

General Comments

This manuscript presents a rare and valuable case study of an extreme convective outbreak south of the Himalayas on 19 May 2022, during which both a massive TLE outbreak and multi-layer concentric gravity waves were observed. The combination of amateur photography, ground-based airglow imaging, satellite observations, and model results provides a strong basis for studying vertical atmospheric coupling from the lower atmosphere to the thermosphere, and offers a valuable test case for understanding how extreme convection drives multi-layer electrical and dynamical coupling.

The study is generally well organized, and the scientific storyline is clear. The observations of long-distance MLT CGW propagation and thermospheric CGWs are particularly interesting. The interpretation that the thermospheric waves are likely secondary gravity waves is plausible, and the proposed role of background winds in controlling their asymmetric observability is physically reasonable.

The manuscript is suitable for publication after the authors clarify several methodological details and improve the presentation. In particular, the authors should better explain the uncertainty of the ray-tracing results, the criteria used to identify MLT ducting, and the evidence linking the multi-station OH wave observations to the same CGW system. I recommend minor revision.

Overall, this is a scientifically interesting contribution with a valuable multi-instrument dataset. The required revisions are mainly related to clarity, reproducibility, and wording rather than the main conclusions.

Specific Comments

1. The phrases “first large-scale detection” and “largest documented sprite outbreak observed from China” should be made consistent.

Reply:

Thank you for pointing this out. We have reworded the sentence about the sprite outbreak to make clear that it was detected from China, not that the storm occurred there: “This event represented the first large-scale detection from China of a massive red sprite outbreak.”

2. Please provide uncertainties for the 260–280 m s⁻¹ phase speeds, or describe the main error sources.

Reply:

Thank you for this comment. The 260–280 m s⁻¹ range itself is the phase speed uncertainty. This spread comes directly from the wave’s propagation evolution: closer

to the source, the wave has a shorter wavelength and lower speed; farther away, the wavelength stretches and phase speed increases.

3. The inferred source altitude near 150 km should be accompanied by an uncertainty range or a brief explanation of ray-tracing sensitivity.

Reply:

Thank you for this suggestion. We have added shaded boxes to Fig. 14b,c to indicate the broad region where the reverse-ray trajectories approach one another (approximately 30–36°N, 88–98°E, and 115–155 km).

4. Please explain more clearly why the OH wave packets observed at Lhasa, Xining, and Xinglong are identified as the same wave system.

Reply:

Thank you for pointing this out. To examine whether other thunderstorms or potential sources could have contributed to the waves observed at this remote distance, we inspected multi-temporal FY-4A/AGRI 10.8 μm brightness temperature images over the region between the source area and the observing stations, as shown in the newly added Figure R. The satellite observations show that the dominant deep convection was concentrated near the identified source region. Some quasi-stationary cold/patchy features are present over the Tibetan Plateau, likely associated with high terrain, cold surface emission, and/or terrain-locked clouds. However, they are much weaker and less organized than the deep convective system south of the Himalayas, and no comparable cold cloud-top system is evident along the inferred propagation corridor after 16 UTC. We have added this clarification and the supporting satellite analysis in the revised manuscript.

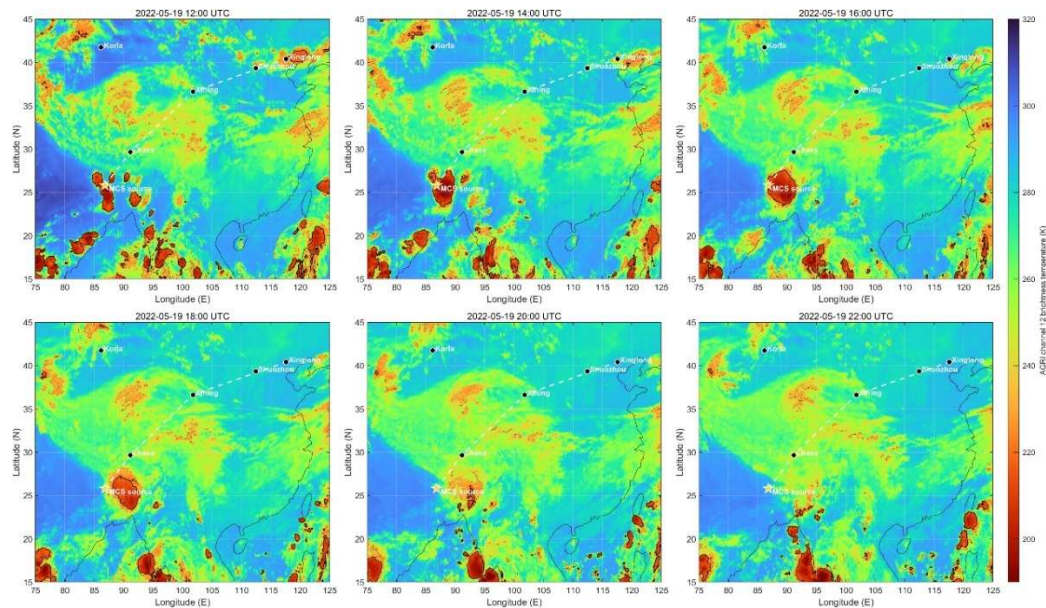


Figure R FY-4A/AGRI 10.8 μm brightness temperature images from 12:00 to 22:00 UTC on 19 May 2022. The yellow star marks the convective source region, and the white dashed line indicates

the inferred propagation path toward the airglow stations. Dark red contours denote cold cloud tops associated with deep convection.

