Authors response on "Simultaneous observations of NLC and MSE at midlatitudes: Implications for formation and advection of ice particles" by Michael Gerding et al.

Anonymous Referee #1

We thank the reviewer for careful reading and the positive feedback. Answers to the specific comments are given below (in italics). New line numbers refer to the manuscript with marked changes.

General comments

The title describes well what is shown in this manuscript, so I will not try to formulate it better. The authors use a large dataset from collocated, simultaneous radar measurements of MSE and lidar measurements of NLC. They select cases when MSE and NLC were present at the same time to characterize these two different, but related middle atmosphere phenomena. In the Introduction and the Discussion, the authors summarize well our present knowledge of the phenomena, and they show where their findings agree with existing knowledge, and where they can add new knowledge. The figures are excellent, clear and well described. The text is generally formulated clearly. The authors describe well how they selected and analyzed the data.

Specific comments

What is new knowledge in this manuscript? - This can be found in the second paragraph of section 6 Summary and Conclusions, the first 2/3 of that paragraph. Section 5 Discussion and the excellent Figure 7 explain what this means, and why the differences between the combination PMSE/NLC at high latitudes and MSE/NLC at intermediate latitudes are as observed. I can imagine Figure 7 being used in lectures and review talks in the future.

We thank the reviewer for this comment. This is indeed the main conclusion of the paper, taking the limitations because of the complex origin of MSE into account.

The mechanism that creates MSE or PMSE is a complex one involving the existence of aerosol particles (ice particles), turbulence and the presence of free electrons and ions - three ingredients. The authors describe this well and with sufficient detail for this manuscript on lines 4/5 on page 13 in the Summary and conclusions. At other places in the text, the authors understandably shorten this already brief description, for instance on p. 2 l. 12, p. 2 l. 25, p. 8 l. 1, p. 10 l. 3, and p. 12 l. 1. They mention only the fact that particles must be present, but not the other two "ingredients", except on p. 10 l. 3, where they add turbulence but omit free electrons and ions. The authors, this reviewer, and many readers of the published paper know that all three ingredients are necessary, but scientists new to MSE and PMSE most likely do not. They may learn "small ice particles make MSE or PMSE", which is not a true statement. It would be clumsy to repeat the sentence from p. 13 l. 4/5 every time. Therefore I do not know an easy solution to the problem that I am trying to point out.

We apologize for explaining the complex origin of MSE and the limitations for the interpretation of the signal too late in the manuscript. Following also the suggestions of Referee #2, we added a short description of the origin of MSE in the beginning of Section 1 (p. 2 l. 6-8) and repeated the issue throughout the manuscript (e.g., p. 7 l. 1-5).

As a tentative suggestion, the instance on p. 2 l. 12 could be formulated like this: "... (NLC), while radar echoes ((P)MSE) require ice particles, large or small, where smaller particles may be freshly formed in the ...". The word "require" seems to include the meaning that something else is required, too (turbulence and ionization).

Many thanks. Inspired by this formulation we changed the phrasing to "… radar echoes ((P)MSE), ionization and turbulence provided, indicate small or large ice particles, where smaller particles may be freshly formed in the …" (p. 2 l. 21).

For the case of p. 8 l. 1, my tentative suggestion might be a small addition: "... visible for radars (signal strength proportional r^2, if turbulence and ionization in addition allow)."

We rephrased to "… if turbulence and ionization allow)" *(p. 9 l. 3).*

For p. 10 l. 3, my tentative suggestion is: "... turbulence is needed to create radar echoes (Rapp and Lübken, 2004), as well as sufficient ionization.

We want to make another point here and rephrased: "and continuous turbulence is needed to create radar echoes in contrast to intermittent turbulence being sufficient in combination with larger ice particles (Rapp and Lübken, 2004). Additional ionization is needed in both cases." (p. 11 l. 17/18)

I ask the authors to kindly understand this paragraph of mine as a suggestion, no more. I leave it to them to find brief but complete solutions for the other instances that I have pointed out earlier in this paragraph.

We hope, the complex issue of (P)MSE and the influence on the interpretation are much better described now.

Technical corrections

"to allow" is a verb with a distinctly different meaning than "to allow for", see Oxford, Cambridge, or Webster dictionaries. On p. 1 l. 4 (twice) and p. 5 l. 5, it seems "to allow" is what is really meant.

Rephrased or corrected

p. 1 l. 17 "... respectively, have been performed since..."

Changed (cf. Reviewer #2)

p. 1 l. 19 and 20: Consider "equatorward" instead of "south" to make the statement global.

Done

p. 2 l 10/11: The subject and the verb of this sentence do not agree logically. I suggest "give additional information", which is better, or perhaps "From simultaneous observations by lidar and radar, we gain additional..."

Done (p. 2 l. 18)

p. 2 l. 15 The verb "to sediment" is intransitive. Therefore I recommend to delete the "been".

Corrected

p. 2 l.18/19: Consider adding "During darkness and outside the auroral oval, the ionization..."

Done

p. 3 l. 1: Replace "like" with "such as"

Done

p. 3 l. 19 I recommend "is achieved by a narrow field of view of the telescope". "Field-of-view" with dashes is an adjective. Without dashes, it is a noun.

Corrected

p. 3. l. 33 Here, I would recommend adding a dash in "phased-array" because "phased" and "array" belong together, but "phased" is not a qualifier for "field".

Corrected

p. 4 l. 2 and l. 8: "For receiving, ..." (comma)

Corrected

p. 4 l. 12 might be better formulated like this: "As we do not have an absolute calibration of the radar, we use SNR as an approximation for the echo intensity..."

Rephrased. Many thanks for the suggestion.

p. 5 l. 18 "The MSE quickly grew...";

Corrected

p. 5 l. 26, p. 13 l. 8 and elsewhere: Just a comment from my side: Usually in everyday life and in laboratory physics, "high" is often used as synonymous with "large" and "low" as synonymous with "small". Here is a case where it becomes ambiguous, because we are writing about the atmosphere: Is the ionization too small, or is it too low in altitude? I know the former is meant, but there is a slight ambiguity.

Checked throughout

p. 6 l. 5 "1 km bins" (no dashes) p. 6 l. 7 lowercase "figure", as it is not a name in this case.

Corrected

p. 11 l. 1 and l. 13: "... in our observations suggest that the layer of only small particles..." ; "(Hervig et al., 2016), suggesting different cloud formation mechanisms..."

Rephrased

p. 13 l. 10 "understanding of quickly sublimating..." . "Fast" does not form an adverb by adding "-ly". Correct the "grew" as well.

Corrected

p. 13 l. 18 "extent"

Corrected

p. 13 l. 21 "descent"

Corrected

I do not understand the very last sentence with the verb "acknowledged". Perhaps "This formation process must be taken into account..." is meant or "This formation process must be allowed for" (here in the correct meaning of this verb).

Yes, this was meant. Rephrased.

Authors response on “Simultaneous observations of NLC and MSE at midlatitudes: Implications for formation and advection of ice particles” by Michael Gerding et al.

Anonymous Referee #2

We thank the reviewer for the careful reading and the helpful comments. Answers to the specific comments are given below (in italics). New line numbers refer to the manuscript with marked changes.

The authors combine two datasets from co-located instruments. A Rayleigh lidar observes NLC which is a direct measure of ice particles in the mesopause region, while a VHF radar observes mesospheric summer echoes which are by complicated physics linked to the presence of ice particles as well. Both phenomena are known to be closely related from detailed studies at polar latitudes. Both datasets from a mid-latitude site used here by the authors were described in detail before, so no new data is presented. As there is scientific interest regarding the occurrence of NLC at mid-latitudes, it seems nevertheless worthwhile to undertake this combination of the datasets.

Many thanks for this comment. We truly estimate the combination of both data sets to be worthwhile. This has rarely done on a large data set before, and never for midlatitudes. We think to gain additional knowledge from this combination, even if the process for MSE is indeed complex and does not only involve ice particles.

However, the study presented here is not as extensive as the studies at polar latitudes. Basically it is reduced to the comparison of three layer parameters: the lower and the upper layer edge of simultaneous NLC/MSE and their centroid altitude. The only relevant result of this study is a difference of 500 m between the upper edges, which differs significantly from 3.3 km found at polar latitudes. Even the authors do not seem to be surprised, though. They attribute it to reduced thickness of the MSE layer – but it is not clear if this has been shown before, and they don’t think it is necessary to show it here as well.

The reviewer is right that the MSE data can also be described by their thickness that is on average lower compared to polar latitudes. For the comparison with the NLC layer we found it reasonable to differentiate between upper and lower edges because the layer thickness on its own does not say anything about the relation to NLC altitudes. Kaifler et al. (2011) were able to do a more detailed analysis based on a much larger data set from high NH latitudes, while Klekociuk et al. (2008) made an initial study on a smaller data set from high SH latitudes. Given our limited data set and the instrumental changes of the OSWIN radar we hesitate to do an extensive analysis like Kaifler et al. (2011). Edge altitudes are comparatively robust against instrumental changes, while, e.g., occurrence rates may not. Furthermore we wanted to focus on potential differences to higher latitudes, which we mainly found in the upper edges.

We have tried to sharpen the description of the relevant results in different parts of the manuscript (see below).

Their only conclusion from the study is that advection is the main process for NLC occurrence at the observation site. This is by no means a new conclusion. From Gerding, JGR, 2007: “We conclude that NLC at midlatitudes are strongly coupled to the advection of preexisting ice particles from northern latitudes." and Gerding, GRL, 2013 "Comparing NLCs and ambient winds, we find strong indications for the meridional wind (advection) being the main driver for NLC occurrence above our site."

Yes, we have truly claimed this before. But there are other, partly newer publications that propose local processes. During the analysis of the NLC/MSE data we found this additional indication for advection, supporting our previous papers. We see this observation and conclusion as relevant, especially since these combined observations are only possible with our (still unique) combination of instruments.

The authors claim to undertake the first statistical study at mid-latitudes. I acknowledge that this is a difficult task, and with their instrumentation they are also the only ones able to do this. The reason is that the NLC occurrence frequency is low, so with a lot of effort, only a very limited dataset is to be gained. At the same time, this makes these measurements highly valuable, and they should be treated accordingly. I fear that with 64 or 67 hours of data available to this study, it does not qualify to being statistical, or to being representative for NLC. The authors are not clear about the number of events or the number of independent profiles, but there is reason to suspect these numbers are low.

We are happy that the value of our observations is acknowledged. We apologize if the term "statistical analysis" is misleading here. We have replaced it in the revised version (e.g. "comparative" (p. 1 l. 3), "vertical distributions" (p. 3 l. 15), "on average" (p. 8 l. 13)). We now mention the number of 31 days with NLC/MSE in Section 2.4 (p. 7 l. 16). These events are representative for all NLC in terms of their altitude structure, as described in Section 5 (p. 11 l. 31 – p. 12 l. 6 , see also comment below). Of course, they may not in terms of brightness or diurnal variation. Furthermore, the MSE during simultaneous NLC are not representative for all MSE, as already described in Section 5. There are many high and/or weak MSE not represented here. But these MSE just support the presented conclusion about the formation processes.

