Response to Reviewer 1:

We thank the reviewer for the constructive and helpful comments, which helped us to improve the manuscript. We took all comments into account when revising the manuscript. In the text below we describe the modifications and list our responses together with the reviewer's comments that are repeated here in blue color. Our answers are given in black.

This a quite interesting study of PMSE layers and should be published in AnGeo after suitable corrections are made. I have very little questions concerning the observations. This was done quite well. However I do have some comments/questions about the conclusions and implied physical causes.

Comments

1- Title. It would be best to spell out PMSE for the readers of AnGeo. I suspect that many of the readership will not know what that is. Also since you have a strong focus on multilayers, perhaps a better title would be "Polar Mesospheric Summer Echo (PMSE) Multilayer Properties During Solar Maximum and Solar Minimum"? Something like that?

We agree that it would make sense to emphasize the multilayer aspect of the study in the title, and to spell out the acronym "PMSE". The title was modified accordingly to the reviewer's comment in the following way:

«Polar Mesospheric Summer Echo (PMSE) Multilayer Properties During Solar Maximum and Solar Minimum»

2- Since you have invoked particle precipitation as a possible source for the radar wave scattering, you should mention that the magnetic latitude of Tromso. I believe it is 67 degrees. The geographic latitude is 69 deg, but for particle precipitation, the magnetic latitude is more important. The "auroral zone" is 60 to 70 deg magnetic latitude, so your observations have been taken in the center of it. During relatively quiet intervals the auroral precipitation occurs in the auroral zone. During solar maximum and during storms the precipitation is at slightly lower magnetic latitudes, as low as 55 deg. The greatest auroral precipitation is now known to occur in the declining phase of the solar cycle associated with high speed solar wind streams. A reference to this can be found in JGR, 100, A11, 21717, 1995. This precipitation occurs in the auroral zone. I think what you have stated about precipitation during solar max and solar min is okay as is. However I point out some of the subtleties for your information.

Thank you for sharing this very interesting information and providing a deeper understanding of the relationship between the phases of the solar cycle and auroral precipitation. We have incorporated additional details in the manuscript with the following sentence:

«The geographical coordinates of the EISCAT VHF radar are 69°35′N and 19°14′E; its geomagnetic latitude and longitude are respectively 66.73° and 102.18°.»

3- During solar maximum there is more EUV radiation. Depending on season, perhaps that can be a cause for greater electron densities during solar maximum? Also could solar heating expand the atmosphere slightly giving you your height difference during solar maximum? Please discuss in the body of the text.

The solar maximum phase is characterized by an increased number of sunspots and higher levels of EUV radiation compared to the solar minimum phase. This EUV radiation has impacts on various parameters in the atmosphere, including temperature (as mentioned by the reviewer), water vapor content, electron density, maybe also atmospheric circulation, and gravity wave activity. Given all these parameters, it is challenging to determine with certainty how the mesosphere would behave during solar maximum when there is a greater amount of EUV radiation. We now have included the sunspot number and the F10.7 index in Table 1. Here is the new Table 1 :

	F10.7 cm Flux	Sunspot Number	Year	Date	Start time	End time	Observation Hours per Day	Observation Hours per Year	Observation Hours per Solar Max. or Min.	Total of Observation Hours
Solar Maximum	9.95000e-21	90.9	2013	27/06/2013	07h02m	10h58m	03h56m	57h52m	130h18m	230h32m
	1.01000e-20	90.9		28/06/2013	07h02m	12h58m	05h56m			
	1.19900e-20	94.6		09/07/2013	00h00m	00h00m	24h00m			
	1.17900e-20	94.6		10/07/2013	00h00m	00h00m	24h00m			
	9.91000e-21	112.6	2014	23/07/2014	00h00m	09h26m	09h26m	09h26m		
	1.01000e-20	68.3	2015	15/07/2015	08h00m	00h00m	16h00m	63h00m		
	9.96000e-21	68.3		16/07/2015	00h00m	00h00m	24h00m			
	9.74000e-21	68.3		17/07/2015	00h00m	23h00m	23h00m			
Solar Minimum	6.70000e-21	3.7	2019	18/06/2019	06h59m	00h00m	17h00m	59h13m	100h14m	
	6.80000e-21	3.7		19/06/2019	00h00m	12h59m	12h59m			
	6.80000e-21	3.5		04/07/2019	07h07m	12h21m	05h14m			
	6.70000e-21	3.4		20/08/2019	00h00m	00h00m	24h00m			
	6.90000e-21	9.0	2020	06/07/2020	07h58m	09h08m	01h06m	41h01m		
	6.80000e-21	9.0		07/07/2020	00h00m	11h59m	11h59m			
	6.70000e-21	9.0		08/07/2020	00h00m	11h59m	11h59m			
	6.90000e-21	9.0		09/07/2020	00h00m	11h58m	11h58m			
	6.90000e-21	9.0		10/07/2020	08h00m	11h59m	03h59m			

