Review of Grandin et al., Dune aurora: Statistical survey from a citizen science database

Summary

This is an exciting and truly excellent piece of research. Dune aurora is a phenomenon which has only recently been reported in the scientific literature. This paper builds upon the earlier reports of this phenomenon by presenting the first statistical study of dune aurora. There are limited science-grade observations available at present, and the authors overcome this challenge by using citizen science observations of dune aurora. Using such observations is challenging and, barring a few points that I have highlighted within this review, the authors have met this challenge magnificently. The work is novel and exciting, and the paper is exceptionally well written. This work will be of great interest to the readers of Annales Geophysicae. On a personal note, I would like to add that I this is the most enjoyable paper which I have ever been asked to review.

However, before I can recommend publication, there are some issues that need to be addressed.

Major comments

Comment 1: Lines 69-73: Are dune aurora more than just a projection effect?

Please would you expand upon the statement "the dunes have so far remained challenging to identify from all-sky camera images" to explain why it's so tricky for scientific instruments to capture an effect which amateur aurora hunters readily observe. More importantly, your comment that dune aurora "tend to be more visible when viewed at relatively low elevations" suggests that these are not a real physical phenomenon at all, instead they are simply a projection effect. I don't believe this to be the case (as there have been previous publications on dune aurora), but please would you clarify and revise this statement?

Comment 2: Distribution of observations

Figure 2 shows that the observations were primarily made in the European sector, with a relatively small proportion coming from both North America and Australia / New Zealand. I appreciate and understand that a project which uses citizen science observations needs to use what is available, but some additional checks are needed to see how this distribution influences your results.

What concerns me is that if there is a marked difference between these locations (due to, for example, changes in driving by the lower atmosphere) then it is possible that this could be responsible for some of the patterns observed (if, for example, all of the observations of dune aurora from the southern hemisphere were in October, then removing them may change both Figure 3 and the arguments which follow from it). Figures 3-7 need to be reproduced using just the observations from Europe. If the results remain unchanged, then this gives confidence that results are robust to the mix of locations. If the results do change, then this may shed some further light onto the driving processes.

I appreciate that you don't want to add another five figures to the paper, so I suggest that the additional versions of Figure 3-7 go into appendix C (unless they show something that fundamentally changes the results).

I do not suggest repeating the study with just the north American or Australia/New Zealand samples, as it seems likely that there are insufficient observations there to give robust results.

Comment 3: Lines 90-95: Consistency in the interpretation of images

You have explained that you visually inspected all of the events. I agree that this is the best way to approach a newly-reported phenomenon which is not fully understood, however steps need to be taken to ensure consistency in the interpretation of such images. For example, some authors who have undertaken similar types of studies have done a second pass through all images to check that the same results are obtained (even if a small number of images are classified differently on the second pass). Other authors have used other approaches. Please would you explain what was done to ensure consistency and, if tests were not done, then these should be conducted.

Comment 4: Observer bias

You have correctly commented upon how human behaviour may influence your results (lines 156 – 157). However, there are two additional points that may be important:

- Amateur observers are more likely to go out to conduct observations when aurora is predicted, so it is likely that a greater number of people are observing when conditions are predicted to be disturbed.
- Once amateur observers have observed the aurora, and have been outside for a number of hours, they are likely to return their accommodation. Therefore, since dune aurora appear to be primarily associated with earlier MLTs than all aurora, dune aurora may be somewhat over-reported in the present study.

I believe that it is worth mentioning both of these points in lines 156-7, and the second of these points in the discussion.

<u>Minor comments</u>

Comment 5: Lines 12-17: Level of detail

I think that these lines of the abstract could really do with some numerical details, so that the key findings are clear within the abstract. I suggest amending these lines as follows (providing all of the statements remain justified, given my comments under 'major comments').

"We find that the vast majority (**XX %**) of dune observations take place **within XXX degrees latitude of** the equatorward boundary of the auroral oval. The majority (**XX %**) occur in the dusk sector … " etc.

