“A dynamic and thermodynamic analysis of the 11 December 2017 tornadic supercell in the Highveld of South Africa”

Response to reviewer #1

Reviewer: The authors of this manuscript present a case study of a tornadic supercell that affected parts of South Africa and led to extensive damage and injuries due to severe weather including a tornado that hit Vaal Marina in Gauteng Province. The study is relevant given the low number of tornado / supercell case studies in South Africa and can help to better understand conditions favorable for severe weather is this part of the country. I therefore recommend publication in Weather and Climate Dynamics. However, work is needed to increase the value of this paper since I have some concerns regarding some of the results presented in the conclusions, in particular the presented model forecasts.

Authors: Thank you very much for your positive and detailed critical comments which have improved our manuscript. We provide a point-by-point response to all the major and minor comments below.

Reviewer: 1) Results that need to be discussed in much greater depth to convince the reader
The lack of mid-level vorticity and low-level moisture flux convergence in the model field could be a consequence of the missed convection initiation. In other words: High mid-level vorticity and strong low-level moisture flux convergence would be a consequence of a supercell that develops in the model forecast. Since the model failed to initiate storms, it is also not able to increase the low-level moisture flux convergence and mid-level vorticity.

Authors: Moisture flux convergence (MFC) has historically been used, from both observations and models, as a prognostic quantity for forecasting convective initiation (Banacos and Schultz, 2005). Hence, we concluded that a lack of MFC could be a precursor of, and not a consequence of, a lack of convective initiation or as in our case study, missed convective initiation. We attribute lack of storm during our analysis to lack of MFC. Perhaps there are more reasons, than just one, of why as noted by a recent study by Keat et al. (2019) which found that SA1.5 seems to consistently struggle with missed convection initiation over South Africa. They concluded that it might be due to physics set-up and the way sub-grid processes are parameterised in the model which might not be suitable for the region. In our revision we cite this study as one more possible reason why SA1.5 could be a case of missed convective initiation.

Reviewer: Since SA4.4 has limited resolution, wouldn’t you expect that this already causes the vorticity of modelled supercells to be smaller? Again, please discuss if the model resolution allows to directly indicate the effect of the developed convective storm on the presented parameters. Is it possible that you just analyse difference fields in the model that are affected by the initiated convective storm and therefore cannot be used to explain why a storm has formed or not?

Authors: Indeed Glickman (2000) indicated that the horizontal scale of the vortex is normally between 2 to 10km. This does indeed indicate that a grid length of 4.4km is too coarse (and in the grey zones really) to be able to resolve this process. We note that some previous studies (e.g. Weisman et al., 1997) have indicated that a grid spacing of 4 km may be sufficient to reproduce mesoconvective circulations and net momentum and heat transport of midlatitude type convective systems. We note also others who argue that models of grid spacing of 1 km or less are the ones adequate to represent dynamics and local processes responsible for triggering convection (see Roberts, 2008, and Bryan et al., 2003). Our revised manuscript will include a clear discussion on the effect of resolution on our results.

Reviewer 2) Ingredients-based methodology
I miss an analysis of the main ingredients for convective storms. These are low-level moisture, (mid-level) lapse rates, and lift. For low-level moisture and lift, I would highly appreciate a surface analysis including temperature, dewpoint, and wind barbs. The 15 UTC chart clearly indicates the presence of a dryline and shows the advection of moist air masses ahead of it. Are these drylines typical for that region or was this event special with respect to the intensity or location of the dryline? Two ascents have been operated at 9 UTC in the area of interest to indicate the presence of lapse rates (I recommend including FABL Bloemfontein Airport since it shows deep boundary layer mixing upstream although it is farther away). Please discuss if these soundings are representative since the launch time is many hours prior to the discussed event. Please check the sounding time. In the manuscript, the presented sounding is said to be launched at 12 UTC, but according to raw data it is launched at 9 UTC. To discuss the magnitude of vertical wind shear, I also would include FABL Bloemfontein Airport sounding that has much greater mid-level winds upstream several hours prior to the event (45 knots at 500 hPa compared to 24 kts in the presented sounding).