There is one flaw in their discussion regarding the mean centroid altitude compared to their previous NLC statistics. I think they either made a mistake or the dataset cannot be considered to be representative. A large percentage of the NLC dataset (two third) was not included in this study, which is sad, and the reason wasn't explicated in sufficient detail.

We apologize for the mistake about the mean NLC height in the beginning of Section 5. Indeed, the mean peak height here is 83.3 km. Many thanks for making us aware of this flaw in our discussion. We have revised and extended this section (p. 11 l. 31 – p. 12 l. 6), but we still state that the presented data are representative for all NLC. In the 2013a paper (data 1997-2011, nighttime only) we gave a number for the mean centroid altitude that is typically 0.2 km below the mean peak altitude. The mean peak altitude is easier to identify, and is 82.8 km for all NLC 2010 – 2016. The mean peak altitude for the selected days of simultaneous MSE is 83.0 km (mean centroid altitude 82.8 km). From this data set the very weak NLC profiles (beta < $0.3*10^{-10}$ /m/sr) are removed, e.g. during beginning and end of the event, as well as some profiles with very low NLC (80 km and below), because here the ionization is reduced and MSE are less likely.

For this study we needed to remove NLC during nighttime (or low solar elevation, i.e. ionization) because of missing MSE. Furthermore we excluded the faintest NLC (beta < $0.3*10^{-10}$ /m/sr) because of typically bad SNR and therefore unreliable edge detection. We explain this in more detail in the revised manuscript (p. 7 l. 18-20).

In my impression the potential of the data shown was not fully exploited. The authors dedicate one section to the display of four cases with varied, sometimes intriguing morphology, but no physical explanation is offered. It is therefore not clear why they are shown at all. The following statistics of lower edges makes the reader wonder if the morphology with a double layer is correctly represented. Especially the extreme cases of the statistics would be worth taking a closer look at, e.g. when the MSE lower edge is located 3 km below the NLC lower edge. I also doubt that the statistics of lower and upper edges result in the same correlation coefficient, as they look different to me.

> *We agree that the events presented in Figure 2 are worth further analysis, and we thank for the encouragement. Nevertheless, this is outside the scope of this paper. While showing very interesting dynamical structures, detailed analysis of these cases needs further information about ionization (electron densities) and turbulence. Wind data is available only with limited temporal and spatial resolution, while temperature data is completely missed for most cases. Figure 2 is presented to make the reader aware of this highly dynamic behavior of NLC and MSE – and the limitations for detection of layer edges from independent, asynchronous instruments. We have improved the description in the revised manuscript (p. 5 l. 20 and p. 6 l. 13 - p. 7 l. 8).*
>
> *Figure 2 shows some cases with larger differences of NLC and MSE edges. These are worth further analysis, but so far observations of electron density and turbulence are lacking at our site. Other large differences occur for technical reasons like different FOV sizes or asynchronous data.*
>
> *We have double-checked the correlation coefficients. The "outliers" are mainly single profiles, while the majority of events (dark color in Figures b)) are along a line.*

Another critisicm is that the authors invoke an incorrectly simplified image of PMSE physics in particular, by stating that NLC are created by large ice particles and MSE are created by small ice particles, or even simpler, that lidar observes large and radar observes small particles. Here and there some references to our understanding of the physics of PMSE are interspersed, mostly when some explanation for some discrepancy is needed.

> *We thank the reviewer for making us aware of the insufficient explanation of MSE physics. We have added some explanation, e.g., in the beginning of the Introduction (p. 2 l. 6-8, see also below) and mention this topic also in the Abstract (p. 1 l. 5). The potential influence of the MSE physics on our results is, e.g., more clearly described in Sections 2.3 and 2.4, now (page 7).*

Questions and comments regarding science are following sorted by line numbers. A second set of comments with more technical corrections is appended.

p. 1, l. 1 This is the very first sentence, and it is not very precise: radar measurements are not a direct observation of ice particles, you shouldn't make such a statement in the very beginning. And they can also be observed optically by eye or camera. And why the focus on ground-based observations here? Its not yet clear what you are after.

> *We have changed the first sentence to "We have combined ground-based observations of ice particles in the summer mesopause by lidar (then often called Noctilucent Clouds, NLC) and radar (then called (Polar) Mesospheric Summer Echoes, (P)MSE) for a first comparative study on ice cloud altitudes at midlatitudes (Kühlungsborn/Germany, 54° N, 12° E)."*

p. 1, l. 2 Second sentence: that's too much of a simplification, reality is more complex

We have added "but require sufficient ionization and turbulence at the ice cloud altitudes" at the end of the sentence.

p. 1, l. 4 "allows for some insight" – yes, but that's now a very complicated task

Phrase is changed to "…provides some rough information about …".

p. 1, l. 5 I feel the need to object to the "statistical study". It is only 67 hours of data. It is more a compilation of cases, but not statistics.

We have deleted "statistical", now saying "comparative study" (p. 1 l. 3) and avoid this term with respect to this study (cf. above).

p. 1, l. 6 MSE is not a direct measurement of ice clouds

Yes. Limitations are now mentioned, e.g., in the second sentence, in the Introduction and in Section 2.3. See also below.

p. 1, l. 18 and from space. You mention "stations", which I read as ground-based, but then cite results from satellite observations in the second sentence, so it's worth being included in the first sentence that there are also satellite observations.

We thank the reviewer for the careful reading. We have changed the sentence to "Noctilucent Clouds (NLC, also known as Polar Mesospheric Clouds, PMC) and Polar Mesospheric Summer Echoes (PMSE) are observed since several decades mainly in the polar regions by ground-based and space-based instruments as well as by human eye […]." (p. 1, l. 19-22)

p. 1, l. 22 this might be the most suitable place to explain in necessary detail the relation between lidar-observed NLC and radar-observed (P)MSE, and not only give the citation. The differences are not restricted to occurrence and vertical extension, but the physical mechanisms are very different. As you only give this information piece by piece throughout the manuscript, you might want to take the chance to make this very clear here. Then the reader won't be misleaded and then be surprised while reading that it's in fact more complicated then you had hinted.

We added a first sentence on the complex origin of PMSE here ("Later on it was revealed that PMSE additionally require sufficient ionization of the ambient air to get the ice particles charged and turbulence to produce plasma structures for scattering of the radar wave." p. 2 l. 6-8) and provide information about the implication of these requirements throughout the manuscript.

p. 2, l. 12 already here it would be useful to have the physics of PMSE explained

We added here "ionization and turbulence provided".

p. 2, l. 14 that's not very obvious. It could have been created within the NLC layer for all we know

The formation of ice particles from condensation nuclei happens most likely at the mesopause, i.e. above 85 km, where supersaturation is largest (e.g. Rapp and Thomas, 2006). At these altitudes NLC are extremely rare. Typical altitudes of NLC and MSE are mentioned on p. 2 l. 4/5.

p. 2, l. 25 equating “local ice formation” with “observations of PMSE” is too much of a simplification

We changed this part to “Li et al., JGR 2010, revealed from PMSE observations average ice particle radii being larger above 85 km than below. This can be explained by …” (p. 2 l. 34/35)

p. 3, l. 16 you should motivate why the diurnal variation of NLC is of relevance for this paper if you cite it

We deleted this part of the sentence.

p. 3, l. 23 do you not normalize to density? I thought the common technique is to normalize to density and then take the ratio of the Mie scatter to this?

The reviewer is right. We have added this information (“…from the aerosol backscatter normalized to the molecular backscatter, the molecular backscatter cross section, and a reference air density to quantify the cloud brightness”, p. 4 l. 5/6).

p. 3, l. 27 i.e. smoothed with 15 min width?

Yes. We have changed the phrasing.

p. 3, l. 32 now you proceed with the radar. I suggest subsections per instrument. You started the paragraph by mentioning the commissioning of the instrument in summer 2010, and with no word you give any numbers on observations statistics!

Many thanks for the suggestion of subsections. The observations statistics is given in the last subsection 2.4, which is now introduced earlier in an overview sentence (p. 3 l. 23-25 and p. 7 l. 10-24).

p. 5, l. 1 There is a break here. There was a description of the radar dataset and then, with no subsection change, the text continues with different types of agreement between the observations

We made a new subsection here and added a short introduction (p. 5 l. 20).

Fig. 2 it might help the reader to indicate times with solar elevation above 5 deg, as it seems to be important to PMSE occurrence

Many thanks for this suggestion. Done.

p. 5, l. 7 “often filled the same volume” the expression is not elegant, it’s not very precise and it’s not even true when I look at the figure!

We changed the phrasing to “showed good agreement” and give more precise information thereafter (p. 5 l. 28-30).

p. 5, l. 12 the observation of MSE is not a detection of ice particles, once again

Ice particles are necessary for MSE. Therefore we can conclude from the presence of MSE to the existence of ice in the observed volume.

p. 5, l. 23 especially Fig. 2d seems to be a case with lots of features sparking many questions regarding the physics. No explanation is given! That’s a bit frustrating to the reader.

We agree that this event is very interesting and has the potential for further studies. Unfortunately we have no electron density and turbulence measurements available to explain, e.g., the gap in the MSE at 3:30 UTC. Examination of gravity wave dynamics *would be very interesting, but is beyond our scope for this paper. To make the reader aware of the high potential of this event we added (p. 6 l. 13-15): "The variable structure of the ice layer with double layers indicates a highly dynamic behavior of the atmosphere with presence of strong gravity waves. Nevertheless, a detailed examination of the dynamical structure is beyond the scope of this paper."*

p. 5, l. 23 Again on this paragraph, it is not clear what the intention is. You want to show four cases to make what point? That you also see features that others have described? It is not comprehensive, there is no explanation given, no conclusion is drawn, so why? You show layers with intricate morphology, but you do not do justice to this. In the following you restrict yourselves to three parameters only.

We are sorry for not describing the purpose of these examples. We added a new paragraph at the end of the subsection (p. 7 l. 1-8): "The examples shown above demonstrate the different relations of the NLC and MSE layer edges and the different degrees of accordance of the layers. This is in general agreement with observations at polar latitudes (e.g. Klekociuk et al., 2008; Kaifler et al., 2011). The examples indicate an often good concurrence of the lower edges but a worse agreement of the upper edges. If solar elevation (i.e. ionization) is sufficiently large, NLC are often but not always accompanied by MSE. The latter might be explained by missing turbulence, but this cannot be proven here because a lack of appropriate measurements. Periods with MSE but absent NLC can be caused by mainly small ice particles, resulting in lidar signals below the NLC detection threshold. In the following we neglect profiles of NLC without MSE as well as MSE without NLC to be sure that for this study all requirements for the observation of small and large ice particles are fulfilled (see below)."

p. 5, l. 27 MSE that are too high to be observed by lidar? Surely there is no limit at e.g. 85 km for the lidar? And MSE that are too weak to be observed by lidar? They are not observed by lidar in any case.

