EGUSPHERE-2026-1030

Automated Detection of Low-altitude Isolated Mesospheric Radar Echoes Using YOLOv8: Evidence for a C-Layer Phenomenon near 60 km Altitude?

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Answers to Reviewer #2

We thank the reviewer for the valuable points addressed based on our submitted manuscript. The comments are certainly helpful in improving it for the next revision.

The authors present a statistical study of Saura radar echoes from ~58km altitude, classified using the YOLO pattern recognition tool. They argue that these echoes may be caused by ionization from galactic cosmic rays and describe the phenomenon as a potential 'C-layer'.

I found the preparation of the manuscript to be somewhat sloppy and many of its claims to be exaggerated or speculative. However, the radar detections themselves are interesting and, to my knowledge at least, novel and worthy of publication. Therefore I recommend major revisions for the paper.

We like to thank the reviewer for expressing the content being relevant for a publication and we're certainly open for improvements of the manuscript.

The authors should remove any claim of a "C-layer phenomenon" from the title and body of the manuscript. The presentation of the work should be reoriented towards the important central findings (occurrence rates, characteristics etc.) and away from process issues (choice of computer tool etc.) and speculative conclusions.

We thank the reviewer for this statement. However, for both raised points the authors believe that they are important and should be stressed. We probably didn't explain those clearly enough, and we would like to improve on that. We certainly agree that statistical parameters such as occurrence rates are important for characterising the echoes and potentially linking them (later) to a plausible cause.

Our current explanation is indeed speculative as we have not directly correlated the events with GCR, but we aimed to exclude two other possible processes, that could cause the radar echoes at the lower D-region.

The machine learning approach is employed and described to reliably detect the often weak radar echoes following an initial manual and thus time-consuming search. We aim to improve on the motivation.

Major comments:

1. Novelty claim is overstated

Previous studies cited by the authors have reported similar low-altitude reflecting layers (e.g., Rasmussen et al., 1980; Bain & Kossey, 1987). The authors should reframe the novelty as systematic detection and characterization rather than first discovery – in particular the term “first evidence” should not be used.

This criticism relates to our statement in the abstract: “To our knowledge, this study might be the first evidence of such a phenomenon through consistent radar observations.”

That was indeed too vague and imprecise. We will rephrase the statement, placing the emphasis on MF/HF radar measurements. None of the mentioned references covered observations in the MF/HF range, but only VLF/LF. Furthermore, all of them originate from bi-/multistatic observations, interpreting the interference pattern of the ground- and sky-wave. In this study, we report on monostatic (without geometric dependencies etc.) and altitudes purely based on echo runtime. It has now become clear to us that we need to back up this argument.

1. Physical interpretation is speculative

The proposed link to galactic cosmic rays is not sufficiently supported. Correlations with solar flux are weak and no quantitative ionization modeling is presented.

We agree, that the link to galactic cosmic rays is speculative and indirect and we tried to phrase it like that. The correlation of the detection of the echoes under investigation to the solar flux indeed is weak, since - to our understanding - they are not primarily caused by solar radiation.

The D region is formed by Lyman alpha radiation ionising NO, whose extend changes with local time depending on the solar zenith angle. The echo intensity basically increases with altitude as the electron density and thus the possible gradients increase.

Lyman alpha is normally not able to ionize at these low altitudes at a high latitude (69°N). This is why we also observe a clear gap in the observations between the EUV ionised D region and the LIME near 58 km. We actually use this gap as a prerequisite for the detection.

We directly exclude energetic particle precipitation (EPP) as a cause by removing EPP-events from the data.

Furthermore, X-rays could be a possible cause of ionisation, but it is certainly unlikely that such frequent and continuous X-ray exposure would occur over several hours. This would also coincide with enhanced solar flux, which, however, is not observed.

Furthermore, if ionisation was caused by X-rays, the entire D region would be affected, resulting in weak or even absent echoes in the upper D region, which contradicts our observations.

At this stage of the study no dedicated modelling efforts are undertaken, as this manuscript is meant to report on the observations only, providing the initial occurrence statistics and separating these from other sorts of radar echoes seen at near 60 km.

Considering e.g. FIRI model, the typical maximum electron densities at polar latitudes near 60 km is around 1-5*10^7 / m^3. Observations tend to show the same density for noontime (Renkwitz et al, 2023). Our current speculation is, that we basically filtered these faint LIME for the electron density estimations in the just mentioned article, as we rejected non-plausible values at lower altitudes of the profiles. Neither FIRI nor any other model we are aware of suggests a more or less pronounced enhancement near 60km, which could explain our observations.

We currently work on modelling processes that might explain the required ionisations, but this will still need time and is meant for a subsequent publication.

1. Single-instrument limitation

All results rely on one radar system, limiting generalizability. How do these results compare to VLF/LF data, or to data from optical/other instruments? A 3 MHz plasma layer (equivalent to 10^5 el. m-3) should be easily visible using ionosonde data, with suitable processing. Particle or FUV data (see e.g. DMSP) could be used to test for energetic precipitation.

