Response to Reviewer 1 / Round 2 – Minor revisions

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 discuss the questions raised by the reviewer and describe the modifications made in the manuscript. We list our responses together with the reviewer's comments that are repeated here in blue color. Our answers are given in black.

Minor Comments:

- In the Introduction section, the authors mention that PMSE multilayers are related to Noctilucent Clouds. What is not mention is does the height of the Noctilucent Cloud layer vary with solar cycle? This should be discussed in the Conclusion section of the paper in connection with PMSE multilayer height variations.

- In the Conclusion section of this paper, the authors have not discussed the cause of the multilayers. The authors should mention existing theories of this for the readership. In fact it would be highly beneficial for the readership if the authors could comment on the possible explanations. They may wish to agree or disagree with the theories and even propose one of their own. Right now the paper is purely observational. It should be broadened to give physical understanding to the journal readership.

- Finally the authors mention that "future work should include further investigating the connections between multi layered PMSE formation and winds and gravity waves". Please mention to the readership if such phenomena can be directly measured or only modeled. Do you mean the Fritts method for gravity waves? Please cite. What about wind measurements? It should be noted that JGRSP, 121, 2016 doi:10.1002/2016JA022499 was written for a mechanism to understand Sudden Stratospheric Warmings (the Berlin Effect). Atmospheric scientists contrarily believe that the cause is gravity waves, but no gravity wave event observations have been correlated to a SSW event. Only models, which are a bit of a disappointment. Thus without observation there is no resolution. You need to explain to the readership that there can be some resolution. Please comment on this as well.

Our answers to the Reviewer's comments:

- In the Introduction section, the authors mention that PMSE multilayers are related to Noctilucent Clouds. What is not mention is does the height of the Noctilucent Cloud layer vary with solar cycle? This should be discussed in the Conclusion section of the paper in connection with PMSE multilayer height variations.

We appreciate the reviewer's valuable input on this intriguing question. As referenced in our manuscript, the study by Schäfer et al. (2020) highlights the altitude variability of NLC layers. However, their study did not focus on investigating the solar cycle effects on the NLC layers, and their research period spans the summers from 2011 to 2018. Nevertheless, we would like to draw attention to the recent work by Vellalassery et al. (2024) (https://www.mdpi.com/2073-4433/15/1/88), which addresses the variation of NLCs throughout the solar cycle. Their findings provide additional insights into this aspect of NLC behavior.

Vellalassery et al. (2024) found that the altitude of NLC exhibits a positive correlation with the solar cycle primarily as a result of temperature changes induced by the solar cycle. The way NLC properties respond to the solar cycle varies across different latitudes, with higher latitudes (69° N and 78° N) showing more pronounced and similar responses compared to mid-latitudes (58° N).

Among those changes, there is the decrease in altitude of NLC over time. Here is an extract from the Vellalassery et al. (2024) paper :

"We found solar cycle responses in the vertical distribution profiles of ice particle number, mean radius and NLC brightness. The solar cycle influence is present at all altitudes and peaks at the altitude of maximum NLC brightness. The magnitude of the ice particle radius and brightness response increases with time, mainly due to the increase of H_2O, while the downward shift of the profiles is due to atmospheric shrinking."

Our findings align with those results, as we observed a lower altitude of the PMSE during the solar minimum period (years 2019 and 2020) compared to the solar maximum phase (years 2013 to 2015). We included a short discussion in the conclusion where we cite the Vellalassery et al. (2024) paper.

- In the Conclusion section of this paper, the authors have not discussed the cause of the multilayers. The authors should mention existing theories of this for the readership. In fact it would be highly beneficial for the readership if the authors could comment on the possible explanations. They may wish to agree or disagree with the theories and even propose one of their own. Right now the paper is purely observational. It should be broadened to give physical understanding to the journal readership.

We appreciate the reviewer's insightful observation and the opportunity to further elaborate on this aspect. As mentioned in our manuscript, while the formation conditions of PMSE are well-understood, the precise mechanisms of PMSE multilayer formation remain uncertain. However, other authors hypothesized other mechanisms through which multi-layered PMSE can be formed. (e.g., Li et al., 2016; Hoffmann et al., 2005).

Li et al. (2016) introduced a model where they explored variations in the vertical wavelength of gravity waves to assess their impact on PMSE multilayers. They observed a decrease in the number of multilayers with increasing wavelength. Similarly, Hoffmann et al. (2005) employed a model simulation to examine the formation of PMSE multilayers and concluded that "the layering of PMSE can be explained by the layering of ice particles due to subsequent nucleation cycles in the vicinity of the mesopause and following growth and sedimentation." While these studies suggest a potential connection between PMSE multilayers and gravity waves, it's important to note the limitations inherent in these models.

Also, Li et al. (2016) explored the impact of particle size variation in their model and observed that larger ice particles lead to a quicker decrease in layer altitude and make layer formation more challenging. They also suggested that the multi-layer structure pattern is influenced by the vertical wavelength of the gravity wave, ice particle size, and wind velocity generated by the gravity wave. ("…we feel confident that the pattern of the multi-layer structure, at least

partially, depends on the vertical wavelength of the gravity wave, the ice particle size and the wind velocity caused by the gravity wave.")

Hoffmann et al. (2005) suggested that according to their model calculations, the layering of PMSE is expected to be more pronounced in the presence of long period gravity waves: "According to our model calculations the layering of PMSE should be particularly pronounced in the presence of long period gravity waves, i.e., waves that allow for the "correct" timing between nucleation, growth and sedimentation on the one hand and the phase propagation of the wave on the other (i.e., if the wave period is too short, the wave will only lead to an up- and downward- motion of the PMSE-layer because the microphysical processes are too slow to lead to significant changes of ice number densities and radii [see *Rapp et al.*, 2002]."

In conclusion, our hypothesis on the formation of multi-layered PMSE is that gravity waves transport particles into regions of low temperature, and varying altitude. In these conditions, ice particles can form and grow. This process may impact the size of ice particles, which in turn could affect their spatial distribution via sedimentation, and potentially influencing the formation of multilayers. We added a few sentences in the conclusion section regarding this mechanism.

- Finally the authors mention that "future work should include further investigating the connections between multi layered PMSE formation and winds and gravity waves". Please mention to the readership if such phenomena can be directly measured or only modeled. Do you mean the Fritts method for gravity waves? Please cite. What about wind measurements?

We thank the reviewer for for raising this intriguing point. It is possible to measure gravity waves using the EISCAT radar as the recent paper from Günzkofer et. al. (2023) shows (https://doi.org/10.5194/angeo-41-409-2023). Then, utilizing the dissipative anelastic gravity wave dispersion relation, Günzkofer et. al. (2023) derive vertical wind profiles within the lower thermosphere.This is a promising avenue for further measuring of gravity waves during PMSE occurrences. We included a comment in the conclusion where we cite the Günzkofer et. al. (2023) paper.

- It should be noted that JGRSP, 121, 2016 doi:10.1002/2016JA022499 was written for a mechanism to understand Sudden Stratospheric Warmings (the Berlin Effect). Atmospheric scientists contrarily believe that the cause is gravity waves, but no gravity wave event observations have been correlated to a SSW event. Only models, which are a bit of a disappointment. Thus without observation there is no resolution. You need to explain to the readership that there can be some resolution. Please comment on this as well.

While this topic is intriguing, it falls beyond the scope of this manuscript.