We deleted the ice cloud "too high" for lidar but left "too weak". The ice cloud may produce an optical signal below the threshold but is detected by the radar, e.g. in case of small particles. We add "detected as MSE" for clarity.

p. 5, l. 30 might be worth giving an update on the occurrence rate: 188.5 h / 3337 h is ~ 5 %. And is 3337 hours the "operation time" or the time with high-quality data suitable for NLC detection? Cause that might be significantly lower than the operation time. And it is only this that is relevant information for scientific purposes, the former is of interest to the laser engineer only.

We prefer not to mention the occurrence rate of NLC in general, as only NLC accompanied by MSE are used here. The 3337 h are the number of hours suitable for detection of NLC with ß>0.3. We added the term "usable" for clarity (p. 7 l. 20).

p. 5, l. 29 I am surprised by the low number of 67 hours. You are throwing away 64 % of your precious, rare data on NLC. Might be worth to state why: So many hours due to solar elevation below 5 deg, so many hours due to missing PMSE at night, so many hours due to radar downtime

We do not distinguish why the data are not used here, but have added a short list of reasons (p. 7 l. 18/19). Indeed, we would be happy if we could use more of the rare NLC data here, but at our site many NLC profiles either show a quite low backscatter *coefficient (20-30% with ß<0.3, estimated from Fig. 4 of Gerding et al., JGR, 2013) or appear during nighttime, when the ionization is typically too small to support MSE (cf. 8.5 h of solar elevation below 5° on 21 June).*

p. 5, l. 32 it makes you wonder if the study is representative for NLC, if you only use 36 % of the data. . . Fig. 1, 2 the five events shown amount to 17 hours out of the 67 hours. So I extrapolate that your statistics is based on 20 events? You withhold that number, but you should give it

As mentioned above, we do not see a significant difference between the layer parameters of the NLC used here and of all NLC. We discuss this in more detail in Section 5. Therefore we consider our results representative for all NLC.

We added on p. 7 l. 16-18: "These data are distributed across 31~days with an average ice cloud duration of 2.2 h. For this study it is not relevant whether the ice observation is uninterrupted in time or not, because the layer parameters are derived based on individual (but smoothed) profiles."

p. 6, l. 4 as shown in Fig. 1, but what about the multiple layers in Fig. 2d? These are several hours at least. In a dataset this small, it would be worth taking very good care of this.

We added on p. 7 l. 29 "In the rare case of a double layer we take the lower edge of the lower layer and the upper edge of the upper layer together with the absolute maximum."

p. 6, l. 4 1931 profiles a 2 minutes are 64 hours. But you said the NLC data was smoothed with 15 min running mean, so only 256 profiles are independent, aren't they, and not 1931?

The reviewer is right, not all profiles are independent. We added on p. 7 l. 30/31: "…, even if the respective smoothing needs to be taken into account for interpretation."

p. 6, l. 7 82.6 km for the lower edge seems quite high, how does this compare to polar latitudes? This is 82.1 km, I checked, so you might want to discuss this

The ice layer altitude is on average increasing with latitude, which is related to the changing temperature profile (smaller likelihood for supersaturation at, e.g., 82 km at 54°N compared to 70°N). Following the suggestion, we have added a short section in the discussion (p. 12 l. 15-18): "In their Table 3 they report also quasi-identical lower edges of NLC and PMSE, even if the z^{low} at higher latitudes are observed 0.5 km above the midlatitude values. This latitudinal difference of z^{low} can be explained by the general increase of NLC altitudes with latitude (Lübken et al., GRL, 2008; Chu et al., GRL, 2011) which is related to the ambient temperature structure."

p. 6, l. 14 any physical explanation for the 4-5 km difference?

We already tried to provide an explanation in the following sentences.

p. 6, l. 15 "can also be explained" and what was the first explanation if this is the second? The "morning twilight" is no obvious physical explanation

We rephrased the sentence before to make clear that this is a first explanation (p. 8 l. 8/9: "… in cases of MSE onset in the morning twilight where sometimes the MSE only agrees with the uppermost part (i.e. largest ionization) of the ice layer").

Fig. 3b there are MSE altitudes 3 km below the NLC altitude, you didn't mention this

We now expanded the explanation of the few larger altitude differences by "Rarely, the different size dependency of lidar and radar signals can lead to MSE even a few km below the NLC." (p. 8 l. 12/13)

Fig. 5b I can't believe that this distribution has the same correlation coefficient as the one in Fig. 3b. Can you check this number again?

We double-checked this number without finding an error.

p. 8, l. 1 no ice particles are visible for radars

We changed the phrasing to "detected by".

p. 9, l. 4 so this is evidence for local formation of ice clouds then?

Potentially, but a final proof cannot be given from the available data.

p. 9, l. 9 "as expected" you should state the observations and then draw conclusions, and not expect something

We added "from previous observations" (p. 11, l. 1). We want to make clear that this is not the first observation of southward wind during NLC/MSE.

p. 9, l. 16 atmospheric conditions like haze and solar background are the same to the two lidars, so they can't be the reason for a smaller dataset in one? Either it's a technical limitation or operational?

The potassium lidar at 770 nm suffers more from hazy conditions than the RMR lidar at 532 nm due to enhanced scatter of the longwave fraction of solar radiation. We added "at near-infrared wavelengths" (p. 11 l. 8).

p. 9, l. 17 seven events are how many independent profiles?

The seven events cover more than 25 h of data, but this number includes also periods during night/twilight, when the MSE has not set in, yet. The temperature data set for these days is much larger because it is not limited to NLC. On the other hand, temperatures have been calculated every 15 min with 2 h integration. We hesitate to provide all these numbers in the paper. We do not observe that the ambient conditions change drastically within the individual events, i.e. an event-wise classification is justified.

p. 10, l. 12 as you showed, multi-year is not enough to be either statistical or representative

We replaced "statistical analysis" by "analyses of average layer parameters".

p. 10, l. 15 The mean peak altitude of this study is 83.3 and not 82.6 km. This was the mean lower edge. So this does not compare at all to the centroid altitude statistics and must be explained. Either you made a mistake, or this study is not representative at all.

We are sorry for this mistake and thank the reviewer for his careful reading. As described above the selected cases are still representative for NLC in general. We have corrected the numbers and explain these now in more detail.

p. 10, l. 24 and the lower edge in Kaifler et al. (2011) is 82.1 km, which is 500 m below your results

As mentioned above, we have added and explained this difference in the Discussion (p. 12 l. 16-18).

p. 10, l. 30 you didn't evaluate the thickness of the PMSE layer, so you need to cite for this statement

We have added a reference (Kaifler et al., 2011).

p. 11, l. 5 is this a result of Kiliani et al. (2013)? 150 km is not a large distance at all, I'd be surprised

This is a result of Kiliani et al. and relates to a mean wind speed of 7 m/s (or 23 m/s for their upper limit). However, we see the old phrasing potentially misleading and changed it to (p. 12 l. 32/33): "In this period, the ice particles typically travel 150-500 km southward. Before, the ice particles remained small (< 20 nm) for more than 60 h."

p. 12, l. 12 if -14 dB gives similar results than -12 dB, then -12 dB is not the noise limit, or am I wrong?

We rephrased "The threshold is set to -12 dB based on the noise limit of the radar." to "The threshold is set to -12 dB to be above the typical noise limit of the radar." (p. 14 l. 5)

p. 13, l. 5 here, in the conclusions, this is the first time that structures in the plasma are mentioned

As mentioned in the above comments we now explain the complex origin of MSE much earlier. We thank the reviewer for making us aware of this.

Technical corrections:

p. 1, l. 8 Please don't italicize indices (low, NLC, MSE, I mean: typeset with z_NLC in LaTeX)

Done

p. 1, l. 10 expression: "typically do not expand much above". (expression: ".." in the following always means that I feel the language could be improved here)

Changed to "typically do not stretch much higher than the NLC" (p. 1 l. 13).

p. 2, l. 2 expression: "indicator for temperatures being below the frost point"

Deleted "being"

p. 2, l. 4 "we utilize"

Changed

p. 2, l. 6 expression: "particular important"

Changed to "in particular"

p. 2, l. 6 "partly used" that might be an unfortunate expression. You might mean all kind of things.

Deleted "partly"

p. 2, l. 10 the observations do not gain additional information

Changed to "give additional information" (cf. Reviewer #1)

p. 2, l. 16 expression: "observations to examine this question"

Changed to "solve this question"

p. 2, l. 16 delete “obviously”

Done

p. 2, l. 24 expression: “extend several kilometers higher”

Changed to “stretch several kilometers higher” (p. 2 l. 32)

p. 3, l. 11 expression: “observations are performed”

Changed to “made”

p. 3, l. 15 you already noted in line 11 that it is daylight-capable

We kept this but added “… and replaced the former RMR lidar used for nighttime NLC statistics.” (p. 3 l. 27)

p. 3, l. 19 “of _60 murad”, you already mentioned that it is narrow

Deleted “narrow”

p. 3, l. 22 Noctilucent Clouds -> NLC

Done

p. 3, l. 22 remove “in the NLC altitude “

Done

p. 3, l. 30 “evaluated manually”

Word order changed

p. 3, l. 31 “identified by software” you mean by some algorithm, which could be described here, or not

Changed to “by an algorithm”

p. 4, l. 2 “For reception”

Done

p. 4, l. 3 please spell 6 as six, 7 as seven, throughout the manuscript

Done

p. 4, l. 4 expression: “Time series resulted in length of 34.1 s”

Changed to “Time series of 1024 data points are acquired within 34.1 s.” (p. 5 l. 8)

p. 4, l. 5 expression: “the available time resolution for observations amounted to 2 min”

Changed to “the time resolution for MSE observations is 2 min.”

p. 4, l. 12 expression: “Due to the not available absolute calibration”

Changed to “As we do not have an absolute calibration of the radar, we use SNR as an approximation for the echo intensity.” according to the suggestion of Reviewer #1 (p. 5 l. 17).

p. 5, l. 1 expression: “different types of agreement” that could be phrased somehow better

Rephrased to “Similar to previous studies we find partly very large agreement between NLC and MSE, while there are differences in other cases” (p. 5 l. 21/22)

p. 5, l. 2 if it is the first or last event or one in between doesn't matter, I think

Changed to "shows an events that was observed on 17 June 2010"

p. 5, l. 6 you might want to start a new paragraph for the discussion of each case

Done

p. 5, l. 18 growed to -> grew into? Or maybe: developed into

Changed to "grew into".

p. 5, l. 20 expression: "slightly after each other"

Deleted

p. 5, l. 23 This paragraph starting at p. 5, l. 1 should be put into a separate subsection with paragraphs

Done

p. 7, l. 1 expression "more pointlike"

Rephrased to "only ~1/1700 of this" (p. 8 l. 11)

p. 7, l. 4 delete blank between 4 and .

will be done late when the \marginpar command is removed

p. 7, l. 6 (Fig. 4, right)

Done

p. 8, l. 1 "regions extends" one s is too much

Corrected

p. 8, l. 2 "getting finally visible for lidars"

Rephrased to "and become …"

p. 9, l. 2 "new ice layer" well, "new" in what sense, maybe "another"?

