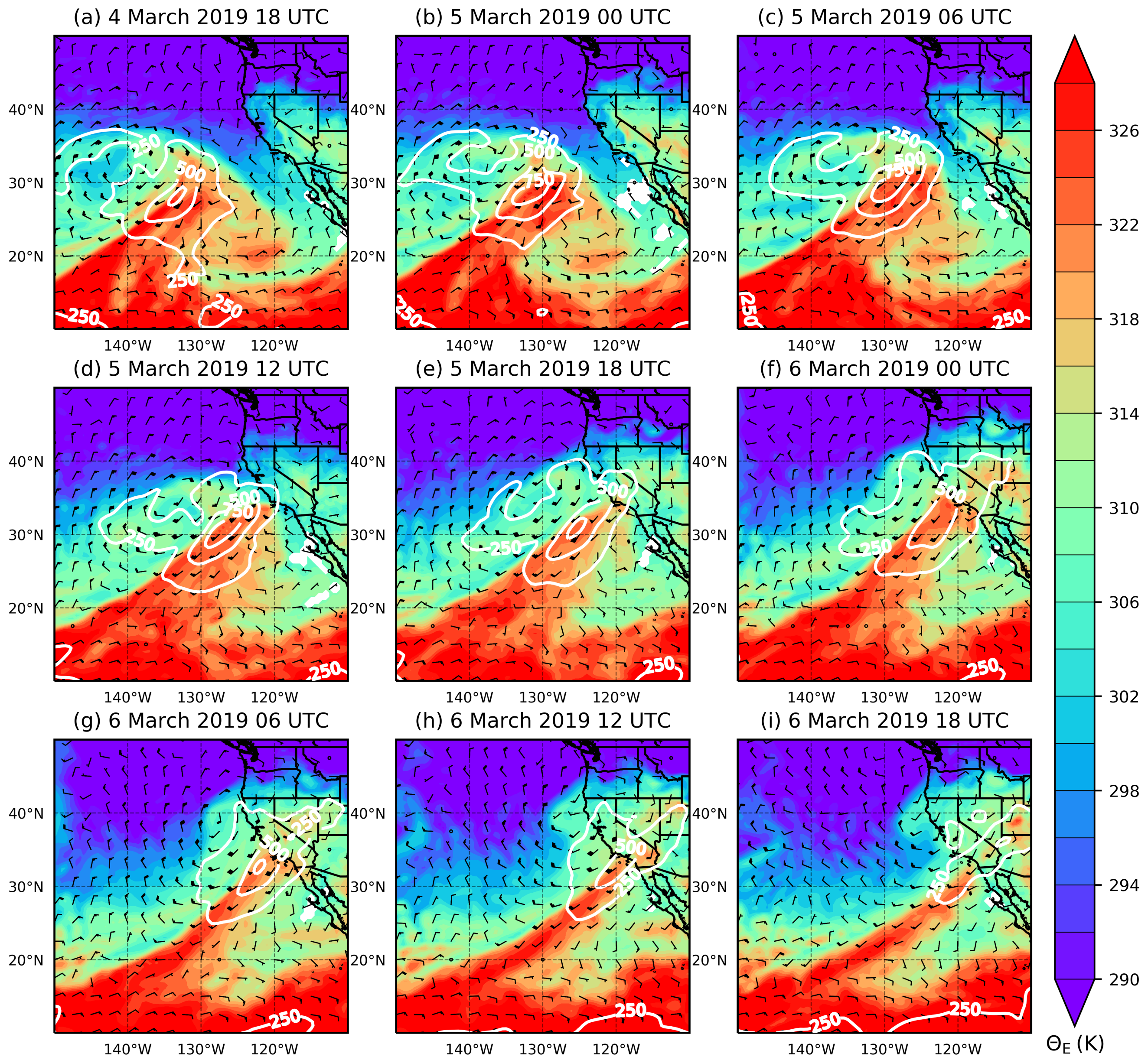


Figure S3. CFSv2 ~~CAPE~~ 850 hPa Equivalent Potential Temperature (shaded; K), ~~J kg^{-1}~~ 850 hPa winds (barbs; knots), and IVT greater than 250 kg m^{-1} s^{-1} (~~grey~~ white contours; every ~~100~~ 250 kg m^{-1} s^{-1}) ~~, and 500 hPa geopotential height (black dashed contours; m)~~ for each 6-hour time step between 4 March 2019 18 UTC and 6 March 2019 18 UTC.

