Reply to comments from referee 2:

Comment on acp-2022-559
Anonymous Referee #2
This paper presents results from a single mesoscale model simulation of a thunderstorm. In its present form, I do not think the paper sufficiently advances the state-of-the-art to warrant publication. My reasons are as follows.
Reply: Thank a lot for your important comments. We carefully consider all comments and reply as following.

- The model seems to be over two decades old. In the late ’90s, when many of the referenced articles were written, 3D mesoscale models had 1 to 2 km horizontal grids, 0.5 km vertical grids, 100 to 500 km horizontal domains, and vertical domains reaching the Stratopause. This model seems to belong to that family with a 35km horizontal domain. By comparison, the 2018 Muller et al. paper looks at convection-allowing simulations with a 5000 km horizontal domain.

  Reply: The main result in our study find that the upper-level high loading of graupel/hail can generate downward propagating gravity waves when descending rather than thermal or mechanical processes. It means that the model used for this purpose must have an ability to simulate hail and hailstorm in details.

  Hail and hailstorms simulations are not available in most GCM models or climate models owing to that the inclusion of hail process in models not only require the high resolution but also need relevant physical processes. The very high terminal velocity for hail particles always causes stability problems. In our paper we use a hail-bin microphysics rather than hail parameterization scheme as used in most previous storm-scale models in order to appropriately simulate the hail falling process and associated gravity waves. For this purpose, the storm-scale high-resolution cloud models with detailed hail processes are the best choice for theoretically interpret the observed phenomenon.

  Muller et al. (2018) conducted many sensitivity experiments to resolution for convection-allowing simulations, however, cloud water, cloud ice, snow and rainwater processes are included in their models but no hail process (Stevens et al., 2013; Satoh et al., 2014). Therefore, these models can be used for thermally or mechanically induced gravity waves in convection, and cannot be used for gravity waves generated by hailstorms as this study.

- It is not clear to me how the authors can confidently ascribe the downward propagating gravity waves to the novel process since the “buoyancy restoration force” occurs in the same area where the updraft overshoots the tropopause. I would have expected the authors to conduct a spectral analysis of the downward propagating gravity waves in order to identify clear distinguishing spectral properties (vertical and horizontal wavelengths and frequency) to associate with the length scales of the suggested originating process. The authors claim that it is necessary to understand these new waves because of the role they play in tropospheric dynamics. I do not see where the authors make the case for an important role for downward propagating waves. The only argument I discern is that these waves cause storm splitting. But storm splitting by downward propagating waves is argued based on the fact that the split occurs at a given time. This explanation is unsatisfying. Storm splitting is a common phenomenon. Is it always caused by downward propagating waves?

Reply: The main reason to ascribe the downward propagating gravity waves reported in this study to a novel process is that the downward gravity waves are generated by the hail process rather than thermal or mechanical forcing although the "buoyancy restoration force" induced by the descending of graupel/hail is similar to those induced by thermal and mechanical forcing （Fig.1） .

The upward propagating gravity waves are also generated by the storm top in the development stage for our simulated storm as reported in previous studies (Fig.2), however, the downward gravity waves generated by hail process occurs in the mature and decaying stages and the generation mechanisms are completely different from those found in previous studies.

To date, we found that the important role for the downward propagating gravity waves can cause the storm splitting rapidly (Fig.3), the issue is very important to the storm tracking and forecasting since the severe storms always cause significant damages to the public property. As you said, the storm splitting is a common phenomenon. The mechanisms that cause the storm splitting have been intensively investigated. The main mechanisms can be attributed to two aspects, one is related to interactions among wind shear, pressure perturbation and updraft development. The other is related to the precipitating-induced downdraft. We indicate that downward gravity waves generated by severe overshooting storm can be critical to storm splitting. However, issue relevant to storm splitting is not a main topic of this study.

For your suggestions to conduct spectral analysis in the downward propagating gravity waves, we will consider carefully. This study just physically interprets the generation process for gravity waves induced by a hailstorm and their potential impacts. The wave properties such as wave lengthen, duration and amplitude are estimated and found to be generally consistent with those found by previous studies.

- As far as the upward propagating waves caused by reflection from the surface go, the authors claim that they "significantly change the dynamic and thermodynamic structure in the lower stratosphere". I do not see that a significant effect was measured or even described. Did the waves break and deposit momentum?