Changed

p. 10, l. 10 observation probability == occurrence frequency?

Changed

p. 10, l. 13 "the first RMR lidar" doesn't really matter here if it was the first?

Changed to "previous" to make clear that it was not the lidar used for the current study

p. 10, l. 31 descend -> descent, also p. 13, l. 21

Corrected

p. 11, l. 1 expression: "hint to the conclusion"

Changed to "suggest" (cf. Reviewer #1)

p. 11, l. 1 expression: "the layer of only small particles"

Deleted "small"

p. 11, l. 16 to allow "for"

Corrected

p. 12, l. 8 “which” is slightly smaller

Corrected

p. 13, l. 18 extent

Corrected

Simultaneous observations of NLC and MSE at midlatitudes: Implications for formation and advection of ice particles

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Abstract. ~~Ice~~ We have combined ground-based observations of ice particles in the summer mesopause region ~~can be observed from ground either optically by lidars~~ by lidar (then often called Noctilucent Clouds, NLC) ~~or using radars~~ and radar (then called (Polar) Mesospheric Summer Echoes, (P)MSE) for a first comparative study on ice cloud altitudes at midlatitudes (Kühlungsborn/Germany, 54° N, 12° E). Lidar observations are limited to larger particles (>10 nm), while radars are also sensitive to small particles (<10 nm), but require sufficient ionization and turbulence at the ice cloud altitudes to receive an echo. The combination of lidar and radar observations ~~allows for some insight into~~ provides some rough information about the size distribution within the ~~clouds~~ cloud and by this ~~for an indirect information~~ about the 'history' of the cloud. ~~We will present a first comparative statistical study on ice cloud altitudes and thickness from simultaneous and co-located observations of NLC and MSE at midlatitudes (Kühlungsborn/Germany, 54° N, 12° E). Soundings~~ The soundings for this study are carried out by the IAP RMR lidar and the OSWIN VHF radar. We find a ~~large~~ good agreement of the lower edges (~~z_{NLC}^{low} and z_{MSE}^{low}~~ $z^{\mathrm{low}}_{\mathrm{NLC}}$ and $z^{\mathrm{low}}_{\mathrm{MSE}}$), showing a mean difference of only 40 m. The mean difference of the upper edges ~~z_{NLC}^{up} and z_{MSE}^{up}~~ $z^{\mathrm{up}}_{\mathrm{NLC}}$ and $z^{\mathrm{up}}_{\mathrm{MSE}}$ is ∼~~400~~500 m, which is much less than expected from observations at higher latitudes. In contrast to high latitudes, the MSE above our location typically do not ~~expand much above~~ stretch much higher than the NLC. In addition to earlier studies from our site, this gives additional evidence for the supposition that clouds containing large enough particles to be observed by lidar are not formed locally but are advected from higher latitudes. During the advection process, the smaller particles in the upper part of the cloud either grow and sediment, or they sublimate. Both processes result in a thinning of the layer. Nucleation of new ice clouds (usually visible as high MSE) rarely happens at the same time as the NLC events.

1 Introduction

~~Ground-based observations of~~ Noctilucent Clouds (NLC, also known as Polar Mesospheric Clouds, PMC) and Polar Mesospheric Summer Echoes (PMSE) ~~by lidar and radar, respectively, are performed~~ have been observed since several decades ~~at different stations~~ mainly in the ~~northern and southern polar regions (e.g. Chu et al., 2003; Morris et al., 2007; Collins et al., 2009; Latteck a~~ polar regions by ground-based and space-based instruments as well as by human eye (e.g. Leslie, 1885; DeLand et al., 2003; Chu et al., 200
. Observations at mid latitudes showed that mesospheric ice clouds can exist also ~~south~~ equatorward of 60° ~~N~~ latitude and oc-

casionally even ~~south~~ equatorward of 45° ~~N~~ latitude (Thomas et al., 1994; Chilson et al., 1997; Wickwar et al., 2002; Ogawa et al., 2011; Russell et al., 2014). First simultaneous soundings of both phenomena have been achieved by Nussbaumer et al. (1996) at the ALOMAR observatory at 69° N. The observations stimulated the impression that both phenomena are related to ice clouds in the mesopause region, even if there are some differences in occurrence and vertical extension. NLC are usually observed between ∼80-86 km (e.g. Fiedler et al., 2017), while PMSE stretch higher and appear at ∼80-90 km (e.g. Latteck and Bremer, 2017). Later on it was revealed that PMSE additionally require sufficient ionization of the ambient air to get the ice particles charged. Additionally, scattering of the radar happens only on structures in the plasma that are produced by turbulence but can persist even if the turbulence ceased. Rapp and Lübken (2004) published a comprehensive interpretation of PMSE and their relation to ice clouds in the mesopause region. Though, NLC and PMSE are both an indicator for temperatures ~~being~~ below the frost point, i.e. the ice clouds provide indirect temperature information in a region of the atmosphere, where other data is sparse.

In this study we ~~will~~ utilize combined observations by lidar and radar to gather information about the origin of the NLC layer at midlatitudes. There is some debate about the role of advection from higher latitudes compared to local ice particle formation. This is in particular important for the interpretation of trends in midlatitude ice clouds that are ~~partly~~ used as an indicator for climate change in the middle atmosphere (e.g. Thomas, 2003; Russell et al., 2014). Some studies found a strong dependence of ice observations on equatorward directed wind (Morris et al., 2007; Zeller et al., 2009; Gerding et al., 2013b) or planetary wave activity (Nielsen et al., 2011), while other studies explained the observations mainly by local temperature structure (e.g. Herron et al., 2007; Hultgren et al., 2011; Stevens et al., 2017). Simultaneous observations by lidar and radar ~~gain~~ give additional information on this topic due to their different size dependencies. Lidars are mainly sensitive to ice particles with diameters of some ten nanometers (NLC), while radar echoes ((P)MSE)~~are also generated from smaller ice particlesthat are~~ , ionization and turbulence provided, indicate small or large ice particles, where smaller particles may be freshly formed in the mesopause region and just start to sediment. Local NLC formation therefore ~~requires~~ implicates the simultaneous existence of freshly formed particles, i.e. of typically an MSE layer extending above the NLC. If the advection of NLC dominates, the initial ice particles should have already ~~been~~ sedimented and grown.

Simultaneous observations of NLC and (P)MSE to ~~examine~~ solve this question are technically challenging and rare. They ~~obviously~~ require a powerful lidar and a VHF radar being co-located. The lidar needs to be daylight-capable because (P)MSE are mainly limited to daylight conditions (e.g. Thomas et al., 1996; Zecha et al., 2003; Rapp and Lübken, 2004). During darkness and outside the auroral oval, the ionization in the D-region is typically too small to create radar echoes in the mesopause region. Additionally, the lidar needs to be sensitive enough for the typically weak NLC backscatter signals. So far, the only statistical studies on joint NLC and (P)MSE occurrence and layer parameters from simultaneous observations by lidar and radar are performed at polar latitudes (e.g. von Zahn and Bremer, 1999; Klekociuk et al., 2008; Kaifler et al., 2011). For most of the time of NLC detection also PMSE have been observed, while, on the contrary many PMSE have been detected in the absence of NLC. Typically, PMSE and NLC layers have very similar lower edges, but PMSE ~~extend~~ stretch several kilometers higher than NLC. ~~This is generally understood as~~ Li et al. (2010) revealed from PMSE observations that average ice particle radii are smaller above 85 km than below. This can be explained by local ice formation in the high latitude mesopause region (observed as PMSE), happening in parallel to the occurrence of larger ice particles below 85 km (observed as NLC and PMSE). These main layer properties are similar in northern and southern polar regions, even though observations at Davis (69° S) show typically less and weaker echoes compared to ALOMAR (69° N) (Morris et al., 2007; Latteck and Bremer, 2017). For midlatitudes, either only MSE or NLC statistics have been described so far. Midlatitude MSE layer properties have been published by Latteck et al. (1999) and Zecha et al. (2003) based on data of the OSWIN radar at Kühlungsborn (Germany, 54°N). They found a much lower occurrence rate compared to high latitudes in the Northern Hemisphere, but a similar altitude distribution. Midlatitude NLC layer properties have been described by Gerding et al. (2013a), using the Rayleigh-Mie-Raman lidar co-located with OSWIN. Similarly, they found a much smaller occurrence rate compared to high latitudes, but comparable NLC altitudes. Nevertheless, a joint examination of ~~observations from these instruments~~ lidar and radar observations at our site is lacking.

In this paper we compare NLC and MSE layer properties ~~like~~ such as lower and upper ~~edge~~ edges for all periods with simultaneous observations. By this we concentrate on events when at least part of the ice particles have been grown to sizes of some ten nanometers. By the combination of NLC and MSE signals we also avoid confusion of the ice-related MSE with other mesopheric echoes in summer that are sometimes observed at much lower latitudes, i.e. at much too high temperatures for ice existence (Muraoka et al., 1989; Kubo et al., 1997).

In the following Section 2 we describe the instrumentation and the available data set. The ~~statistics about~~ vertical distributions of layer edges and maxima are presented in Section 3. In Section 4 we examine the influence of local wind and temperature profiles on the ice NLC/MSE. In Section 5 we compare our results to data from polar latitudes, leading to our conclusion about the relevance of advection for NLC occurrence at our site.

2 Methodology and single layer comparison

The NLC and MSE observations used here are ~~performed~~ made at Kühlungsborn (54° N, 12° E) with the daylight-capable Rayleigh-Mie-Raman (RMR) lidar and the OSWIN VHF radar, respectively. Additional data are provided by the co-located potassium resonance lidar measuring temperatures above the NLC (e.g. von Zahn and Höffner, 1996; Alpers et al., 2004) and by the nearby (120 km to the north-east) meteor radar at Juliusruh (55° N, 13° E) (Stober et al., 2012, 2017). In this section we describe the main instruments, show some examples for edge detection and the general appearance of NLC and MSE, and give an overview on the used data and its representativeness.