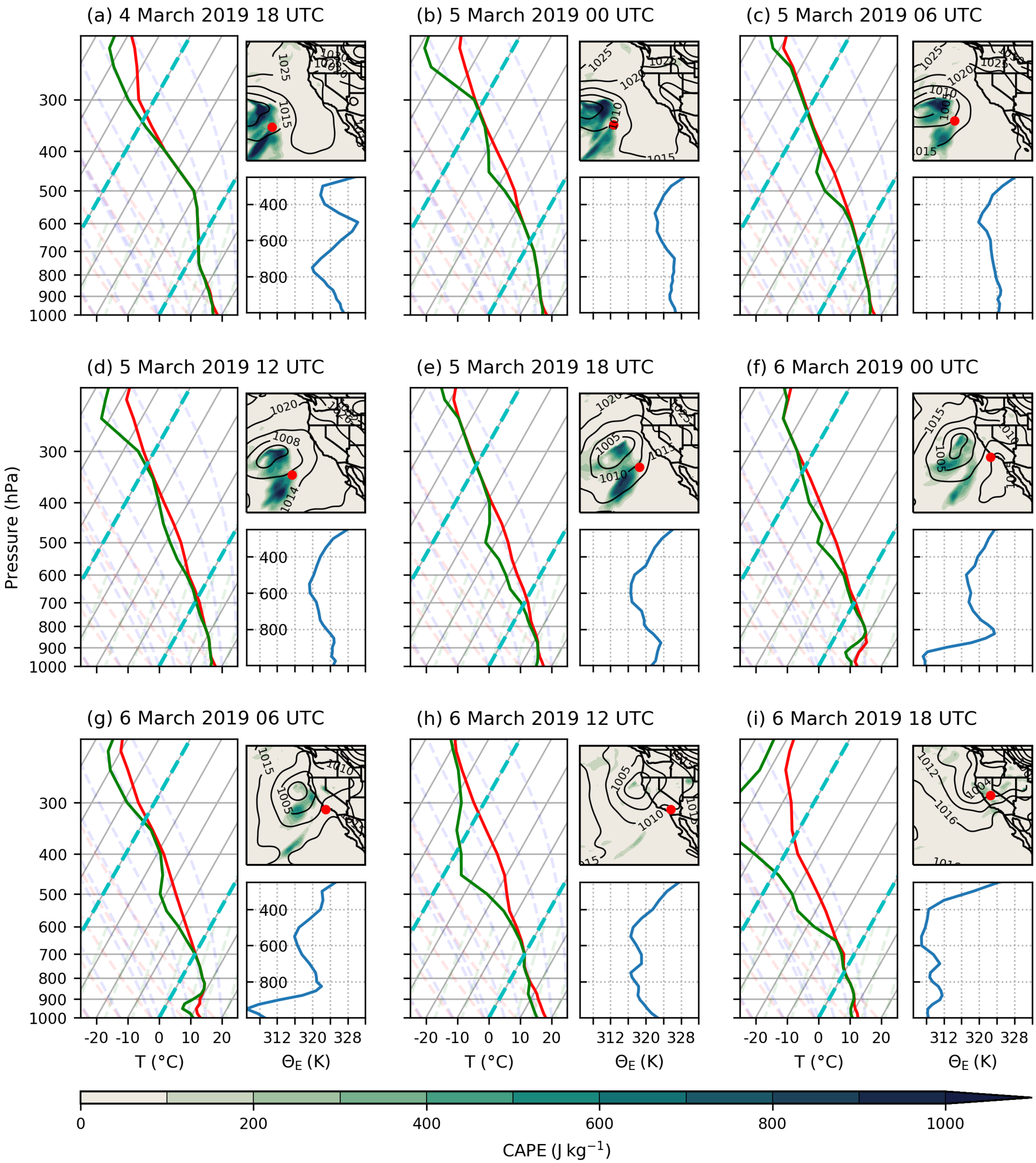


Figure S4. *(left panel)* Skew(t) - log(p) vertical profile of CFSv2 850 hPa Equivalent Potential Temperature temperature (shaded red line) and white contours to emphasize regions dew point (green line) at the grid cell with strong gradients; Kthe highest flash density (per 6 hours); *(right top panel)* CFSv2 CAPE (shaded, J kg^{-1}) and 850 MSLP (black dashed contours; hPawinds) with the location of the highest flash density indicated by the red dot; *(right bottom panel)* CFSv2 Equivalent Potential Temperature (barbsblue line; knotsK) at the grid cell with the highest flash density for each 6-hour time step between (a) 4 March 2019 18 UTC and (i) 6 March 2019 18 UTC.