Moreover, Figure 2.7 from the "Handbook of physics and space environment" by Adolph S. Jursa (https://www.cnofs.org/Handbook_of_Geophysics_1985/Handbook.pdf) shows that except for Lyman alpha, all solar UV shorter than 170 nm is absorbed above 100 km. There is not much EUV radiation left at our specific altitudes of interest (80 to 90/92 km).

Furthermore, the results from the study by Zhao et al., (https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020JD032418) indicate that despite the mesopause temperature's high sensitivity to solar radiation (as shown in Figure 6b of Zhao, 2020), the temperature has been decreasing over the 18 years of observation used in the study (ranging up to −0.14 K/year). (Also, in Figure 6a, the author specifies the corresponding error bars to the values shown in Figure 6b, which are large). Additionally, the mesosphere's altitude has also been decreasing over time at our latitude of interest (Figure 8a from Zhao, 2020). The study by Zhao et al. (2020) suggests that the declining mesopause reflects the contraction effect at lower altitudes caused by cooling from greenhouse gases, as discussed in other studies (Lübken et al., 2013; She et al., 2019; Yuan et al., 2019).

Considering these factors, the higher levels of EUV radiation alone cannot explain the higher mean altitude of PMSE layers during solar maximum. Further investigations, comparing the next solar maximum to the previous one, would be necessary. Additionally, it is important to note that again, this is a complex question with multiple parameters that vary with changing EUV radiation levels. This is discussed now in section 3.1 of the revised manuscript, accordingly to the reviewer's comment.

4- Abstract, lines 12-13. I don't see much evidence in your paper for gravity wave generation of the multilayers. In Figures 1 and 2, I can see evidence for a two multilayer form evolving into a monolayer. How can that be explained by gravity wavelength separation? From that description one would expect these multilayers to be separated equidistantly. My suggest is to point this out to the readership and stay with the observations. If you do have cases of say 3 or 4 layers, please add a figure and show an example of these for the readership. Are they separated equidistantly? Some discussion would help. But from what I have seen so far, I would say that gravity waves are not the answer.

We are not attempting to provide a comprehensive explanation for the formation of multi layers using gravity waves. Instead, we mention a study conducted by (Li 2016), where they developed a model and varied the vertical wavelength of gravity waves. Interestingly, their findings indicated that as the number of layers increased, those layers tended to become thinner, with smaller wavelengths. In our own study, we observed a similar trend where an increase in the number of multi layers corresponded to thinner layers. As a result, we speculated that gravity waves might play a role in this phenomenon, although we did not state that they were a certain explanation. It is crucial to note that the study by (Li 2016) only modeled a single gravity wave, meaning there was only one wavelength considered. In reality, there are numerous gravity waves with varying wavelengths, making it more complex to determine the layer spacing (equidistant or not). Additionally, in (Li et al., 2016)'s study, the particle size was held constant while the vertical wavelength was varying, whereas in reality, we encounter a wide range of particle sizes. Therefore, the relationship between gravity waves and the formation of multi layers is not as straightforward.