2.1 NLC observations by the daylight-capable IAP RMR lidar at Kühlungsborn

The daylight-capable RMR lidar started operation in summer ~~2010.~~ 2010 and replaced the former RMR lidar used for nighttime NLC observations. A general description of the lidar has been given by Gerding et al. (2016)~~and first results on the diurnal variation of NLC have been published by Gerding et al. (2013b)~~. In summary the lidar uses a frequency-doubled Nd:YAG laser at 532 nm with ∼20 W average power. The backscatter signal is collected by a single telescope of 80 cm diameter and detected by an Avalanche Photo Diode. The daylight capability is achieved by a ~~narrow field-of-view of~~ field of view of the telescope of only ∼60 μrad, a narrow-band interference filter (130 pm), and a double Fabry-Pérot etalon (∼4 pm full spectral width at

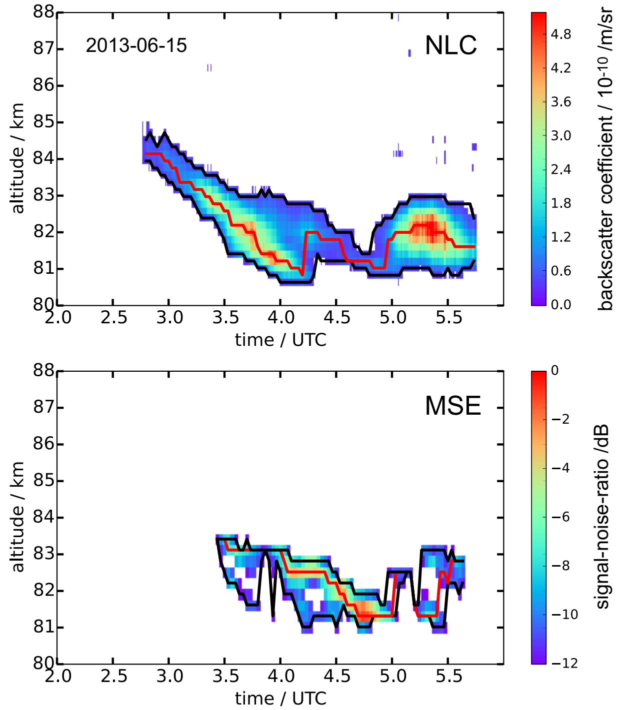

Figure 1. Examples for detection of NLC (top) and MSE (bottom) using observations on 15 June 2013. The black lines show the upper and lower edges (z^{low} z^{low} and z^{up} z^{up}), the red line the layer maxima (z^{max} z^{max}). Edge detection is done on the temporal resolution of the radar (2 min). Edges are defined at $\beta = 0.3$ (NLC) and SNR = -12 dB (MSE).

half maximum). The lidar is designed for observation of middle atmosphere temperatures and their variability due to gravity waves and tides (Kopp et al., 2015; Baumgarten et al., 2018) and for detection of Noctilucent Clouds NLC in summer. For NLC measurements, aerosol and molecular scattering in the NLC altitude range are separated by exponential interpolation of the background-corrected Rayleigh (molecular) backscatter signal above and below the cloud. The NLC backscatter coefficient at 532 nm (β_{532}) is then calculated from the aerosol backscatter to normalized to the molecular backscatter, the molecular backscatter cross section, and a reference air density to quantify the cloud brightness. Under typical transmission conditions and during full daylight the sensitivity limit of the lidar for NLC is at $\beta_{532} = 0.3 \cdot 10^{-10}\,\mathrm{m}^{-1}\mathrm{sr}^{-1}$ (in the following we describe β_{532} in units of $10^{-10}\,\mathrm{m}^{-1}\mathrm{sr}^{-1}$, i.e. here $\beta = 0.3$). For this study, the backscatter signal has been integrated for 30 s and smoothed by a running average over ±7.5 15 min. The vertical resolution is set to 195 m. The individual profiles have been manually inspected for NLC and only positively identified profiles are used for further processing (cf. Gerding et al., 2013a). NLC backscatter maxima (z^{max}_{NLC} $z^{\mathrm{max}}_{\mathrm{NLC}}$) and layer edges ($z^{low}_{NLC}$ and z^{up}_{NLC}) are automatically evaluated $z^{\mathrm{low}}_{\mathrm{NLC}}$ and $z^{\mathrm{up}}_{\mathrm{NLC}}$) are evaluated automatically. A typical NLC case is shown in Figure 1 (upper panel). The layer edges, defined at $\beta = 0.3$, and layer **Fig.1**
maxima are identified by software an algorithm and marked in the Figure by black and red lines.

2.2 MSE observations by the OSWIN VHF radar at Kühlungsborn

The monostatic OSWIN VHF radar (53.5 MHz) operated in an unattended and continuous measurement mode during the summer seasons. Until 2013 a ~~phased array~~ phased-array antenna field consisting of 12 x 12 Yagi antennas was used. The beam could be tilted, but for the comparisons of MSE and NLC only the vertically directed beam with a beam width of 6° was selected. Two 16-bit complementary codes with 2 μs pulse elements were used. The repetition frequency was set to 1200 Hz. For ~~receiving~~ reception, the antenna array was split in ~~6~~ six subgroups with 24 antennas each, which were connected to ~~6~~ six receivers. Data points were created by coherent integrations of 20 samples. Time series of 1024 data points ~~resulted in length of~~ are acquired within 34.1 s. Considering the time of further alternating measurements, the ~~available~~ time resolution for MSE observations ~~amounted to~~ is 2 min. After 2013 the antenna array was refurbished. The new array is based on 133 Yagi antennas arranged in a hexagonal structure. The width of the vertically directed beam is about 6° again. Two 32-bit-complementary codes with 2 μs pulse elements and 625 Hz repetition frequency are used. For ~~receiving 6~~ reception, six subgroups of 21 antennas each are connected to ~~6~~ six receivers. Time series of 1024 samples (inclusive of ~~8~~ eight coherent integrations) result in length of 26.2 s. In summary we assume fairly similar technical conditions regarding the radar measurements during the summer seasons. In both periods a height resolution of 300 m is maintained. The backscattered signals received by the ~~6~~ six receivers are combined phase conform. Signal-to-noise ratios (SNR) are estimated from the autocorrelation functions of the time series in each height channel. ~~Due to the not available~~ As we do not have an absolute calibration of the radar~~these values are used as a rate~~ , we use SNR as an approximation for the echo intensity~~depending on height~~. The lowest signal level used for MSE observations is chosen at an SNR of -12 dB. A typical example with identified edges is presented in Fig. 1 (lower panel).

2.3 Examples for simultaneous NLC-MSE observations

In the following we show different cases of simultaneous NLC-MSE observations to demonstrate the variability of the layers. Similar to previous studies we ~~find different types of~~ partly find very large agreement between NLC and MSE, while there are differences in other cases (cf. von Zahn and Bremer, 1999; Klekociuk et al., 2008; Kaifler et al., 2011). Examples are given in Figure 2 . Figure 2 a) shows ~~one of the first simultaneous events (~~an event that was observed on 17 June ~~2010).~~ 2010. While **Fig.2** the NLC (filled contours) was first detected above the limit of $\beta = 0.3$ at 2:45 UTC, the MSE (contour lines) was only observed after 3:30 UTC, when the solar elevation exceeded ∼5° and the ionization of the atmosphere was ~~high~~ large enough to allow ~~for~~ a radar backscatter signal. Then both phenomena follow the same vertical movement, presumably related to the cold phase of a gravity wave, with the MSE sometimes reaching to higher altitudes.

Also on 10 July 2015 (Fig. 2 b) NLC and MSE ~~often filled the same volume~~showed a good agreement. The lidar was switched on at 13:50 UTC when the MSE already existed, and NLC were observed from the beginning of the lidar sounding, but in a smaller altitude range. Between 15:30 and 16:50 UTC the NLC vanished, but the MSE showed only a short gap of 10 min and set in again at a much higher altitude about half an hour before the NLC occurs again. Then both layers agreed well until the MSE disappeared at ∼19 UTC at a solar elevation of ∼4°. The NLC observation continued for another 5 h, until the layer descended below 80 km at 0 UTC.

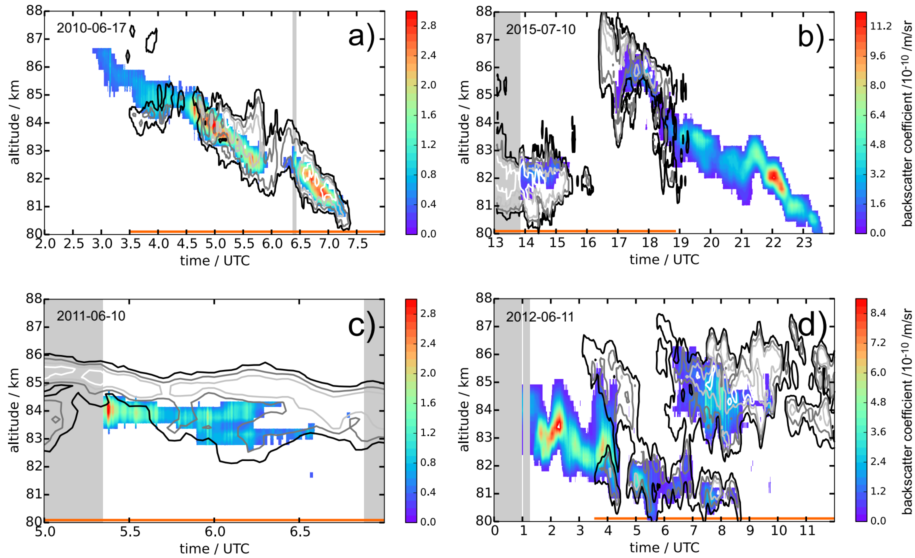

Figure 2. Examples for observations of MSE (contour lines at -12/-6/0/6 dB, if applicable) and NLC (filled contours with scale on the right). The orange lines indicate periods with solar elevation >5°. The gray shaded areas mark periods without lidar soundings due to presence of clouds. a) 17 June 2010: MSE starts after sunrise into existing NLC. b) 10 July 2015: MSE vanishes after sunset while NLC continuous. c) 10 June 2011: When lidar starts operation NLC is immediately detected, but does not extend as high as the MSE. d) 11 June 2012: MSE starts into existing NLC after sunrise and continues especially at higher altitudes when NLC disappears.

On 10 June 2011 (Fig. 2 c) NLC were observed from the beginning of the lidar sounding at 5:21 UTC. Earlier, the ice particles were already detected by the radar as MSE, but tropospheric clouds inhibited lidar operation. In contrast to the other cases, here only the lower edges of the phenomena agreed, but the MSE extended above the NLC and was in fact strongest at altitudes above the NLC upper edge. Later on, the NLC ceased while the MSE continued.

A rare example of a double ice layer was observed on 11 June 2012 (Fig. 2 d). The cloud was first confirmed by the lidar, showing that the NLC was very variable in altitude due to the presence of gravity waves. After ∼3:20 UTC the NLC layer thickness increased to ∼5 km (81 – 86 km). Just at the same time the radar echo started due to increasing solar elevation, i.e. increasing ionization. The MSE ~~fastly growed to~~ quickly grew into a double layer, with a gap around 83 km altitude, where the NLC was found brightest. The NLC and MSE around 82 km faded away at 4:23 UTC and set in again ~~slightly after each other~~ at 4:40/4:45 UTC (MSE/NLC). In the meantime, the only remaining ice signal was observed by the radar above 83 km. Past ∼5 UTC the upper MSE layer vanished, but reappeared shortly after. At ∼6:15 UTC also the NLC formed a (very rare) double layer until ∼8:30 UTC, when the lower layer of both, NLC and MSE, ceased. Despite being weak, the upper NLC layer remained observable until ∼10 UTC, while the MSE still continued in a broad range (83 – 87 km). The variable structure of the ice cloud with double layers indicates a highly dynamic behavior of the atmosphere with presence of strong gravity waves. Nevertheless, a detailed examination of the dynamical structure is beyond the scope of this paper.

