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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 #1

We like to thank the reviewer for the thorough reading of the manuscript and also suggesting many possible improvements. This is certainly much appreciated.

This paper describes an automated deep learning approach for the detection of faint echoes at altitudes below the D-region as observed by the Saura HF radar. The authors used the pattern recognition tool YOLO (You Only Look Once) to derive statistical information on the occurrence of these radar echoes over four years of radar measurements. The preferred altitude of these radar echoes is found to be near 58 km, with substantial annual variability in the detection rate and altitude and spectral width parameters.

The paper is of significant interest to the ionospheric physics community but requires substantial revision to be acceptable for publication. The main issues are:

- There is no reference to any previous MF/HF radar measurements of similar low altitude layers.
- The explanation of the deep learning approach contains a lot of jargon which will not mean much to readers unfamiliar with the field. More explanations of the terms used are required.
- The English needs improving in some sections.

It is also peculiar that the authors reference the hypothetical “C-layer” in the title but do mention this layer at all in the article.

That is indeed true and been intentional, but perhaps not advantageous. We so far only used this term in the title to refer to previous publications and make the article more visible. We’re far from defining or justifying the term C-layer, a potentially useful designation might also be “lower D-layer”, similar to F1 in the F-region.

We agree, that this should have been explained more clearly and discussed within the discussion or conclusions sections. We will modify this accordingly for a revised version.

My review is divided into two sections. The first section includes issues that the authors need to address before the article is acceptable for publication. The second section includes suggested changes that will improve the readability of the article.

Issues to address

- In the abstract the authors state "this study might be the first evidence of such a phenomenon through consistent radar observations." While it is true that these results represent the first long-term measurements of layered phenomena around 60 km, layers around this altitude have been reported previously by other authors. For instance, *Hocking, W.K. and Vincent, R.A., 1982. Comparative observations of D region HF partial reflections at 2 and 6 MHz. Journal of Geophysical Research: Space Physics, 87(A9), pp.7615-7624*, shows persistent layers at 62 km at 2 MHz (Figure 2). Furthermore, *Holdsworth, D.A. and Reid, I.M., 1997. An investigation of biases in the full correlation analysis technique. Advances in Space Research, 20(6), pp.1269-1272, show a five-hour averaged SNR profile with a peak at around 57 km (Figure 4)*. There may well be other such example from early MF radar observations made in Saskatoon, Canada and Christchurch, New Zealand. I suggest the authors conduct a thorough search and acknowledge such observations in their article.

We admit that we have been reticent with other MF/HF radar references, but this is primarily because we are not convinced that we can identify the same radar echoes in these manuscripts. However, we should have supplemented the introduction with additional examples of radar observations at an altitude of approximately 60 km. While radar observations at an altitude of about 60 km are not rare, they generally reflect the continuous stratification within the D-layer, which extends, for example, from 60 km to 90 km. This 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. We realized this needs to be improved in the introduction.

In addition to Lyman-alpha radiation, energetic particle precipitation (EPP) can rapidly increase ionization in the D region and near the 60 km altitude in the polar region. Such events appear most frequently for the descending phase of a solar maximum and during spring and autumn period.

In Hocking, W.K. and Vincent, R.A., 1982, there is indeed an enhancement of detected power near 62 km, however, the corresponding statement of the authors is not supportive for this study. “The peak at 62 km for 2 MHz is a ground echo effect.“

In Holdsworth, D.A. and Reid, I.M., 1997, are indeed also shown enhanced intensities between 52 and 60 km in the 5 h averaged profiles. It seems difficult to interpret this enhancement as originating from the same type of radar echoes. The local minima in the power and SNR profile at 60 km also does not exceed the receiver’s background noise, as can be seen at 50 km. In fact, the temporal progression and, of course, observations over several days could provide some insight, but this is not presented in the paper.

Nevertheless, we should have mentioned this paper in the references as a possible candidate.

The specialty of the radar echoes described in our manuscript is, that these echoes are clearly separated from the ordinary D region echoes. This means the detected echo power above LIME literally drops to the receiver’s background noise similar to what is seen near or below 50 km. We will make this more prominent in the description.

We keep searching for other references, where possible other detections are shown.

- Lines 328 and 358, The authors need to provide more evidence regarding their claim that “GCR represent a significant ionisation source for altitudes just below 60 km during solar minimum years”. This conclusion seems to be made solely on the results of Figure 14. While there appears to be an inverse correlation between sunspot number (i.e. solar cycle) and the detection of LIME, and there is a well-established inverse correlation sunspot number and the detection of GCRs, this does not imply GCRs are responsible for LIME. Correlation is not the same as causation. Having said that, I suspect the authors are likely correct, but the evidence presented is somewhat circumstantial. I strongly suggest the authors introduce the word “may” into the sentences on lines 328 and 358 – e.g. “which suggests GCR **may** represent a significant…”

We agree with the reviewer, the link to the GCR flux is essentially speculative due to the weak correlation with solar flux, but it still appears to be the best explanation so far. We will look for GCR-related time series to include in Fig. 14. It is possible that even the correlation between the GCR and LIME will not be convincing without further dynamics and chemistry modeling.

We’ll rephrase the corresponding statement as suggested.

- The authors frequently use the term “bottomside of the ionosphere” to describe the altitude region of interest. This is a misuse of the term, which is typically used to describe the entire ionosphere below the peak of the F-region electron density (hmF2). I strongly recommend the authors replace "bottomside of the ionosphere" with something like "lower ionosphere" or maybe "lower D-region".

We thank for this clarification. With the statement we indeed did not mean the entire D, E, F regions. We will rephrase this formulation.

- Line 69, "4-bit-complementary codes are frequently used to increase the average power". This is incorrect. Complementary codes increase signal-to-noise (SNR) ratio and hence detectability, but they do not increase signal power.

Well, both is correct. On the transmit side, e.g. 4 times the power is used instead of a single pulse of the same range resolution, so the average power is enhanced. For reception, it's correct, the detectability is improved as the random noise or non-matching signals are suppressed. We'll add this to the description.

- Line 227, "The detections above 70 km appear to be outliers possibly caused by interference." Is this the same kind of narrow-band interference that is seen at a Doppler shift of -0.35 in Figure 7. If so, it may be worth pointing this out so the reader can see what the interfering signals look like.

This statement was indeed a bit superficial and we investigated detections near 70 km. Some of them were EPP-related echoes, others actually don't show the typical parabolic EPP image power spectra. The latter were often short-lived and near zero Doppler shift, making them difficult to interpret.

- Line 255, "While the quasi-simultaneous precipitation of similar energies occurs, and thus corresponding altitudes". I don't understand what the authors mean by this. I strongly suggest this sentence is re-written to make it clearer.

We've indeed been too quick on this. To form layers at specific altitudes by EPP, a fairly narrow band of energies will be needed. Furthermore, it is unlikely that such events occur only in very localized areas, but rather simultaneously across an area of several tens of km. The superposition of this then allows to form the parabola-shaped echoes in the altitude spectra.

Furthermore, such intense ionisation leads to significant absorption of the radar wave, resulting in echoes from the upper D-layer being very faint or invisible. This was referred to as "virtual layers" in Renkwitz et al., 2017.

We'll rephrase this statement.