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, line 72 now reads, *"TRMM LIS-OTD records an area climatological 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.

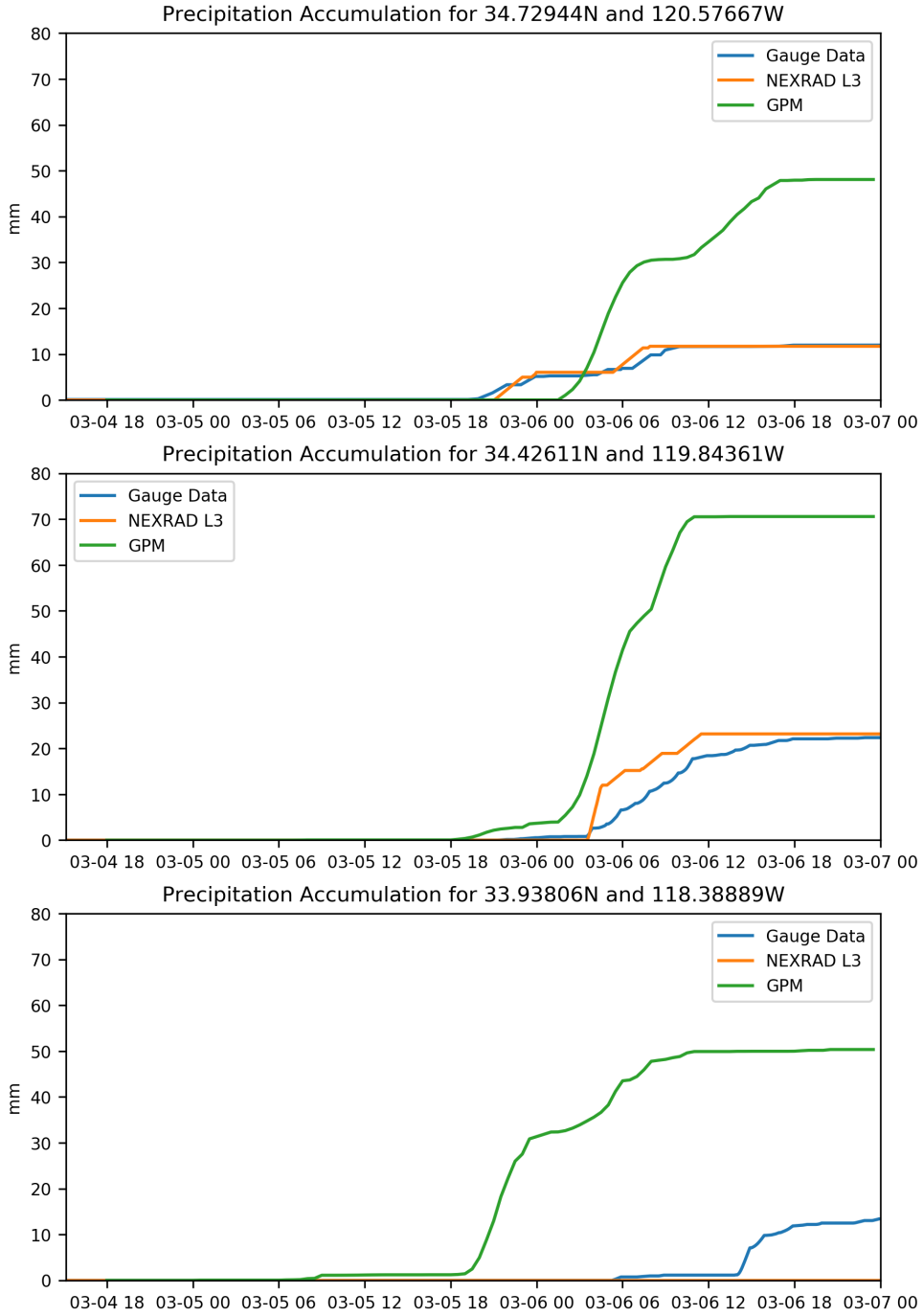

Figure 1. Precipitation accumulation (mm) over the duration of the storm period for 3 different locations near Santa Barbara for 3 different data sources, including NWS precipitation gauges (blue line), NOAA NEXRAD L3 precipitation estimates (orange line), and IMERG GPM (green line).

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.

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. See the updated figure below.