The examples shown above demonstrate the different relations of the NLC and MSE layer edges and the different degrees of accordance of the layers. This is in general agreement with observations at polar latitudes (e.g. Klekociuk et al., 2008; Kaifler et al., 2011) . The examples indicate an often good concurrence of the lower edges but a worse agreement of the upper edges. If solar elevation (i.e. ionization) is sufficiently large, NLC are often but not always accompanied by MSE. The latter might be explained by missing turbulence, but this cannot be proven here because a lack of appropriate measurements. Periods with MSE but absent NLC can be caused by mainly small ice particles, resulting in lidar signals below the NLC detection threshold. In the following we neglect profiles of NLC without MSE as well as MSE without NLC to be sure that for this study all requirements for the observation of small and large ice particles are fulfilled (see below).

2.4 The data set used for this study

Within this study we only focus on simultaneous NLC and MSE events (e.g., after 3:30 UTC in Fig. 2 a, but excluding the little MSE gaps between 4 – 5 UTC), to compare the altitude ranges where both phenomena are observed. Nighttime NLC, where ionization of the atmosphere is typically too low small for MSE generation, are ignored as well as a few NLC where the radar was switched off for maintenance. Vice versa we do not count ice clouds (detected as MSE) that are found too high or too weak to be observed by lidar or that occured when the lidar was switched off, e.g., during tropospheric cloud coverage. Overall, we use ∼67 h of NLC with $\beta > 0.3$ for this study, out of 188.5 h of NLC in total ($\beta > 0$, day and night) in the years 2010 – 2016. The total These data are distributed across 31 days with an average ice cloud duration of 2.2 h. For this study it is not relevant whether the ice observation is uninterrupted in time or not, because the layer parameters are derived based on individual (but smoothed) profiles. About 121 h of NLC detection cannot be used here because of either too weak NLC ($\beta < 0.3$) or absence of MSE (mainly missing ionization at night or missing turbulence). Nevertheless, this subset of NLC is representative for the whole data set in terms of layer heights, as discussed in Section 5. The total usable lidar operation time within the 7seven summers (1 June to 4 August) is 3337 h. MSE are observed by OSWIN for 960 h out of 8600 h of total sounding time. As mentioned above, only for 67 h the MSE (SNR > 12 dB) occur during lidar operation and simultaneously with NLC of $\beta > 0.3$, i. e. . Note that this study is representative for ice clouds containing large particles, but not sufficiently large particles to be detectable by lidar, but it is not representative for MSE (ice clouds) in general.

3 Comparison of NLC and MSE layer properties

Based on the data set of simultaneous NLC and MSE (gridded to 2 min temporal resolution) we identify the lower edges (z_{NLC}^{low} and z_{MSE}^{low} $z^{\mathrm{low}}_{\mathrm{NLC}}$ and $z^{\mathrm{low}}_{\mathrm{MSE}}$), the altitudes of maximum brightness (z_{NLC}^{max} and z_{MSE}^{max} $z^{\mathrm{max}}_{\mathrm{NLC}}$ and $z^{\mathrm{max}}_{\mathrm{MSE}}$) and the upper edges ($z_{NLC}^{up}$ and z_{MSE}^{up} $z^{\mathrm{up}}_{\mathrm{NLC}}$ and $z^{\mathrm{up}}_{\mathrm{MSE}}$) for each profile of both phenomena independently, as shown in Fig. 1. In the rare case of a double layer we take the lower edge of the lower layer and the upper edge of the upper layer together with the absolute maximum. Overall, we get 1931 profiles with their respective properties, even if the particular smoothing of lidar and radar data needs to be taken into account for interpretation. In Figure 3 (left) the altitude distributions of z_{NLC}^{low} and z_{MSE}^{low} $z^{\mathrm{low}}_{\mathrm{NLC}}$ **Fig.3** and $z^{\mathrm{low}}_{\mathrm{MSE}}$ are summarized in 1-km-bins1 km bins. The most striking feature is the similarity between the altitude distributions

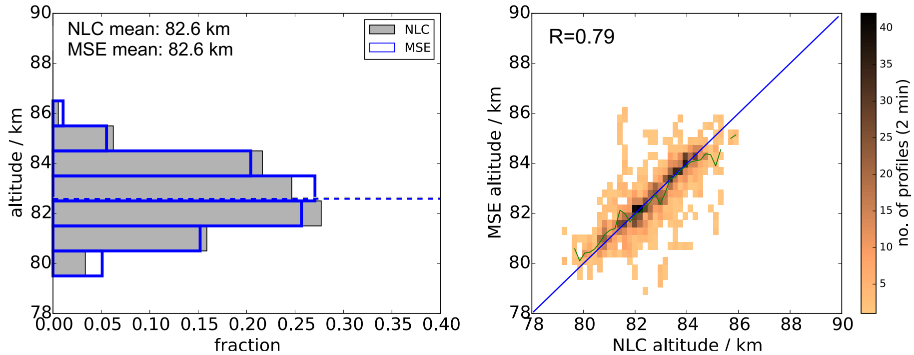

Figure 3. Comparison of lower edges of NLC and MSE (z^{low}_{NLC} $z^{\mathrm{low}}_{\mathrm{NLC}}$ and z^{low}_{MSE} $z^{\mathrm{low}}_{\mathrm{MSE}}$). a) Histogram with NLC edges in grey (filled) and MSE edges in blue (open histogram). Mean values are indicated by the dashed lines. b) Scatter plot of MSE and NLC edges. Only simultaneous soundings based on a 2 minute temporal resolution are evaluated. The green line in b) shows the average MSE lower edge altitude for each NLC edge bin and the blue line indicates identical altitudes.

of NLC and MSE lower edges. In the evaluated data set, no cloud is observed below 80 km. The mean values of both, z^{low}_{NLC} and z^{low}_{MSE} $z^{\mathrm{low}}_{\mathrm{NLC}}$ and $z^{\mathrm{low}}_{\mathrm{MSE}}$ are found at ∼82.6 km (dashed lines). The Figure figure shows only small differences between both distributions. In Figure 3 (right) the lower edges of all individual NLC/MSE profiles are compared. The plot confirms the similarity between both parameters. Most often the z^{low} z^{low} agree within a single altitude bin, which also shows up in the correlation coefficient of R=0.79. The differences between z^{low}_{NLC} and z^{low}_{MSE} $z^{\mathrm{low}}_{\mathrm{NLC}}$ and $z^{\mathrm{low}}_{\mathrm{MSE}}$ can be up to a few hundred meters, and there is no altitude dependence of the differences. Thus, very high ice clouds show the same similarity as low or typical layers. The mean difference between z^{low}_{NLC} and z^{low}_{MSE} $z^{\mathrm{low}}_{\mathrm{NLC}}$ and $z^{\mathrm{low}}_{\mathrm{MSE}}$ is ∼40 m with a standard deviation of 417 m. In a few cases the altitude difference can be up to 4 – 5 km. This can already be seen in Fig. 2 d), e.g., in cases of MSE onset in the morning twilight . where sometimes the MSE only agrees with the uppermost part (i.e. largest ionization) of the ice cloud. Part of the differences can also be explained by the different fields of view (FOV). The radar has a FOV of 6° = 0.1 rad, while the lidar FOV is more pointlike only ∼1/1700 of this (62 μrad). This may lead to some differences at least in cases of very structured ice clouds. Overall, in a statistical mean both Rarely, the different size dependencies of lidar and radar signals can lead to MSE even a few km below the NLC. On average, these effects only have a small influence on the general distribution.

The altitude distribution of the ice layer maxima (backscatter coefficient for NLC and signal-to-noise ratio for MSE) is shown in Figure 4 . The mean of z^{max}_{NLC} $z^{\mathrm{max}}_{\mathrm{NLC}}$ is observed at 83.3 km (grey dashed line in left panel), while the mean of z^{max}_{MSE} **Fig.4**
$z^{\mathrm{max}}_{\mathrm{MSE}}$ is slightly higher at 83.6 km (blue dashed line in left panel). No NLC maximum is observed above 86 km, but a few MSE maxima. This is also resembled in the scatter plot (Fig. 4(right)), right). Similar to the lower edges there is no pronounced altitude dependence of the differences between z^{max}_{NLC} and z^{max}_{MSE} $z^{\mathrm{max}}_{\mathrm{NLC}}$ and $z^{\mathrm{max}}_{\mathrm{MSE}}$ (green line). The correlation coefficient is R=0.80. While again the individual z^{max}_{NLC} and z^{max}_{MSE} $z^{\mathrm{max}}_{\mathrm{NLC}}$ and $z^{\mathrm{max}}_{\mathrm{MSE}}$ sometimes differ by a few kilometers, the mean value of the differences is only ∼300 m with a standard deviation of 375 m.

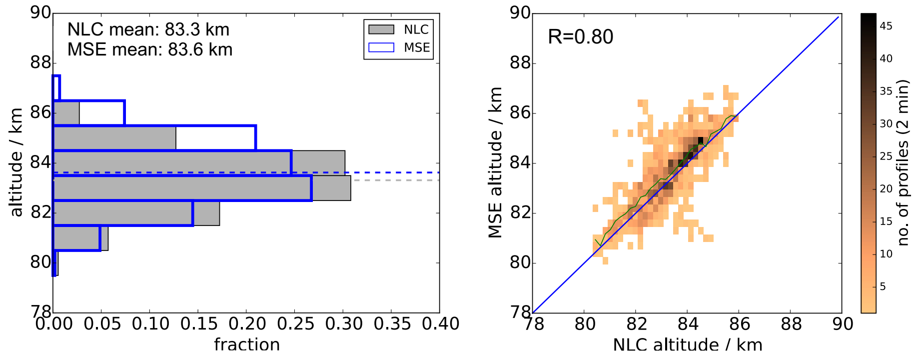

Figure 4. Same as Figure 3, but for the layer maxima (~~z_{NLC}^{max}~~ $z_{\mathrm{NLC}}^{\mathrm{max}}$ and ~~z_{MSE}^{max}~~ $z_{\mathrm{MSE}}^{\mathrm{max}}$).