Reply: This phenomenon can be seen clearly when upward gravity waves reflected by the surface enter the stratosphere and induce strong fluctuations in temperature and vertical velocity (Fig.4-6). As you said, when upward gravity waves enter the stable stratosphere and they will deposit momentum and induce strong perturbations in temperature and vertical velocity, showing horizontal propagating gravity waves in the layer, and then breaking and decaying.

- Perhaps the authors could consider extending the physical and temporal domain of the simulation and produce a spectral analysis of the waves they detect in order to support their conclusions that a new generating process is being observed. They should also produce quantitative arguments that downward propagating GWs cause storm splitting, and that ground-reflected GWs have a significant effect on stratospheric dynamics.

Reply: Thanks a lot for this final comment. As stated above, the storm-scale storm model with hail-bin microphysics is an appropriate choice to simulate the gravity waves generated by the upper-level high graupel/hail loading. We will further revise and improve our manuscript based on your important comments.

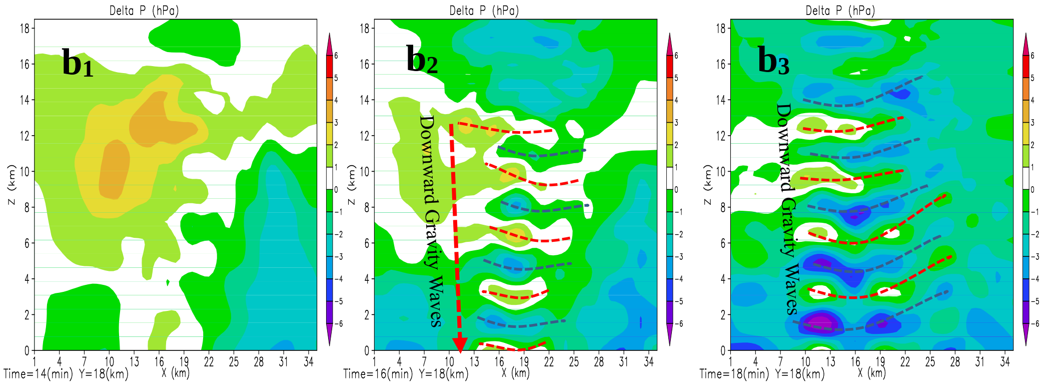


Fig.1 Downward propagating waves induced by the descending of upper-level high graupel/hail loading.