5- Introduction. I have not seen any mention of metallic ions at ~92 km altitude which I believe come from the decomposition of micrometeoroids? Could these be the nuclei of water condensation? Can you add this to the discussion?

In our discussion, we mentioned that Meteoric Smoke Particles (MSPs) are the potential nucleation centers for ice particles. There are several other species discussed as possible nuclei for the ice particle formation and the work by Rapp and Thomas (2005) provides an overview. We are unaware of metallic ions serving as nucleation centers for ice particles. Based on the discussion by Rapp and Thomas, we speculate that metallic ions are possibly too small to start the nucleation process. Another limitation could be that the layers at 92 km would usually be well above the temperature minimum where frost temperatures are reached. Nevertheless, this is an interesting topic for future studies. The manuscript has been revised with more careful wording in accordance with the reviewer's comments.

"Meteor Smoke Particles (MSP), produced by meteor ablation and recondensation have been proposed as potential condensation nuclei along with several other potential nuclei (cg. Rapp and Thomas 2005). In addition to nucleation centers, the presence of cold temperatures and water vapor at mid and high latitudes at the mesopause during the summer months creates conditions favorable for ice particle formation Avaste (1993). Cold temperatures and water ice are known to be at the origin of another phenomenon called Noctilucent Clouds (NLC) Latteck et al. (2021)."

6- Line 19, your first sentence in the Introduction. A review paper on PMSE should be referenced here for the readership. Or if one does not exist, perhaps the discovery paper.

The manuscript has been updated accordingly to the reviewer's comment and the review paper on PMSE from Rapp and Lübken 2004 has been added as a reference in the introduction.

7- Line 46-47. I think perhaps you should mention solar EUV being stronger here during solar maximum? Of course in your data selection I do not know if you have chosen times when the ionosphere over Tromso was sunlit or not. Perhaps a mixture?

In response to the reviewer's question, the time period we selected for our data falls between June and August in Tromsø. During this time, daylight is almost always present. However, it is important to note that our study does not specifically focus on EUV. Therefore, detailing the amount of EUV during our chosen observation times is not what we want to focus on. Instead, we examine the level or background ionization, and we use the electron density at 92 km altitude as a proxy. Our main objective is not to determine the specific causes of ionization, such as particle precipitation or EUV (which goes beyond the scope of our study), but just to have a proxy for the ionization level in general. This point has been now clarified in the revised manuscript.

8- Line 86. Gravity wave breaking. If gravity waves break near the altitude of your study, that will go against the idea of the separation of the multilayers of PMSE by gravity wave wavelengths. So you will need to chose one route or the other. Gravity wave breaking needs a reference. I have talked to an expert on this topic fairly recently and this person speculated that there was no such thing as gravity wave breaking. That the gravity waves evolved into multiple waves instead. So please be careful.

We agree that although it is believed that gravity waves will eventually break as the air becomes less dense at higher altitudes and the wave amplitudes increase; atmospheric dynamics are more complex, and we should not speculate on that in our paper. In order to comply with the reviewer's request, we now refer to a recent publication by Fritts et al. (2019) that presents new observations together with a description of the open questions in this area. (https://doi.org/10.1029/2019JD030298).

9- Line 102. Please give the location of the Magridal website. I do not see it in the acknowledgement section?

The link to the Madrigal website is in the "Data availability" section, instead of the "Acknowledgements" section.

10- Line 104. What is a "manda code"? Please explain to the readership.

Further information has been provided in the manuscript about the 'Manda' code, accordingly to the reviewer's comment:

"The EISCAT VHF radar utilizes many different experimental modes to collect data. The utilized pulse coding for the PMSE measurements we analyzed is referred to as 'Manda'. Detailed information regarding this coding can be found on the EISCAT website (https://eiscat.se/scientist/document/experiments/). For this study, we specifically analyzed data obtained using the 'Manda' code, because it is designed to detect low-altitude signals and layers in the mesosphere."

General Comment for the beginning of the paper. Much of this background material could be put into the Discussion and Conclusion Section. It would be good to shorten the front end of the paper and get to your analyses and results first. Then afterwards compare your results to theory and modeling.