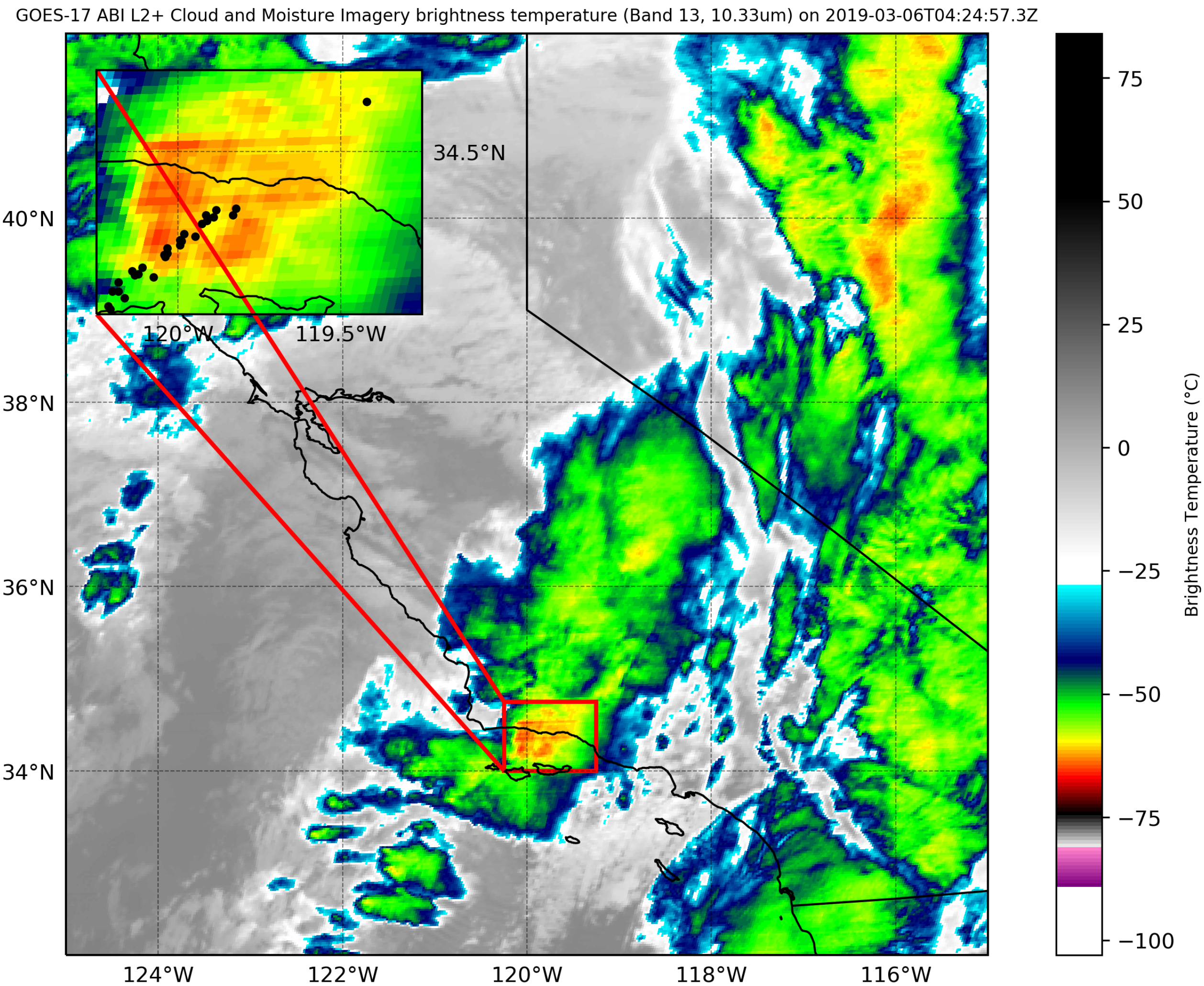


Figure S5. Infrared brightness temperatures (shaded, °C) derived from band 13 of the GOES17 ABI L2 Cloud and Moisture Imagery Brightness Temperature at 6 March 2019 4:24 UTC. Detailed infrared brightness temperatures around Santa Barbara (outlined in red) are shown in the top left area of the map. Locations of NOAA NEXRAD L3 Hail Signatures (black points) identified between 4:15 UTC and 4:45 UTC on 6 March 2019 are shown on the inset map.