5. The ducting analysis should clearly state the criterion used for identifying ducting layers and whether the background wind is projected along the propagation direction.

Reply:

Thank you for this comment. We have clarified how the ducting layers are identified from Fig. 10 (Fig. 9 in the original manuscript). The squared vertical wavenumber m^2 is calculated from the gravity-wave dispersion relation using the observed wave parameters, SABER temperature profiles, and SD-WACCM-X background winds. Positive m^2 indicates vertically propagating conditions, whereas negative m^2 indicates evanescence. We therefore identify potential ducting layers as positive m^2 regions bounded above and below by evanescent regions.

During the entire propagation process, the background wind is not uniformly projected along the wave propagation direction. In some regions, the local background wind vector is nearly perpendicular to the wave's propagation direction. In other regions where the background wind component is roughly parallel to the local wave propagation path.

6. The physical meaning of Fig. 13 should be explained more clearly, especially why the hatched regions imply that gravity waves cannot continue vertical propagation.

Reply:

Thank you for your feedback. Here is the concise version: The shaded region in Fig. 13 marks the range where the horizontal phase speed of internal gravity waves approaches or exceeds the local speed of sound. In this regime, vertical wave propagation is physically blocked, as the vertical energy transfer of these buoyancy-restored waves cannot exceed the local sound speed.

7. Please provide more details on the reverse ray-tracing method, including initial conditions, background fields, integration settings, and stopping criteria.

Reply:

Thank you for your suggestion. We use a fourth-order Runge–Kutta scheme with a 100 m maximum spatial step to integrate the ray equations backward in time. Initial conditions come from OI 630.0 nm airglow observations, TIE-GCM provides the background wind field, and integration stops when $m^2 < 0$.

8. The word “simultaneous” should be used carefully, since AIRS, TLE, and airglow observations occur at different times during the event.

Reply:

Thank you for pointing out this important wording issue. We have carefully reviewed all uses of “simultaneous” in the manuscript, removed this inaccurate term, and added

a clear note in the text to explicitly state that AIRS, TLE, and airglow observations were obtained at different times during the event.

Technical Corrections

1. Line 120: change “between ~50 and500 km” to “between ~50 and 500 km”.

Reply:

Thank you for pointing out this formatting error. We have corrected it to “between ~50 and 500 km” in Line 120 of the revised manuscript.

2. Fig. 4 caption: “Aqua/ARIS” should be “Aqua/AIRS”.

Reply:

Thank you for pointing out this typo. We have corrected “Aqua/ARIS” to “Aqua/AIRS” in the caption of Fig. 4 in the revised manuscript.

3. Fig. 7 caption: “CGWS” should be “CGWs”.

Reply:

Thank you for pointing this out. We have corrected “CGWS” to “CGWs” in the caption of Fig. 7, and have checked the rest of the manuscript to ensure consistent usage of the abbreviation.

4. Fig. 11 caption: “TIEGCM” should be “TIE-GCM”.

Reply:

Thank you for pointing out this inconsistency. We have corrected “TIEGCM” to “TIE-GCM” in the caption of Figure 11 as suggested.

5. Section 3.5.2: “themosphere” should be “thermosphere”.

Reply:

We sincerely thank the reviewer for the careful reading. As suggested, we have corrected “themosphere” to “thermosphere” in Section 4.3 of the revised manuscript.

6. “Prandtlnumber” should be “Prandtl number”.

Reply:

Thank you for pointing out this typo. We have corrected “Prandtlnumber” to “Prandtl number” in the revised manuscript.

7. Remove the extra space in “[https://user.eumetsat.int /data-access/eumetview](https://user.eumetsat.int/data-access/eumetview)”.

Reply:

Thank you for the suggestion. In the revised manuscript, we have replaced the

Meteosat/SEVIRI imagery with FY-4A/AGRI imagery, which provides more suitable coverage for monitoring the convective system investigated in this study and the surrounding region.

8. Please verify the year of Schmetz et al.; it appears inconsistent.

Reply:

We thank the reviewer for pointing out the inconsistency in the citation year. Since we have replaced the Meteosat/SEVIRI imagery with FY-4A/AGRI imagery, the reference regarding Meteosat/SEVIRI imagery, Schmetz et al. (2002), has been removed.

9. Line 433: "p were" should be "p was".

Reply:

Thank you for pointing out this grammatical error. We have corrected "p were" to "p was" in Line 433 as suggested.

10. Check DOI formatting throughout the reference list.

Reply:

Thank you for pointing this out. All DOIs in the reference list have been checked and formatted to the official CrossRef standard.

11. Figure captions should be made fully self-contained, including time, altitude, station, and symbol/color meanings where applicable.

Reply:

Thanks for this careful suggestion. Missing details including time, height, station and legend notes have been added to all figure captions.

12. Please carefully verify that the in-text citations are consistent with the reference list.

Reply:

We appreciate this reminder. A full consistency check between in-text citations and the reference list has been completed.