Changes have been made accordingly to the reviewer's comment.

11- Lines 148. Please give references to Pearson and Spearman.

The references regarding the Pearson and the Spearman correlation coefficients have been added to the manuscript, accordingly to the reviewer's comment. Here is the updated version:

"In order to investigate different PMSE properties, we use the Pearson correlation coefficient and the Spearman's rank correlation coefficient to calculate the correlations between the different parameters, Wilks (1995), Myers and Well (2003)."

12- Figure 2. I have already made comments about Figure 2 (and Figure 1).

The reviewer's comments about this point were answered in question 4.

13- Figures 3, 4 and 5. The height distributions in all 3 of these histograms are quite broad. Compared to the small distances between the mean locations, I would draw the conclusion that there are no differences. Please discuss. You still can say that there are small differences but they may not be statistically significant. I doubt that the mean differences are statistically significant.

To answer the reviewer's comment about the statistical significance of the altitude values of the different layers, we calculated the p-values for all the combinations of all the layers. For our analysis, we used the most common significance level i.e., 0.05 (5%). The results are listed in Table A1 in the appendix. As the reviewer mentioned, some mean values can be very close to each other, indicating a p-value greater than 0.05, and some means are statistically different at 95% confidence, indicating a p-value less than or equal to 0.05. We now have computed p-values for all combinations of layers and parameters presented in our Figures (altitude distribution, electron density distribution, echo power distribution, and thickness of layers distribution). These p-values are listed in a new Table A1. In the table below, we have included only the pertinent column, specifically the p-values related to the altitude distribution, to address the reviewer's comment.

SOL MAX	P- value
Layers 1-2	P = 0.6462
Layers 1-3	P < 0.0001
Layers 1-4	P = 0.0002
Layers 2-3	P < 0.0001
Layers 2-4	P = 0.0014
Layers 3-4	P = 0.8035
SOL MIN	**P- value**
Layers 1-2	P = 0.6808
Layers 1-3	P = 0.1098
Layers 1-4	P = 0.3030
Layers 2-3	P = 0.0481
Layers 2-4	P = 0.2284
Layers 3-4	P = 1.0000
ALL LAYERS	**P- value**
Sol Max-Min	P < 0.0001

Additionally, we made some adjustments to the altitude distribution histograms (Figures 3, 4, and 5) by using smaller bins. The original EISCAT data we used have an altitude resolution of 360 m, so we chose this value as the new bin size on the x-axis, compared to the previous 1 km bins. Our focus is on the altitude range between 80 and 90 km. Within this range, we are examining the presence of PMSE multi layers. Given that we are describing up to 4 layers within this 10 km range and the altitude resolution of the data is 360 m, it can lead to the p-values often vary in terms of statistical significance. We selected the Manda code available in the EISCAT VHF radar data because it provides access to simultaneous measurements of the electron density above the PMSE, giving us insights into the general level of ionization. Also, the observations with Manda code give us the best resolution at altitudes of interest, out of the archived EISCAT VHF data. However, it could be valuable to explore the use of a different radars and/or codes with better resolution at PMSE altitudes in future studies of PMSE multi layers. Here are the new Figures 3, 4 and 5:

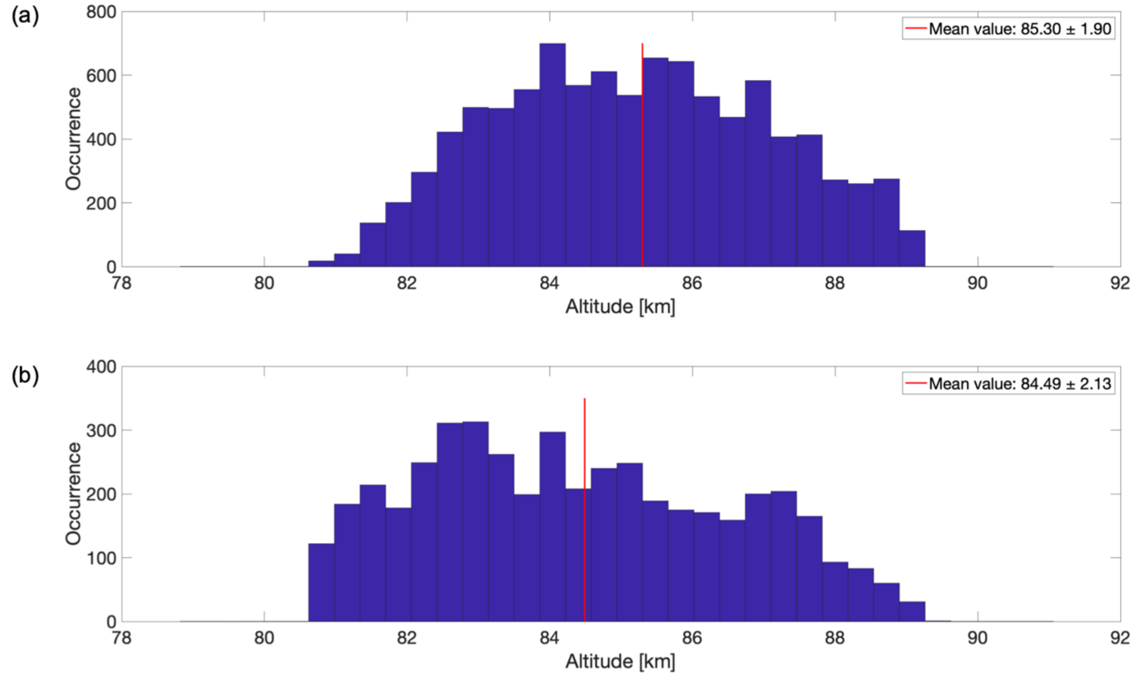

*Figure 3: Altitude distribution of the data for the **(a)** solar maximum and **(b)** solar minimum. Each subplot was its respective mean altitude represented with a red line on the graph, and specified in the legend together with one standard deviation.*