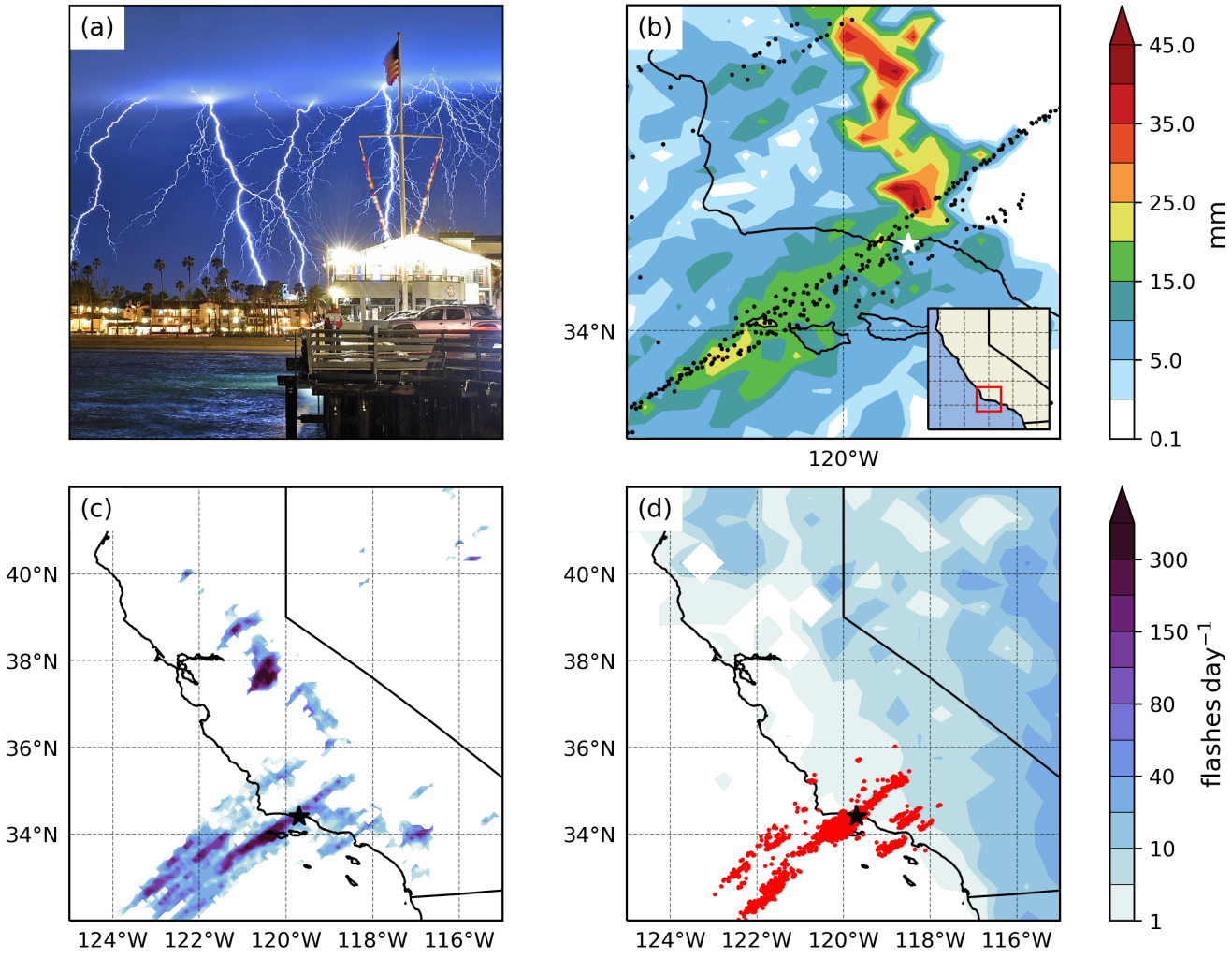

Figure 2. Figure 1. (a) Photo of lightning at the Santa Barbara Harbor in Santa Barbara, CA taken by Mike Eliason from the Santa Barbara County Fire Department during the storm at 6 March 2019 04 UTC. (b) NOAA NEXRAD L3 precipitation accumulation (shaded; mm) and locations of NOAA NEXRAD L3 Hail Signatures (black points) between 5 March 2019 12 UTC and 6 March 2019 23:59 UTC. The location of Santa Barbara is indicated by the white star. (c) ENGLN lightning strike frequency (shaded; flashes day^{-1}) on 6 March 2019. The location of Santa Barbara is indicated by the black star. (d) Climatological 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 and 05 UTC on 6 March 2019 based on ENGLN. The location of Santa Barbara is indicated by the black star.

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 in relation to the WCB.