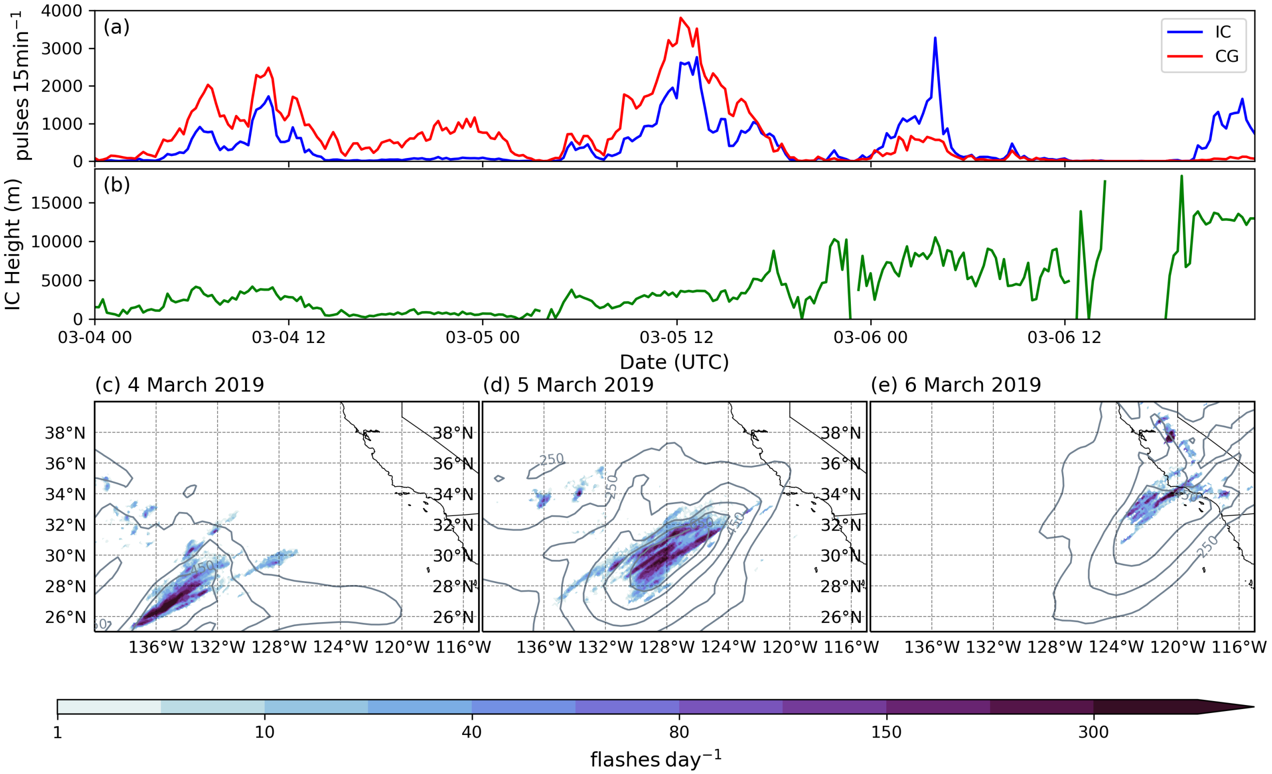


Figure S6. (a) ENGLN number of flashes per 15 minutes between 4 March 2019 0 UTC and 7 March 0 UTC for in-cloud (IC) flashes (blue line) and cloud-to-ground (CG) flashes (red line). (b) ENGLN average IC lightning flash height (green line; m) between 4 March 2019 0 UTC and 7 March 0 UTC. (c) ENGLN lightning flash count (shaded, flashes day^{-1}) interpolated to 0.1° and IVT greater than 250 kg m^{-1} s^{-1} (grey contours; every 100 kg m^{-1} s^{-1}) for the 24-hour period of 4 March 2019. (d) Same as (c), but for the 24-hour period of 5 March 2019. (e) Same as (c), but for the 24-hour period of 6 March 2019.