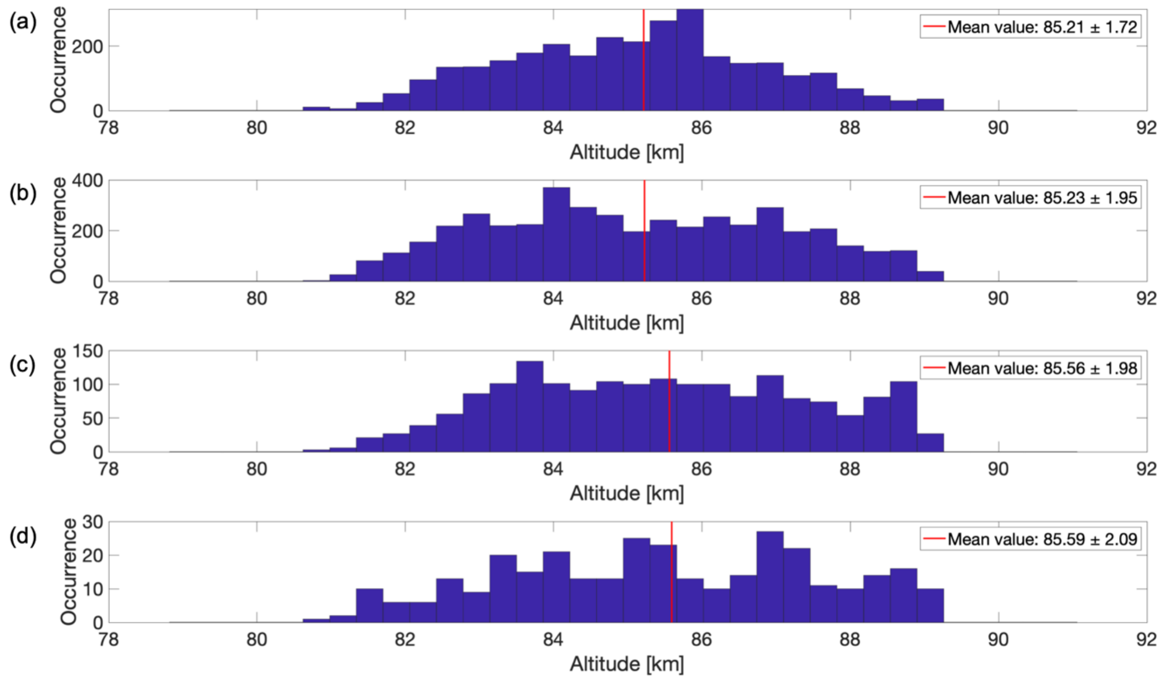

*Figure 4: Altitude distribution of the data during solar maximum for **(a)** mono layers, **(b)** multi layers with 2 layers, **(c)** multi layers with 3 layers, and **(d)** multi layers with 4 layers. Each subplot was its respective mean altitude represented with a red line on the graph, and specified in the legend together with one standard deviation.*

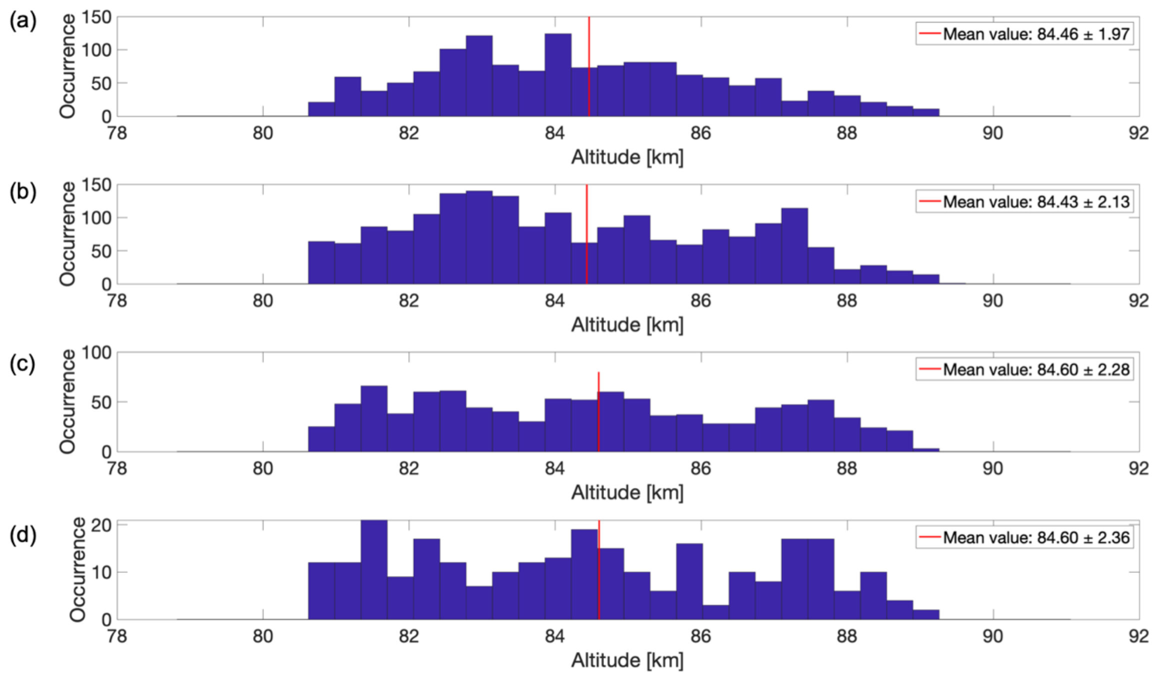

Figure 5: Altitude distribution of the data during solar minimum for ***(a)*** *mono layers,* ***(b)*** *multi layers with 2 layers,* ***(c)*** *multi layers with 3 layers, and* ***(d)*** *multi layers with 4 layers. Each subplot was its respective mean altitude represented with a red line on the graph, and specified in the legend together with one standard deviation.*

14- Page 5, 2 lines from the bottom. "Random forests"? Please describe for the readership.