Comment 6: Line 13: Clarity of text

I found the statement "in the dusk sector earlier than the peak in all auroral report distribution" to be unclear. This could be interpreted as 'dune aurora occur in the dusk sector ***and*** earlier than the peak' or 'when dune aurora occur in the dusk sector (as opposed to the dawn sector), they are earlier than the peak'. A comma after "in the dusk sector" would resolve this ambiguity.

Comment 7: Line 155: Seasonal variation

You correctly state that there are 'no events in June and July'. As this is winter in the southern hemisphere, it seems surprising that there were no reports of dune aurora from New Zealand or Australia. It would be worth commenting on this.

Comment 8: Line 172: okta

Many readers will not be familiar with this unit (I had not encountered this previously). I appreciate that an explanation is given in the first three lines of appendix B, but I think an explanation is also needed in the main part of the manuscript.

Comment 9: Lines 230-260: Results & statistics

This section of the manuscript draws comparisons between the 'dune observations' and 'all aurora observations'. I believe that this analysis would be strengthened by conducting statistical tests to show that the distribution of the 'dune observations' is not consistent with these being drawn from the 'all aurora observations' sample in each case. This a suggestion, not a requirement, as the counter-argument is that detailed statistical tests may overly complicate this section of the paper.

Comment 10: Line 296: Interpretation of Figure 7

The text states that 'both curves [the magenta and black lines in Figure 7b] are relatively close to each other'. I would disagree with this statement, as the magnitude of the gradient varies by a factor of 2. I also note that, if the data points from the southern hemisphere were not considered, the gradient of the black dotted line would change, bringing it closer to Weyland et al. (2023). I suggest that the interpretation of this plot is re-visited once comment 2 has been addressed.

Comment 11: Lines 398-405: Longitude variations

You correctly comment that the latitude of the dune aurora is within +/- 4.2 degrees of the observer. However, a similar comment is needed for the uncertainty in longitude & MLT. This is not needed for every observation (calculating it for every latitude would be somewhat tedious), but simply giving a couple of ballpark values would be sufficient. Perhaps giving a range of longitudes and MLTs for an observer at 70 GLAT and at 60 GLAT would be enough. Of course, if this range of values causes uncertainties about whether dune aurora are in the eastward or westward electrojet (Table 1), or if the uncertainty in the MLT of the observations is larger than the changes in MLT between the 'dune observations' and the 'all auroral observations' (Figure 3), then this also needs to be discussed.

Additional comment

Lines 439 – 445 discuss gravity wave activity, and the filtering of such waves. Such waves can be launched by orography, thunderstorms, fronts, baroclinic instabilities in the troposphere, volcanic eruptions, and the excitation of waves associated with the polar vortex (Fritts and Alexander, 2003). The Northern Annular Mode (NAM) index is a measure of the strength of the polar vortex (Kumar et al., 2025; Gerber and Martineau, 2018), and I wonder if a statistical link could be found between this index and the occurrence of dune aurora or whether a case study could be conducted to look for a link between dune aurora and gravity waves launched by the polar vortex. This is probably beyond the scope of the present study but, if you are interested in pursuing this idea, I would recommend contacting Corwin Wright, Neil Hindley and Juliana Jaen at the University of Bath who, in my opinion, would be exceptionally well-placed to help with this work.

References

Fritts, DC, Alexander, MJ. 2003: Gravity wave dynamics and effects in the middle atmosphere. Rev. Geophys., 41: 1003, https://doi.org/10.1029/2001RG000106

Gerber, EP and Martineau, P. 2018. Quantifying the variability of the annular modes: reanalysis uncertainty vs. sampling uncertainty, Atmos. Chem. Phys., 18: 17099–17117, https://doi.org/10.5194/acp-18-17099-2018

Kumar, A, Stolle, C, Yamazaki, Y, Pedatella, NM, Kunze, M, et al. 2025. Impact of weak and strong stratospheric polar vortices in the northern and southern hemispheres on solar-migrating semidiurnal tides in UA-ICON. J. Geophys. Res. Atmos., 130: e2025JD043550. https://doi.org/10.1029/2025JD043550

Summary

This is an excellent piece of work which will make a valuable contribution to the research field.