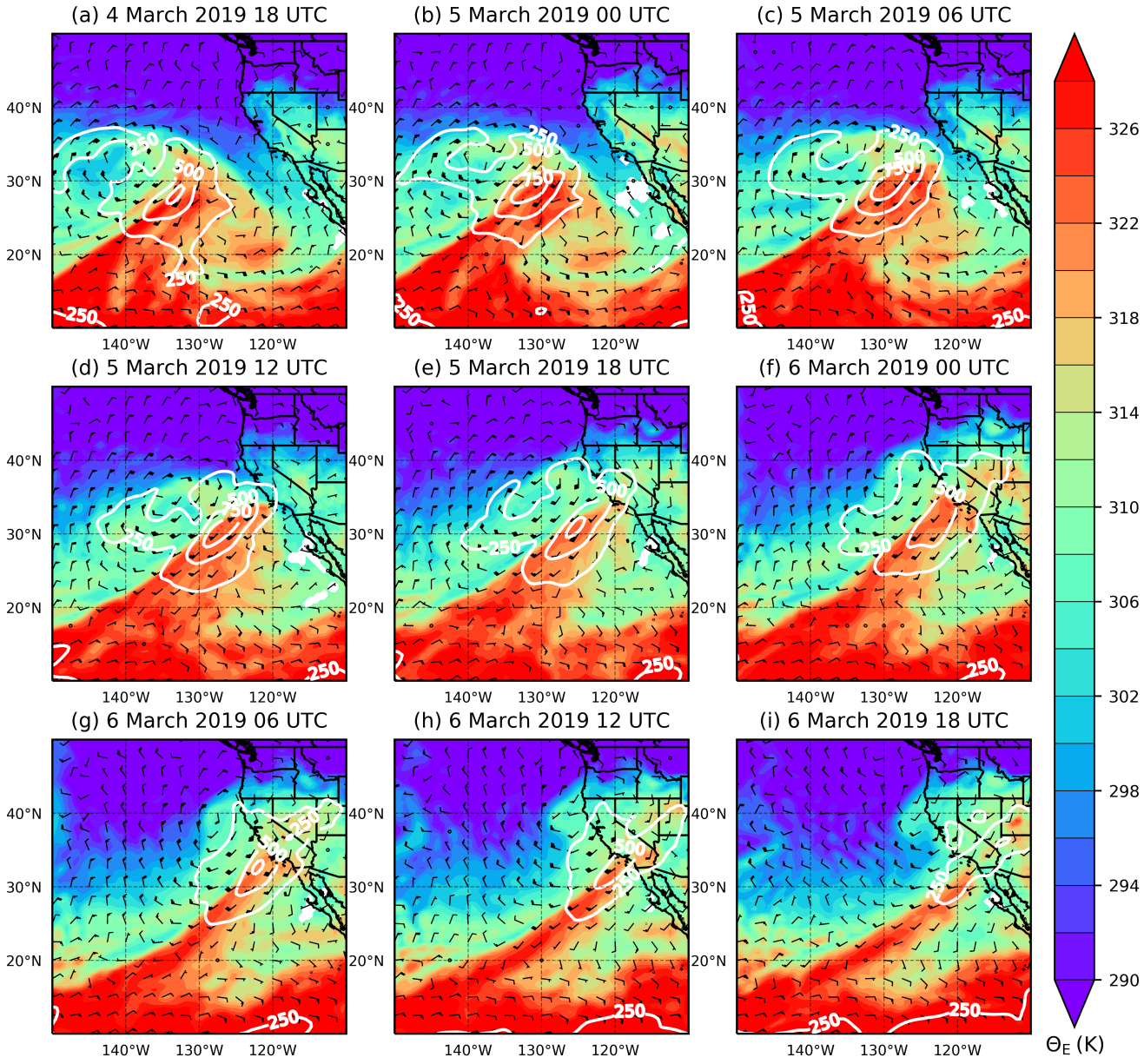

Figure 3. Figure S3. CFSv2 850 hPa Equivalent Potential Temperature (shaded; K), 850 hPa winds (barbs; knots), and IVT greater than 250 kg m^{-1} s^{-1} (white contours; every 250 kg m^{-1} s^{-1}) for each 6-hour time step between 4 March 2019 18 UTC and 6 March 2019 18 UTC.

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.

$$VT_u(ms^{-1}) = q(kgkg^{-1}) * u(ms^{-1}) \quad (1)$$

$$VT_v(ms^{-1}) = q(kgkg^{-1}) * v(ms^{-1}) \quad (2)$$

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

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 for this region that observes, on average, less than 10 flashes per day."* 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 climatological 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 SB and add to the supplemental results (see new Fig. S2 below). 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 event below the average.