We have added the following sentence, providing more detail to the reader about what random forests are:

"Random forests is a machine learning algorithm used for both classification and regression. In this algorithm, a number of decision trees are used during training phase to make predictions."

15- Lines 179-181. It is not known if the auroral particles precipitating are more energetic during solar maximum than during solar minimum at your magnetic latitude, so this argument is not valid. During solar maximum there are more magnetic storms than during solar minimum. But as mentioned previously these storm particles generally will precipitate at altitudes below that of Tromso. And the storm particles form the ring current and have energies of 10 to 300 keV. These particles will deposit their energy well below 92 km.

We have modified the manuscript accordingly to the reviewer's comment. We only stated our observations:

"The average altitude of all layers together is higher during solar maximum than during solar minimum (see Fig. 3)."

16- Line 209. Is the electron density decrease with number of layers statistically significant? This seems weak.

We have computed p-values for all combinations of layers and parameters shown in our Figures (altitude distribution, electron density distribution, echo power distribution, and thickness of layers distribution). These p-values can be found in a new Table A1. In the table below, we have included only the pertinent column, specifically the p-values related to the electron density, in order to address the reviewer's comment:

SOL MAX	P- value
Layers 1-2	P < 0.0001
Layers 1-3	P = 0.0003
Layers 1-4	P = 0.0831
Layers 2-3	P = 0.0804
Layers 2-4	P = 0.4000
Layers 3-4	P = 1.0000
SOL MIN	**P- value**
Layers 1-2	P < 0.0001
Layers 1-3	P < 0.0001
Layers 1-4	P < 0.0001
Layers 2-3	P < 0.0001
Layers 2-4	P = 0.0091
Layers 3-4	P = 0.5707
ALL LAYERS	**P- value**
Sol Max-Min	P < 0.0001

17- Figure 12 and elsewhere (many other figures), the differences seem to be small and not statistically significant?

We have computed p-values for all combinations of layers and parameters shown in our Figures (altitude distribution, electron density distribution, echo power distribution, and thickness of layers distribution). These p-values can be found in Table A1. In the table below, we have included only the pertinent column, specifically the p-values related to the thickness of the layers (Figures 12, 13 and 14), to address the reviewer's comment:

SOL MAX	P- value
Layers 1-2	P < 0.0001
Layers 1-3	P < 0.0001
Layers 1-4	P < 0.0001
Layers 2-3	P < 0.0001
Layers 2-4	P < 0.0001
Layers 3-4	P = 0.0002
SOL MIN	**P- value**
Layers 1-2	P < 0.0001
Layers 1-3	P < 0.0001
Layers 1-4	P < 0.0001
Layers 2-3	P < 0.0001
Layers 2-4	P < 0.0001
Layers 3-4	P = 0.0002
ALL LAYERS	**P- value**
Sol Max-Min	P < 0.0001

18- Conclusions, first paragraph. Yes you are correct, but I think the differences are not statistically significant.

We have computed p-values for all combinations of layers and parameters shown in our Figures (altitude distribution, electron density distribution, echo power distribution, and thickness of layers distribution). These p-values can be found in Table A1. Here is Table A1:

		Altitude	Electron Density	Echo Power	Thickness
Solar Maximum	Layers 1-2	P = 0.6462	P < 0.0001	P < 0.0001	P < 0.0001
	Layers 1-3	P < 0.0001	P = 0.0003	P < 0.0001	P < 0.0001
	Layers 1-4	P = 0.0002	P = 0.0831	P < 0.0001	P < 0.0001
	Layers 2-3	P < 0.0001	P = 0.0804	P < 0.0001	P < 0.0001
	Layers 2-4	P = 0.0014	P = 0.4000	P < 0.0001	P < 0.0001
	Layers 3-4	P = 0.8035	P = 1.0000	P = 0.0012	P = 0.0002
Solar Minimum	Layers 1-2	P = 0.6808	P < 0.0001	P = 0.3483	P < 0.0001
	Layers 1-3	P = 0.1098	P < 0.0001	P = 0.0009	P < 0.0001
	Layers 1-4	P = 0.3030	P < 0.0001	P = 0.0001	P < 0.0001
	Layers 2-3	P = 0.0481	P < 0.0001	P < 0.0001	P < 0.0001
	Layers 2-4	P = 0.2284	P = 0.0091	P < 0.0001	P < 0.0001
	Layers 3-4	P = 1.0000	P = 0.5707	P = 0.0728	P = 0.0002
	Sol Max. - Min.	P < 0.0001	P < 0.0001	P < 0.0001	P < 0.0001