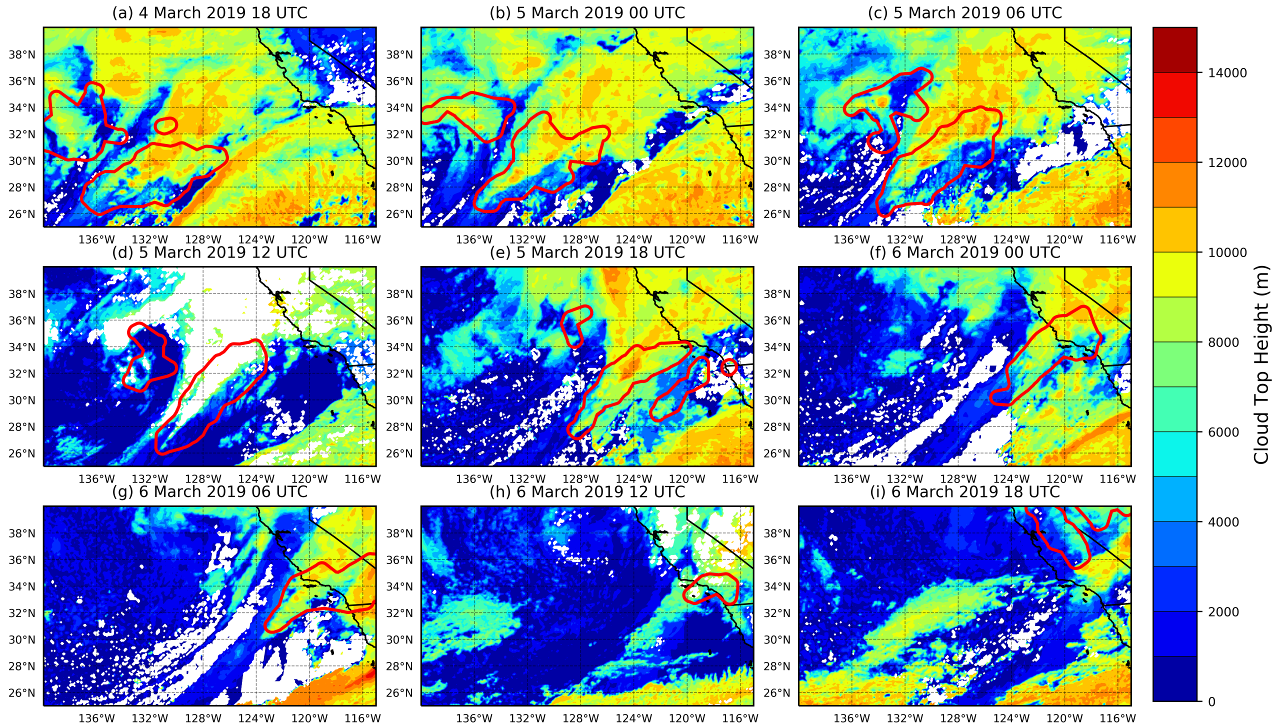


Figure S7. GOES ABI L2 ACHC cloud top height (shaded; m) and the location of the majority of lightning flash points (red polygon) at each 6-hour time step between 4 March 2019 18 UTC and 6 March 2019 18 UTC.