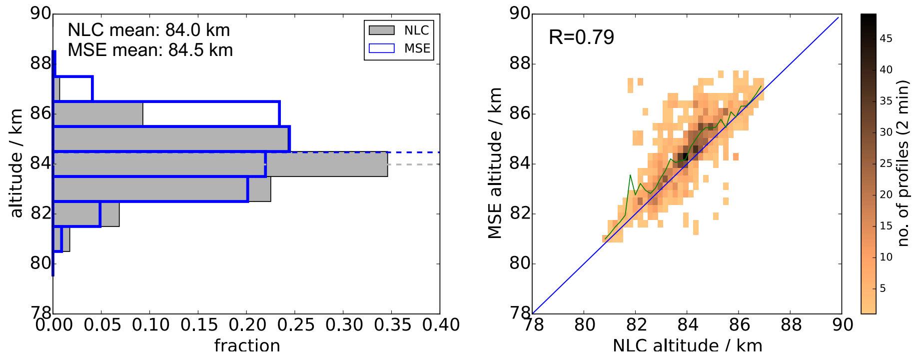

Figure 5. Same as Figure 3, but for the upper edges of NLC and MSE (~~z_{NLC}^{up}~~ $z_{\mathrm{NLC}}^{\mathrm{up}}$ and ~~z_{MSE}^{up}~~ $z_{\mathrm{MSE}}^{\mathrm{up}}$).

The largest differences between NLC and MSE are expected at the upper edges of the layer (cf. Kaifler et al., 2011). This is due to the fact that the nucleation typically starts close to the mesopause, where water vapour saturation is largest. These small particles can already be ~~visible for~~ detected by radars (signal strength proportional r^2, if turbulence and ionization allow). If the supersaturated ~~regions~~ region extends further down, the particles start to sediment and grow, ~~getting~~ and become finally visible for lidars (signal strength proportional $r^5..r^6$). Indeed, we find the mean ~~z_{MSE}^{up}~~ $z_{\mathrm{MSE}}^{\mathrm{up}}$ about 500 m above the mean ~~z_{NLC}^{up}~~ $z_{\mathrm{NLC}}^{\mathrm{up}}$ for all simultaneous observations (Figure 5), i.e. at 84.5 km and 84.0 km, respectively. The scatter plot shows that the height **Fig.5** difference is largely independent of altitude. Only for the very high (>85 km) and very low (<82 km) layers the differences seem to vanish, but the number of such events is ~~low~~ small. The smaller height difference can be explained by the typically smaller width of the ice clouds at these altitudes (not shown). In contrast to the layer maxima and lower edges, differences of a few kilometers are mainly found with the MSE top being much higher than the NLC top. Thus, the distribution of differences is not symmetric, but has a tail towards higher MSE as typically expected. Note that the correlation of ~~z_{MSE}^{up} and z_{NLC}^{up}~~ $z_{\mathrm{MSE}}^{\mathrm{up}}$ and $z_{\mathrm{NLC}}^{\mathrm{up}}$ is still high (R=0.79).

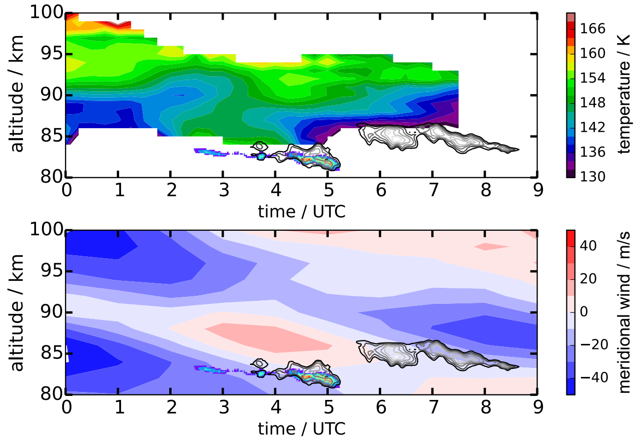

Figure 6. Temperature (top) and meridional wind (bottom) above Kühlungsborn during 26/27 June 2011. The MSE data is embedded in both panels for illustration as open grey contours and the NLC data in colored filled contours. Cloud 1: 2:30 – 5:15 UTC, Cloud 2: 5:30 – 8:40 UTC

4 Comparison of NLC/MSE with local wind and temperature structure

There is general agreement that ice clouds are limited to regions with temperatures below the frost point temperature. For our location we have already shown that NLC occur only in the cold phases of gravity and planetary waves, while mean temperatures are above the frost point in the whole mesopause region (Gerding et al., 2007, 2013a). Additionally, we demonstrated that southward directed winds are necessary for the occurrence of NLC at our site (Gerding et al., 2007, 2013b). Here we want to check whether the ambient wind and temperature conditions are responsible for the altitude of the layer edges, i.e. the thickness of the NLC and MSE. We therefore evaluated the temperatures and winds especially above the layers.

Temperature soundings above MSE require a metal resonance lidar (for the altitude coverage) and daylight capabilities (for observation during MSE). The potassium resonance lidar at Kühlungsborn was in operation until the end of 2012, i.e. it covered part of the examined time period. The upper panel of Figure 6 shows an example of the temperature structure **Fig.6** above two ice layers in the early morning of 27 June 2011. The first layer ('Cloud 1') arose at ∼2:30 UTC in the lidar (NLC, coloured layer) and did not extend above 83.5 km. The MSE (grey contour lines) appeared first at 3:30 UTC in 84.3 km, when ionization was sufficient (solar elevation 4.7°). Above Cloud 1 the potassium resonance lidar observed temperatures of more than 150 K, i.e. higher than the expected frost point temperature for these altitudes. In other words, the temperature structure inhibits an expansion of the layer to higher altitudes. Later, Cloud 1 descends and vanishes at 5:15 UTC. ~~A new~~ Another ice layer ('Cloud 2') appeared at ∼5:30 UTC around 86 km. This coincides with a strong temperature decrease below ∼140 K in the same altitude range. We point out that Cloud 2 was observed by radar only (MSE), but did not contain particles large enough to be observed by lidar (NLC). Lidar observations stopped due to tropospheric clouds at ∼8 UTC. Note the integration time of the temperature data of 2 h, shortened to 1 h at the beginning and end of the sounding.

The lower panel of Fig. 6 shows the meridional wind observed by the nearby meteor radar (120 km north-east of Kühlungsborn). The warm region above Cloud 1 is accompanied by a northward wind, while the wind in the altitude of the layer is southward as expected from previous observations. At the time and altitude of the (higher) Cloud 2 the wind direction has changed to a weak southward wind. Overall, this typical case shows a large likelihood for advection of Cloud 1 that appeared as both MSE and NLC, because local ice formation is inhibited by the high temperatures above 85 km. Note that before 02 UTC low temperatures of ∼140 K have been observed above 85 km, but at this time no ice cloud was observed. The second case (Cloud 2) has the potential for local formation above 85 km, but this layer is confined to higher altitudes and does not contain larger ice particles (NLC). Both clouds are confined to southward winds.

We have analysed the temperature and wind data set above the NLC/MSE for all available coincident measurements. Due to often hazy sky conditions and therefore ~~high solar background~~ large solar background at near-infrared wavelengths, the temperature data set of the potassium lidar is smaller than the NLC data set of the RMR lidar. Between 2010 and 2012 only ~~7~~ seven events can be evaluated, with some of the data sets showing a gap of up to 2 km between the NLC/MSE and the temperature data. The temperature structure above the ice clouds varies between the events. Partly, we find an immediate temperature increase above (~~5~~ five cases), inhibiting ice existence in these heights. In the other ~~2~~ two cases, the supersaturated region extends for some kilometers above the observed ice cloud and includes the height region expected for nucleation (87 – 90 km, e.g. Kiliani et al. (2013)). In this case, ice particles may still exist in the supersaturated region, even if not detected by the OSWIN radar. Low temperatures typically persist only for a few hours at our site (e.g. Gerding et al., 2007). In this time, ice particles only grow to a few nanometers radius (Rapp and Thomas, 2006), and continuous turbulence is needed to create radar echoes~~(Rapp and Lübken, 2004).~~ , in contrast to intermittent turbulence being sufficient in combination with larger ice particles (Rapp and Lübken, 2004). Additional ionization is needed in both cases. Unfortunately, there is no information about ambient turbulence available and the question about ice existence cannot be finally answered.

The wind structure above the NLC/MSE is also not uniform in all events. Overall, 23 events between 2010 and 2016 have been evaluated. During most of the events (~~9~~ nine cases) the wind above the ice layer is southward (as in the ice layer). ~~7~~ Seven cases show northward winds above the cloud. In ~~3~~ three cases the wind direction is changing, while ~~4~~ four cases show only weak winds (less than ±10 m/s).

5 Discussion

~~Statistical studies~~ Studies on the layer properties of NLC and MSE at midlatitudes are rare, because there is only ~~small observation probability~~ a small occurrence frequency of 5 – 10% for MSE and NLC (e.g. Thomas et al., 1996; Zecha et al., 2003; Gerding et al., 2013a). Therefore, ~~statistical analyses~~ analyses of average layer parameters need multi-year observations to yield a representative data base. The only statistical NLC study at midlatitudes has been done at our site at Kühlungsborn based on the nighttime observations of the ~~first~~ previous RMR lidar (Gerding et al., 2013a). The results are in good agreement with the data presented here~~, e. g., the~~ . They report a mean centroid height of 82.7 km ~~reported earlier compares~~ which compares very well with the mean ~~peak altitude~~ centroid height of 82.6 km and mean peak height of 82.8 km of all NLC (daytime and nighttime) in the 2010–2016 period used here. Selecting only days that also show MSE, the mean NLC peak height is slightly higher (83.0 km), but within the geophysical variability. The remaining difference to the mean $z_{\mathrm{NLC}}^{\mathrm{max}}$

of ~~this study.~~ 83.3 km mentioned in Fig. 4 can be explained by the further selection of profiles really showing simultaneous MSE. Especially some very low NLC profiles (below 80 km) are excluded here because of missing MSE, which is potentially caused by the reduced electron density. Furthermore, the faintest NLC profiles with $\beta < 0.3$, e.g., in the beginning and end of events are also excluded in Fig. 4. Therefore the apparent difference in NLC layer heights compared to previous studies can be explained by geophysical variability and treatment of the NLC data. But this does not hamper the representativeness of this study for all NLC.

For MSE there is an earlier study by Zecha et al. (2003) using radar data from Kühlungsborn. They report the occurrence rate of MSE at each particular height bin which is different from the histogram of peak altitudes that we present here. Even more important, we limit the MSE data set to events with simultaneous NLC, because we want to focus on optically visible ice clouds. By this we suppress weak and high (typically >86 km) layers of MSE that are often not accompanied with NLC. We note that we skip the majority of MSE by this selection. Therefore, the results presented here are not representative for all MSE.

As explained above, there are only very few studies for high-latitude, simultaneous NLC and PMSE. Kaifler et al. (2011) evaluated a large data set of NLC and PMSE from ALOMAR (69° N, 16° E). Simultaneous events are summarized in their categories III, IV, and V. In their Table 3 they report ~~a mean difference of the upper~~ also quasi-identical lower edges of NLC and PMSE~~(z^{up}_{NLC} and z^{up}_{MSE})~~, even if the $z^{\rm low}$ at higher latitudes are observed 0.5 km above the midlatitude values. This latitudinal difference of $z^{\rm low}$ can be explained by the general increase of NLC altitudes with latitude (Lübken et al., 2008; Chu et al., 2011) which is related to the ambient temperature structure.