Below is Table A2 where we derived the p-values for the correlation coefficients for all layers together during solar maximum and solar minimum:

P-Value		Solar minimum			
		Electron density	Echo power	Thickness	Altitude
Solar maximum	Electron density		1,53E-27	1,38E-54	1,06E-04
	Echo power	1,02E-203		0	2,51E-28
	Thickness	0	0		1,94E-30
	Altitude	0,772	2,24E-03	0,0175	

Finally, below is Table A3 where we derived the p-values for the correlation coefficients for the mono and multi layers separately, during solar maximum and solar minimum:

P-Value	Solar minimum			
	Electron density	Echo power	Thickness	Altitude

Solar maximum	Electon density		Layer1 = 1,86E-19 Layer2 = 1,49E-14 Layer3 = 4,17E-04 Layer4 = 0,0489	Layer1 = 1,02E-59 Layer2 = 2,84E-08 Layer3 = 4,17E-04 Layer4 = 0,00542	Layer1 = 2,08E-27 Layer2 = 0,800 Layer3 = 0,165 Layer4 = 0,455
	Echo power	Layer1 = 4,06E-183 Layer2 = 5,68E-58 Layer3 = 4,29E-12 Layer4 = 3,19E-05		Layer1 = 3,58E-139 Layer2 = 5,62E-112 Layer3 = 4,17E-04 Layer4 = 6,96E-22	Layer1 = 0,0760 Layer2 = 2,30E-16 Layer3 = 2,51E-14 Layer4 = 5,92E-04
	Thickness	Layer1 = 0 Layer2 = 9,23E-99 Layer3 = 1,65E-17 Layer4 = 3,60E-05	Layer1 = 4,186E-319 Layer2 = 0 Layer3 = 8,51E-205 Layer4 = 1,89E-32		Layer1 = 2,87E-10 Layer2 = 8,82E-06 Layer3 = 4,17E-04 Layer4 = 0,0418
	Altitude	Layer1 = 1,80E-07 Layer2 = 5,19E-04 Layer3 = 0,194 Layer4 = 0,305	Layer1 = 6,87E-10 Layer2 = 5,85E-04 Layer3 = 5,32E-06 Layer4 = 6,02E-04	Layer1 = 2,93E-19 Layer2 = 0,592 Layer3 = 0,0288 Layer4 = 0,174	

19- As stated earlier, it is best to stay with the observations. If they fit theory/code results, fine. If they do not, then fine again.

We have carefully rephrased the conclusion accordingly to the reviewer's comment, and adopted careful wording in the cases where the p-value did not allow us to draw a conclusion. Here is the only instance where this happened in the conclusion:

"Based on our investigation, we have found that the electron density at 92 km altitude and the echo power are positively correlated with the thickness for all the layers and for both solar maximum and solar minimum, except for four multi layers at solar minimum."

Also, we have included the following statement in the conclusion, referring to question 3 of the reviewer:

"While differences between the results from observations during solar maximum and during solar minimum considering all the layers together are statistically significant, the cause for the differences needs to be confirmed by future studies."

New reference:

Rapp, M., & Thomas, G. E. (2006). Modeling the microphysics of mesospheric ice particles: Assessment of current capabilities and basic sensitivities. *Journal of Atmospheric and Solar-Terrestrial Physics*, *68*(7), 715-744.