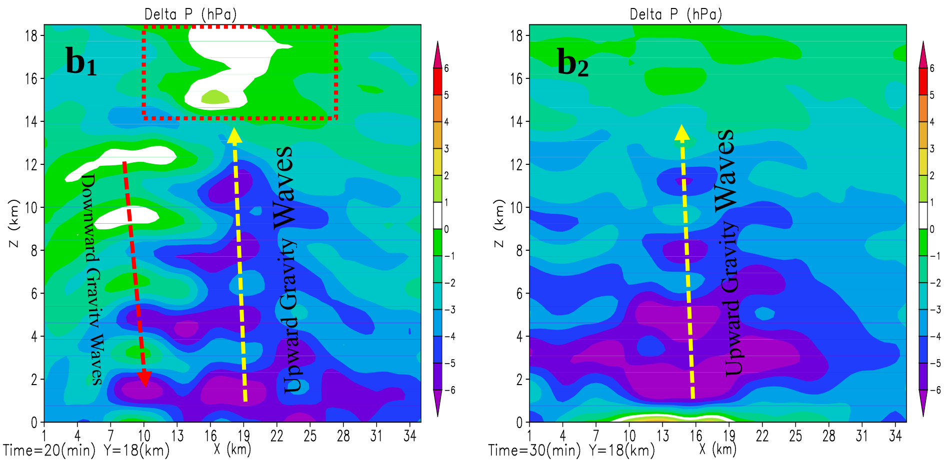


Fig.2 Upward propagating gravity waves induced by the surface reflection process

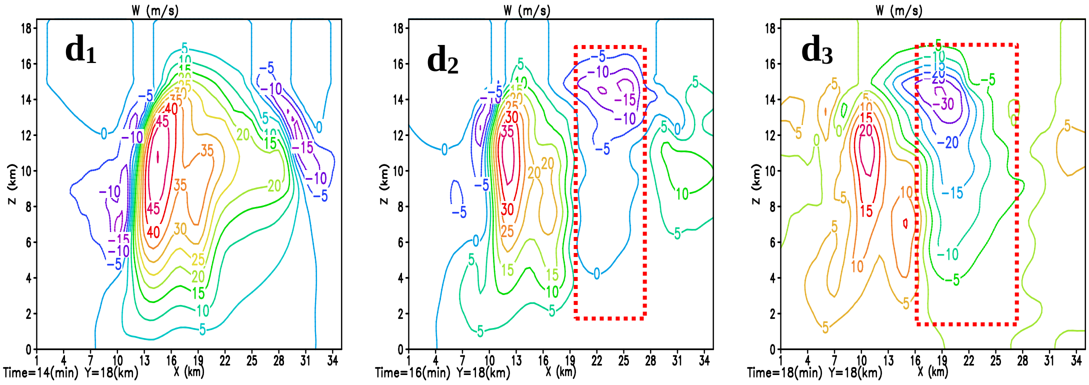


Fig.3 Storm updraft splitting induced by the downward propagating waves.

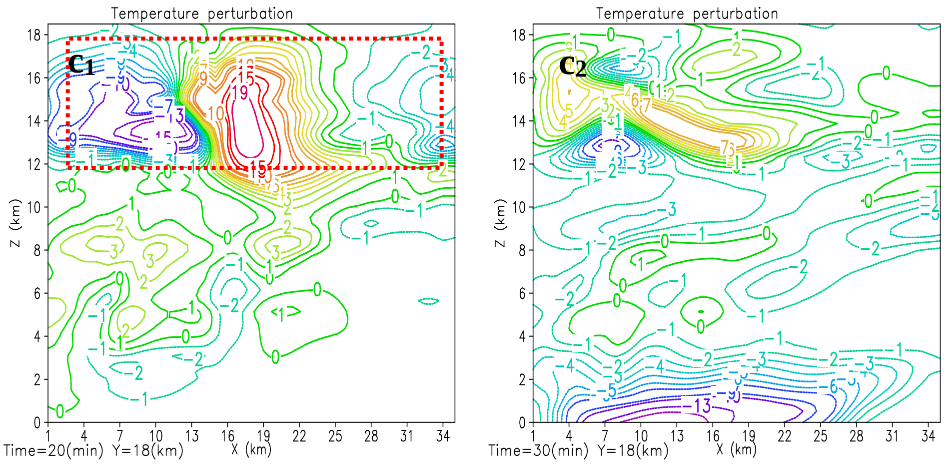


Fig.4 Temperature perturbations induced by upward propagating gravity waves in the lower stratosphere.