That is indeed correct, and somewhat regrettable. For this publication, we analysed data exclusively from the Saura PRR and, have not yet been able to find any clear evidence that the radar echoes in question were also detected by other instruments. Suitable candidates that might be capable are the radars in Saskatoon/Canada, Buckland Park/Australia, Christchurch/New Zealand and Juliusruh/Germany. For the latter (Juliusruh), we have not yet found any evidence of the radar echoes we are reporting here for Saura. One limitation might be the smaller antenna array and thus wider beam and less power density. Ignoring other effects like noise and geographic location, with the low signal-to-noise ratio we might simply not be able to see it with the Juliusruh system.

We're not sure which other data from VLF/LF is meant? Ideally, we would need altitude profiles of VLF/LF soundings to compare it to our measurements. The only known examples are given in the references (another corresponding one will be added in the revised version) and even those are not for mono-static measurements, which might also introduce additional uncertainties. The use of VLF/LF receivers to monitor existing transmitters over very long distances in order to infer the electron density profile is still in the research phase and is inherently challenging, as it involves an integrated process spanning hundreds or thousands of kilometers.

The mentioned density of 10^5 el./m^3 is very small and practically below the threshold of our radar system (Renkwitz et al., 2023). For the observed signal-to-noise ratio we likely require at least one magnitude above that, even for partial reflection.

For a total reflection the required electron density corresponding to a plasma frequency of 3.17 MHz is approximately 1.25*10^11 electrons /m^3. This is far above the observed values for such altitudes (Renkwitz et al., 2023) and rather typical for the E region.

To our knowledge there is likely no ionosonde that can measure at such altitudes (60km or below), given that they typically need to use long codes to compensate for the low peak pulse power and small transmit and receiving antennas. E.g.  16x33us = 533us ~ 80 km range.

For the same reasons ionosondes rely on total reflection as this process is much more efficient, but the plasma frequency is way too small for the typically used sounding frequencies (below 30 kHz for 10^7 el./m^3).

We appreciate the idea of investigating particle data. This would indeed be interesting and also addressing the subsequent point of specific energy distributions of EPP events.

1. Alternative explanations

Other mechanisms (e.g., turbulence, gravity waves) are not sufficiently explored. How do we know this scattering is really caused by ionization, and that the ionization is unrelated to energetic particle precipitation? Could it be mono-energetic precipitation?

We certainly do not rule out any contribution of dynamics, they may actually be important for the species that are ionized. This however is far out of the scope of this manuscript, but we aim for a subsequent manuscript proposing a model-based explanation.

The radar echoes we observe are caused by partial reflection, for this to occur, there must be a sufficient gradient of electrons density per unit volume. Turbulence and also atmospheric gravity and other waves (tidal etc.) are certainly present. The observed spectral width enhancements during October might indeed be an indication for enhanced turbulence and if that's reliable will open a new valuable dataset by itself.

However, none of these processes likely is the primary cause of the observed radar echoes, but their imprint is likely visible.

Mono-energetic precipitation indeed might form layers at specific altitudes. The question is how frequently and continuously such scenarios can occur. From our previous and ongoing studies (Renkwitz et al., 2017) we experience a rather wide range of energies, that then affect the entire altitude range from 60 km, or partly below, up to 90 km. EPP of sufficient energy to reach 60 km altitude will create substantial ionisation, which then causes excessive absorption of the radar wave at the altitudes above 70 km (see Fig. 13b). Such absorption events are then seen as thin virtual layers (Renkwitz et al., 2017, or Hall et al., 2006).

In this study we actually explicitly remove EPP events to not mix the two different sorts of radar echoes. The here discussed LIME are not related to EPP and they can even be easily distinguished as EPP-related echoes showing a very different and parabola-shaped time series spectrum (see Fig. 13b).

Minor comments:

- why was a ~63-km layer chosen for Fig 1a when the abstract claims most of these are ~58 km? The claim in the abstract should be rephrased in terms of mean and standard deviation of the LIME detection altitude – Fig 9 makes it clear that a relatively broad range of altitudes is present.

This example has been chosen as it is one of the strongest events and with the longest duration. Furthermore, it nicely depicts the separation to the regular D region echoes.

We understand the concern as it might be rather a special event than a typical example. We'll replace this example with a more typical scenario.

In our abstract is mentioned "The preferred altitude of these radar echoes is found to be near 58 km with typically little variability,..." With that we're not claiming most of events are seen at 58 km. We will rephrase this statement and also add the spread of the altitude distribution to the abstract.

- What do the authors make of the apparent October-March (and then June-August) concentration of detections, in terms of physical mechanisms? Doesn't it look like two separate phenomena, considering also the spectral width variation? If so, maybe two terms are needed rather than just "LIME" for both?

That indeed is a very good catch and interesting point. As mentioned in a previous point, we hypothesise the detected larger width during October are connected to enhanced turbulence at these altitudes. Please note, the shown width are the detection box widths, not the accurate spectral width of the echoes for each individual altitude. The shown widths therefore tend to represent an overestimation. We intend to analyse the spectral width of every detection more carefully in a subsequent study together with multi-beam data and modelling.

We will incorporate the addressed points in the revised version.

Above mentioned reference to 60km radar echoes at ~3MHz radar frequency, which are caused by EPP / solar proton events.

Hall, C. M., A. H. Manson, C. E. Meek, and S. Nozawa (2006), Isolated lower mesospheric echoes seen by medium frequency radar at 70° N, 19° E, *Atmos. Chem. Phys.*, 6, 5307–5314, doi:10.5194/acp-6-5307-2006.