Regarding the upper edges ($z^{\rm up}_{\rm NLC}$ and $z^{\rm up}_{\rm PMSE}$), Kaifler et al. (2011) report a mean difference of ~3.3 km, i.e. much larger than the difference of 0.5 km that we observe at midlatitudes. Klekociuk et al. (2008) examined one season of simultaneous observations of NLC and PMSE at 69° S at Davis Station (Antarctica). Occurrence rates of both phenomena are much smaller compared to the Northern Hemisphere. The authors do not provide numbers for the upper and lower edges of the layers, but from their Fig. 1 one can expect a difference of the upper edges similar to the numbers given by Kaifler et al. (2011).

The reason for the large height difference between ~~z^{up}_{NLC} and z^{up}_{MSE}~~ $z^{\rm up}_{\rm NLC}$ and $z^{\rm up}_{\rm MSE}$ at high latitudes is the typically much larger thickness of the PMSE layer (cf. Kaifler et al., 2011). In agreement with these observations, Kiliani et al. (2013) demonstrated with a 3d trajectory model the formation of ice-particles at the high-latitude mesopause, and subsequent ~~descend~~ descent and growth. At high latitudes often a layer of small particles (only visible by radar) exists above the larger ice particles that can also be detected by lidar. This situation is in qualitative agreement mit Odin/OSIRIS observations (Hultgren and Gumbel, 2014) and sketched in the upper part of Figure 7 . The small difference between upper layer edges in our observations **Fig.7** ~~hint to the conclusion~~ suggests that the layer of ~~only~~ small particles is missing at midlatitudes. In this case, the larger, optically visible ice particles cannot be formed locally, but typically have to be advected (see lower left part of Fig. 7). Kiliani et al. (2013) found in their simulations the last ~6 h before observation being most relevant for particle growth. In this period, the ice particles typically travel 150–500 km southward. Before, the ice particles remained small (< 20 nm) for more than 60 h. ~~Typically, the NLC at midlatitudes are formed 150 – 500 km farther north.~~ In agreement with this, NLC above Kühlungsborn are generally observed during southward wind conditions (Gerding et al., 2007, 2013a, b), and also in the Southern Hemisphere

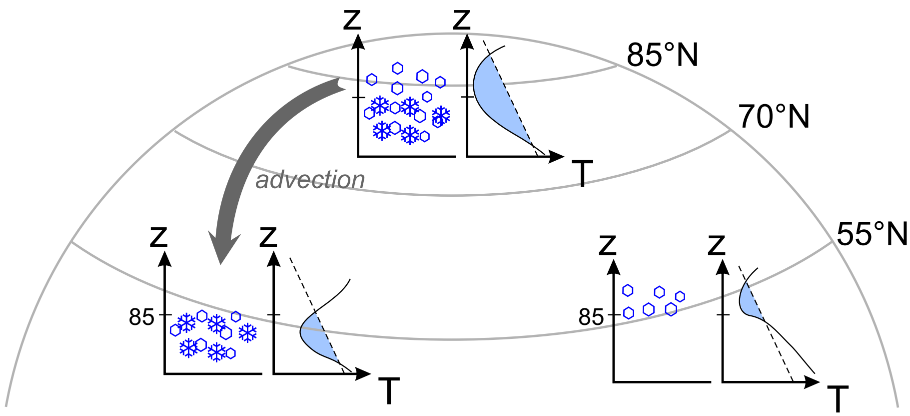

Figure 7. Schematic of the latitudinal differences for ice cloud formation. The x-y-plots represent the ice particle distribution with height (left) and the corresponding temperature profile (right). Small particles only visible for the radar are marked by light blue hexagons, larger particles by blue snowflakes. The light blue part of the temperature profile shows the region of supersaturation (dashed: frost-point temperature). The altitude of 85 km is marked, forming a typical upper limit of NLC.

NLC even at high latitudes (69° S) are typically limited to equatorward winds (Morris et al., 2007; Klekociuk et al., 2008). In contrast, Stevens et al. (2017) found a dominating dependence of NLC on local temperatures even at midlatitudes, using NOGAPS-ALPHA assimilated model data. The authors explicitly neglected transport effects by using a 0-D NLC model, making a direct comparison with our findings difficult. Similarly, Herron et al. (2007) and Hultgren et al. (2011) found local effects dominating the formation of NLC for their midlatitude observations.

Furthermore, we cannot exclude longitudinal differences for the formation of ice clouds. According to SOFIE observations our site is at the longitude of minimal NLC occurrence rates (Hervig et al., 2016), hinting at suggesting different cloud formation mechanisms compared to other longitudes. It has been shown before for our site that temperatures below the frost point as well as southward winds are necessary but not sufficient criteria for NLC observations (Gerding et al., 2007). Supersaturated regions upstream of Kühlungsborn are needed to foster the nucleation process and to allow for the particles to grow to sufficient sizes (Fig. 7, lower left). About one third of the events examined here show southward winds also above the layer. The fact that these air parcels do not contain ice particles again confirms that southward winds are necessary but not sufficient for ice existence above our site. On the other hand, in another third of our events we found northward winds directly above the cloud, i.e. advecting air from (presumably) warmer regions. We would like to note that the OSWIN radar often detects MSE in thin layers above 85 km altitude (e.g. Zecha et al., 2003). We cannot exclude that these MSE are formed by ice particles nucleated closeby. But these particles typically do not reside long enough at our site to grow to sizes that allow optical detection, or the supersaturated height range is too thin to allow effective growth during sedimentation. This is sketched in the lower right part of Fig. 7.

In contrast to the upper edges, the lower edges of NLC and PMSE at 69° N typically agree quite well (Kaifler et al., 2011), similar to our observations. This is in fact expected due to the fast sublimation of the ice particles with rising temperatures at

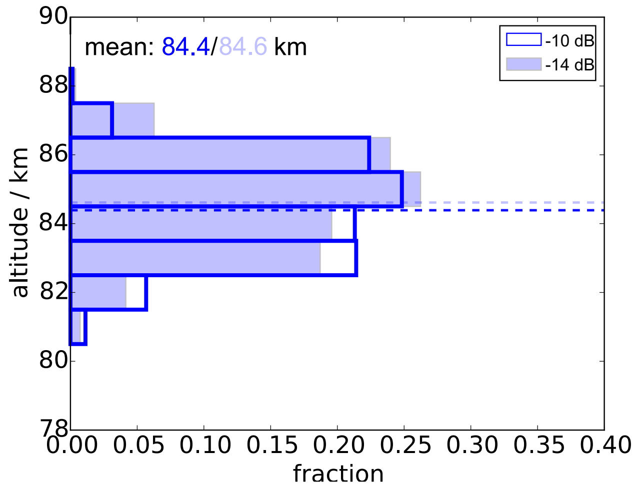

Figure 8. Same as Figure 5, but with different MSE thresholds. blue, open: MSE threshold SNR = -10 dB; light blue filled: MSE threshold SNR = -14 dB.

the lower edge of the layer. Of course, the instrument's sensitivity needs to be taken into account for comparison of layer edges. For the lidar observations described here we set the threshold to $\beta = 0.3$, ~~what~~ which is slightly smaller than the threshold used in Gerding et al. (2013b) for the same lidar ($\beta = 0.5$). We confirmed by manual inspection that the edges of the individual NLC are correctly identified and not affected by background noise. For the radar data we processed the data in units of SNR. The threshold is set to -12 dB ~~based on the~~ to be above the typical noise limit of the radar. We tested the influence of this threshold by setting it to ~~higher and lower~~ larger and smaller numbers. Figure 8 shows the same histogram as Fig. 5, but for thresholds of **Fig.8** -10 dB and -14 dB. As expected, the mean ~~z^{up}_{MSE}~~ $z^{\mathrm{up}}_{\mathrm{MSE}}$ rises to 84.6 km if also weaker MSE are included. Limiting the data to >-10 dB, we found the mean ~~z^{up}_{MSE}~~ $z^{\mathrm{up}}_{\mathrm{MSE}}$ at 84.4 km. In other words, the mean shift between both test scenarios is only 200 m, i.e. less than one altitude bin of the radar (300 m). Changing the NLC threshold has similar results. Also here the gradients at the layer edges are very large (see, e.g., Fig. 2) and a change of the threshold to, e.g., $\beta = 0.5$ would result in only minor changes of the histograms. Therefore, there are only minor effects of the thresholds on layer edges, while the layer maximum is not affected at all. In any case, the changes due to threshold adaptions are much smaller than the difference to observations at higher latitudes.

6 Summary and Conclusions

In this study we compared NLC and MSE altitudes from simultaneous observations at our midlatitude site Kühlungsborn (54° N, 12° E). There is general agreement that both phenomena represent ice clouds, with the visible echoes (NLC) being formed by ice particles of typically some tens of nanometers diameter. The radar echoes (MSE) can also be formed by smaller particles, but require a sufficient density of free electrons as well as structures in the plasma. We have presented examples for NLC-only and MSE-only periods as well as for simultaneous layers with at least partial overlap in the covered altitude region.

For the average layer parameters we only concentrated on simultaneous detections, i.e. we discarded nighttime NLC because of typically too low small electron densities to form MSE. Furthermore we discarded all those high and weak MSE that are not accompanied with NLC. Overall, we got ∼67 h of NLC/MSE data within the summers 2010 – 2016.

On average, the lower edges of NLC and MSE are identical, which is in agreement with the general understanding of fastly quickly sublimating ice particles at the bottom of the layer. The average values for the layer peaks and for the upper edges differ by 0.3 km and 0.5 km, respectively, with the MSE being slightly above the NLC. This comparatively small difference is in contrast to the observations at polar latitudes, where the PMSE often extend several kilometers above the NLC. We conclude that the layer itself is much thinner compared to polar latitudes (under the assumption that the MSE layer thickness at midlatitudes is not limited by smaller electron density or missing turbulence). Clouds that already exist long enough to form large particles (NLC) show only a thin layer of small particles (invisible for the lidar) above the NLC or no such layer at all, at our site. Using simultaneous resonance lidar temperature soundings we typically found the atmosphere above the layer being too warm for ice existence, limiting the potential extend extent of the cloud. Meridional winds above the NLC are often southward or weak. Altogether, these observations give evidence that local formation of NLC/MSE is possible, but these ice particles do not stay long enough to grow to optically visible sizes. All layers that are observed as NLC are already formed and then advected to our site by the meridional wind. During advection and descenddescent, the smaller particles grow to sizes of some ten nanometers. By this, they become detectable by lidar. This formation process needs to be acknowledged must be taken into account if, e.g., midlatitude NLC observations are used to study trends or climate change in the mesopause region.

Competing interests. The authors declare that they have no conflict of interest.

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