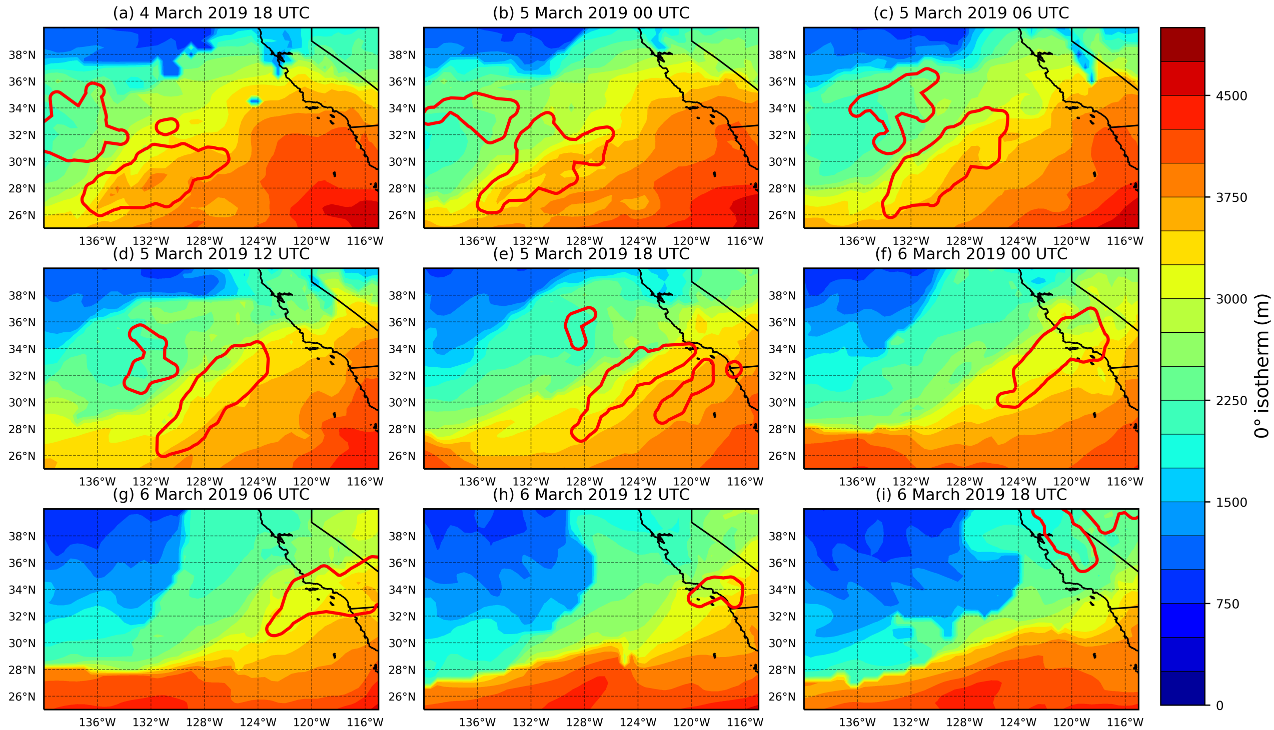


Figure S8. CFSv2 height of 0°isotherm (shaded; m) and the location of the majority of lightning flash points (red polygon) at each 6-hour time step between 4 March 2019 18 UTC and 6 March 2019 18 UTC.