Authors: Thank you for this comment which made us realise that we missed to include the ingredients in a summarised format after our mesoanalysis. We include these in our revised manuscript. It was found that three ingredients were important in strengthening and maintaining this supercell: significant surface to midlevel vertical shear, an abundance of low-level warm moisture influx from the tropics and Mozambique Channel, and mid-level lapse rates. We also now include a surface chart analysis figure from the South African Weather Service which clearly indicates a dryline in the central interior of South Africa (especially the Free State Province). Regarding drylines, yes, they are typical especially in the central parts of South Africa during summer months. As recommended, we now include the FABL ascent which clearly indicates mid-level winds upstream which we believe played a role in the formation of the supercell. We can also confirm that the sounding time was 12 UTC and not 9 UTC. This confirmation is from the South African Weather Service which is responsible for launching radiosondes. We also noted that raw data indicates 09 UTC, but the actual time was 12 UTC. We must say that this is a known problem and seems to be rather a technical error/bug.

Further comments

Reviewer 1) Line 45: Single cells can produce severe weather, e.g., pulse storms.

Authors: That is correct, however rare those cases are in South Africa, they do happen. We rectify this by noting that, however rare, single cells can also become severe as also noted by Ashley and Gilson (2009) who found that in some parts of the United States, lightning-related fatalities are most often produced by unorganized, pulse-style thunderstorms.

Reviewer 2) Line 47: There can be also tornadoes not associated with intense convective storms (non-mesocyclonic tornadoes)

Authors: Indeed there are non-supercellular tornadoes as also presented by Wakimoto and Wilson (1989).

Reviewer 3) Line 79: Which criteria did you use to choose weather stations of interest? Please include a complete surface analysis that contains all data.

Authors: We simply used stations that are closest to the storm track. The surface analysis is included in our revised manuscript which indicate all weather stations across South Africa.

Reviewer 4) Figure 1: How did you produce the track of the cell? Radar site of the southern radar and the provincial borders are hardly visible in printed versions of the manuscript. Please include a reference scale.

Authors: To produce the storm track we used the Thunderstorm Identification, Tracking, Analysis and Nowcasting (TITAN) and QGIS softwares to mark geographic information system (GPS) locations of the cell for each radar scan (for both radars in Irene and Ermelo, individual and merged for validation), from initiation to dissipation of the storm. The reference scale is now included in the figure.

Reviewer 5) Line 104-105: Please explain how the surface data were "regridded". What was the maximum distance between model grid points and surface data? Did you take terrain height differences into account? Was there an objective method to select proximity stations? Again, I would suggest a surface analysis.

Authors: The surface data was regridded using the Cressman objective analysis scheme which is described in detail by Cressman (1959). A Cressman objective analysis is performed on the station data to arrive at a gridded result that represents the station data. Model grid points are 4.4 km apart, while regridded surface data points are 25 km apart (hence it appears coarse). The regridding script does not take terrain height into account. However, observations are taken at 2 m (dewpoint and temperature) and 10 m (winds) above ground at each station. Proximity stations are simply taken to be those closest to the storm track, as indicated in Figure 1 and now in the surface chart analysis.

Reviewer 6) Line 109: What was the distance of the radar sites from the supercell? You could solve this issue by including a reference scale in Figure 1.

Authors: The distance varies (but within 150 km) depending on where the supercell was located at a particular time. We include a reference scale in our revised manuscript to resolve this.

Reviewer 7) Line 110-111: Please check the time between sounding launch and supercell event. The raw data file indicates that the soundings were launched three hours earlier. Please discuss if this has consequences for the classification as proximity sounding.

Authors: As already indicated in response to an earlier comment regarding radiosonde time, it was confirmed that the sounding was launched at 12 UTC, and not 09 UTC. This is therefore a good proximity sounding.

Reviewer 8) Lines 140-144: “The presence of boundary layer water vapour concentration is one of the most important factors for tornadogenesis (Markowski and Richardson, 2009). As a result, to analyse the significance of low-level moisture in the event considered, the convergence of moisture flux is computed at 800 hPa level. Moisture flux convergence (MFC) is a useful diagnostic tool as it combines the effects of moisture advection and convergence and can be computed at any atmospheric pressure level (Banacos and Schultz, 2005).” MFC is not an ingredient for convective storms or tornadoes! Large MFC does not necessarily mean that moisture is high. Furthermore, at the observation sites shown in the paper, there is no moisture increase prior to the event. More discussion is needed to explain why you like to analyse MFC rather than moisture directly.