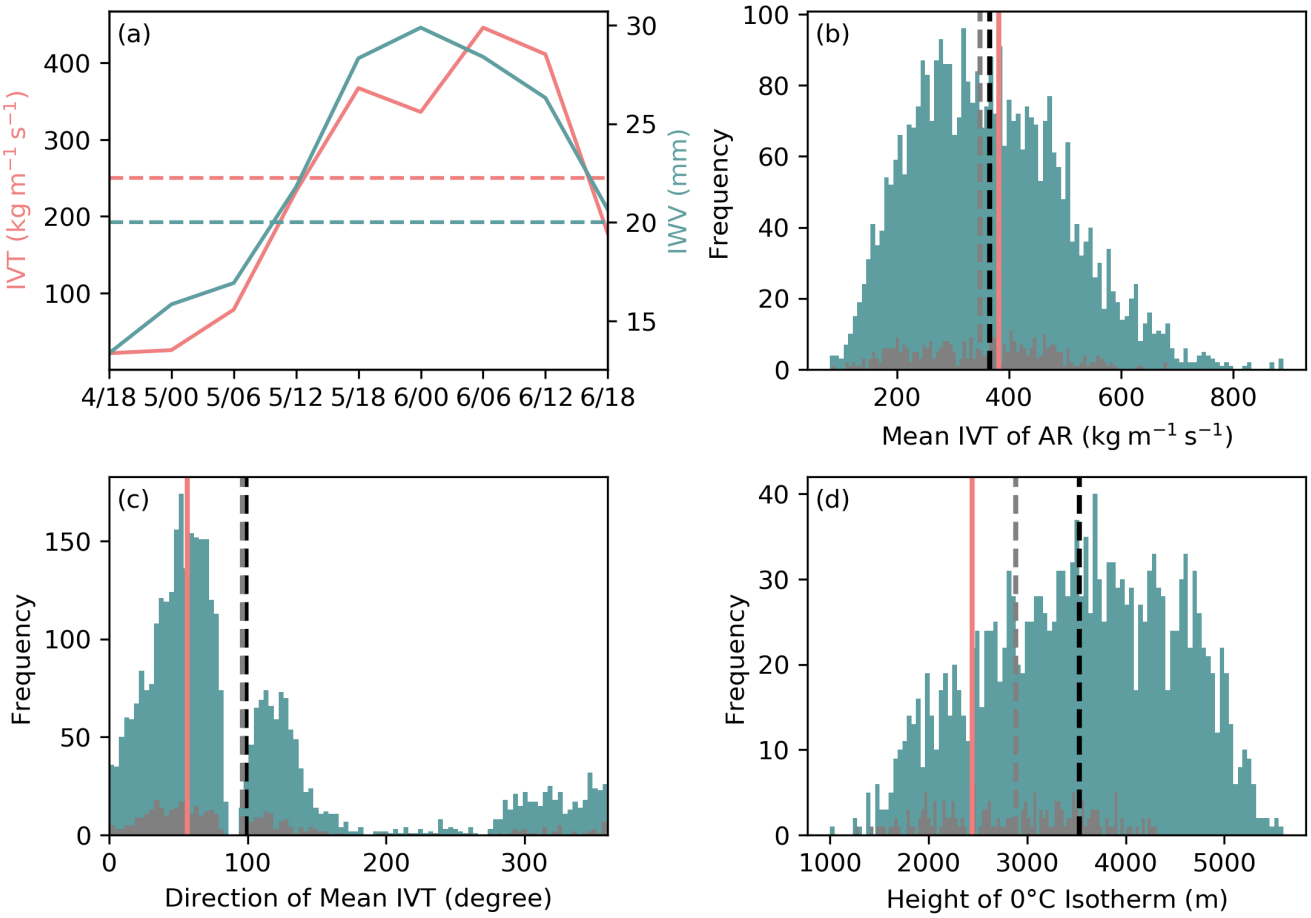

Figure 4. Figure S2. (a) CFSv2 IVT (red line; kg m^{-1} s^{-1}) and IWV (blue line; mm) at the grid cell closest to Santa Barbara (34.5°N, 119.5°W) at each 6-hour time step between 4 March 2019 18 UTC and 6 March 2019 18 UTC. The minimum thresholds for the location to be considered part of an AR event 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.

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).”*

References

Cannon, F., Ralph, F. M., Wilson, A. M., and Lettenmaier, D. P.: GPM Satellite Radar Measurements of Precipitation and Freezing Level in Atmospheric Rivers: Comparison With Ground-Based Radars and Reanalyses, Journal of Geophysical Research: Atmospheres, 122, 12–747, https://doi.org/https://doi.org/10.1002/2017JD027355, 2017.

Guan, B. and Waliser, D.: Detection of atmospheric rivers: Evaluation and application of an algorithm for global studies, Journal of Geophysical Research: Atmospheres, 120, 12 514–12 535, https://doi.org/10.1002/2015JD024257, 2015.

Harris Jr, G. N., Bowman, K. P., and Shin, D.-B.: Comparison of freezing-level altitudes from the NCEP reanalysis with TRMM precipitation radar brightband data, Journal of climate, 13, 4137–4148, https://doi.org/https://doi.org/10.1175/1520-0442(2000)013<4137:COFLAF>2.0.CO;2, 2000.