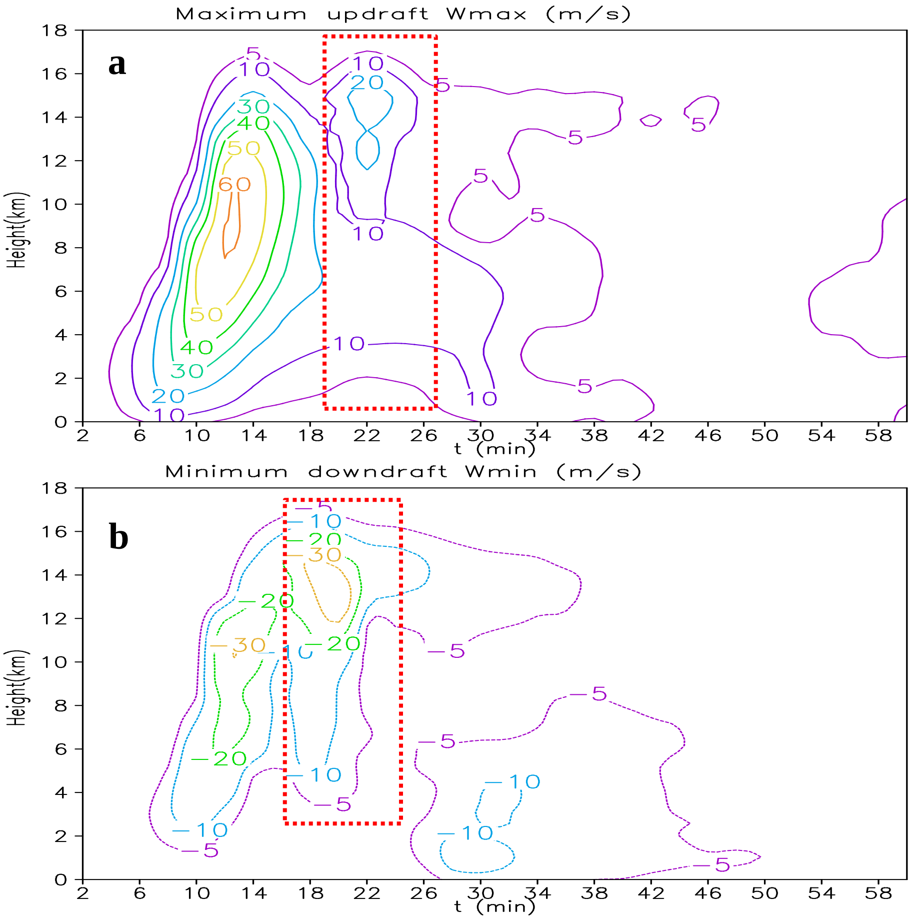
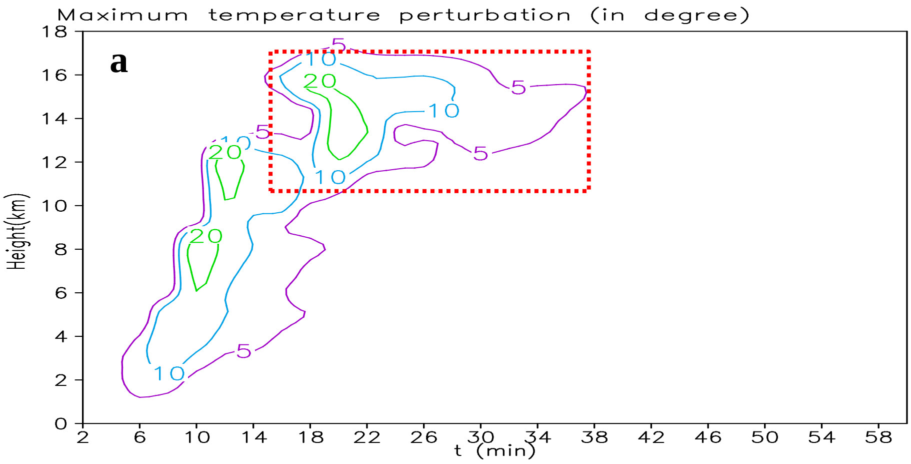


Fig. 5 Temporal-height distribution of (a) maximum updraft (m/s) and (b) downdraft (m/s) for the simulated storm, indicating that downward propagating gravity waves occur at first (a), and then a strong upward propagating waves are formed (b).



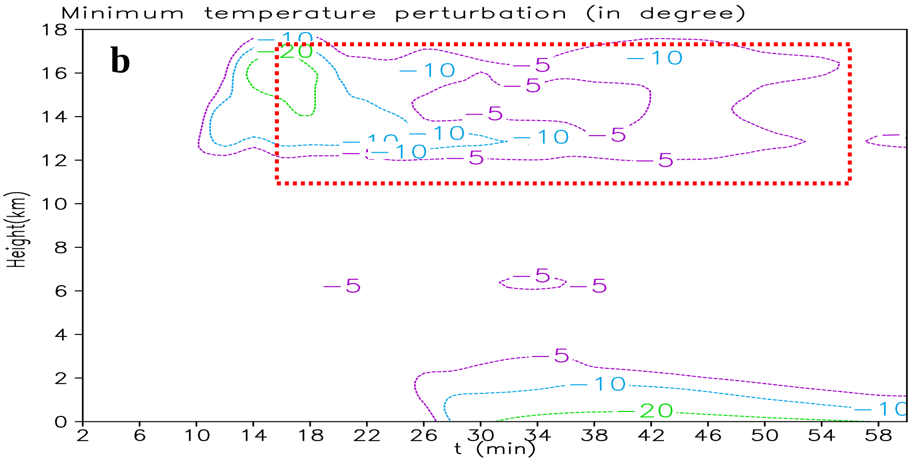


Fig.6. Temporal-height (z-t) distributions of (a) maximum temperature (℃) and (b) minimum temperature (℃) for the simulated storm on 19 June 2017, showing that the upward propagating gravity waves deposit momentum in the stratosphere and induce a significant fluctuation in temperature in this layer.