Authors: We agree that MFC is not an ingredient for convective storms or tornadoes. Nor does high large MFC necessarily mean that moisture is high. We rather use MFC due to its combination of moisture advection and convergence. MFC has been used in the past as it typically occurs 3 hours prior to convective storms (see Hudson,1971; and Newman, 1971; Doswell, 1977; Negri and Vonder Haar, 1980; Waldstreicher, 1989). Not just moisture, but the concentration of moisture, has been shown to be associated with areas of tornadogenesis. Perhaps the reference regarding boundary layer moisture concentration and tornadogenesis, followed by MFC causes misunderstandings. The use of tornadogenesis, or allusions thereof, seems to cause confusion as noted by Reviewer #2 as our focus in our model analysis is not primarily on tornadogenesis, rather we speak of tornadogenesis from observations data and not model data. Therefore, our revised manuscript removes any allusions of tornadogenesis in our model analysis. Lines 140-144 have been changed in our revised paper. Also, in our revised manuscript we integrate MFC from the surface to 600 hPa, and use that to define low-level following Ndarana et al. (2020).

Reviewer 9) "This mid-level circulation patterns resulted in mid-atmospheric south-westerly winds over the interior of South Africa, which enhanced convective instability over the central east of the country as the dry mid-level air advects over the low-level warm and moist-air in the east." Dry mid-level air is not an ingredient for convective storms! There can be very dry air on top of very moist layers and still there is no instability. Please analyse the mid-level lapse rate field and look for regions where steep lapse rates overlap with rich low-level moisture to consider instability.

Authors: Yes, we did not intend to communicate that a dry mid-level is an ingredient for convective storms, rather that the advection of dry mid-level air over low-level warm and moist-air enhances convective instability. Our phrasing is corrected in order to avoid confusion.

Reviewer 10) Figure 2: I would recommend using 300 hPa rather than 200 hPa.

Authors: We now use 300 hPa as suggested and we can see it has a relatively defined wave over the subcontinent than the 200 hPa.

Reviewer 11) Line 182-183: "A weak upper-air trough was also present over South Africa (Fig. 2(a))." If there is no further discussion on the upper level wind field, you may skip the 200 hPa chart. Otherwise, you may discuss in which way the upper trough / jet supported the development of a severe convective event.

Authors: Noted with thanks.

Reviewer 12) Mesoanalysis: The presented data (Figures 3 and 4) are quite uncommon to analyse the mesoscale surface weather chart. A surface analysis would a good addition to these data.

Authors: A surface chart is included for surface analysis in our revised manuscript.

Reviewer 13) Line 207: "After initiation, the storm initially propagated eastwards, then suddenly changed direction to north-east towards the Vaal Dam as it matured into a supercell thunderstorm through energy supply from a continual merger of several cells." This is very vague. Cell merger can also cause supercell decay due to the interaction of outflows. Why did this not happen in this case?

Authors: Cell mergers in the southern African context are still not well understood. Typically, cell mergers are associated with storm intensification (not always), especially in development stages. We suspect storm directions and angle of "collision" played a role in intensifying the favoured storm which became a supercell. This requires further analysis which might be out of scope of our current study. What we know from our analysis is that there was a merger of several storms early on after storms initiated over the dry-line.

Reviewer 14) Mesoanalysis: I would re-organize this section. You start with surface observations, jump to radar analysis, continue with the discussion of one surface observation that might be not representative, jump to the discussion of a sounding, jump back to radar analysis.

Authors: Your suggestion is noted, and we try to re-organise our mesoanalysis so that its clear in our revised manuscript.

Reviewer 15) Line 260: It would be good to compare a surface chart directly to the winds in the lowest model level. The average regridded surface data does not allow for a detailed analysis. Furthermore, it is not explained how the averaging of the station data (due to which criteria are they chosen) is done.

Authors: This suggestion is helpful and greatly appreciated. The regridding method is already addressed in the previous comments.

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