Reviewer #2 Comments from Silvan Leinss

Review, "Wind Transport of Snow Impacts Ka- and Ku-band Radar Signatures on Arctic Sea Ice" by V. Nandan et al.

The manuscript presents waveform and backscatter time series aquired over snow covered sea ice with a ground-based radar altimeter and scatterometer. The instrument has an exceptional bandwidth of 6 GHz at Ku-band (13.6 GHz) and 10 GHz at Ka-band (35 GHz) resulting in centimeter slant-range resolution. The instrument can provide detailed and relevant information to interpret data from existing and future radar altimeter missions like CryoSat-2, CRISTAL, SARAL, etc. Publishing such data and time series is a valuable contribution suitable for the journal The Cryosphere (TC). The manuscript, however, requires thoroughly revision (major) to meet scientific publishing standards and to focus more concisely on the most relevant aspects of the valuable work.

The most relevant points of manuscript are:

- Very few ground-based radar data especially over sea ice exists. The manuscript contains detailed plots of such data which provides valuable observations.

- The time series plots of very high (centimeter) resolution Nadir backscatter returns reveal the dynamics of the relative scattering contribution of the main interfaces air/snow and snow/ice. The data show that air/snow interface is not necessarily the strongest scattering contribution , even at Ka-band, which is valuable for future radar altimeter missions.

- during pre-wind conditions the dominant radar return (at 13 and 35 GHz) at nadir alternates between the air/snow interface and the snow/ice interface.

- The creation of hard Wind slabs causes an increase in backscatter at Nadir and a decrease in backscatter for non-nadir angles (observed at 15...50°).

- The comparison of Nadir radar returns with off-nadir (theta_inc > 15°) is a valuable information regarding penetration depth of radar sounders/altimeters (less penetration) vs. SAR systems (larger penetration due to slant-looking gemometry).

The authors thank Dr. Leinss for their valuable time to review and provide feedback to improve our manuscript. Following is our rebuttal (in black) to reviewer’s comments (in red) and associated changes in the revised version of the manuscript.

General comments:

The manuscript needs considerable improvements in readability and focus.

- Try to focus/condense on most relevant aspects (see above), We agree with your comment on condensing the main points. The revised version now focuses only on the ranging and backscatter analysis, supported by TLS, meteorological and geophysical observations.

a) We have revised the KuKa radar geometry section with detailed schematic of the footprint and measurements (see section 2.1 and revised figure 1 in the revised manuscript)
b) We agree that the phase difference analysis distracts from the main message of this paper and requires more analysis for better interpretation. Therefore, we have removed the phase difference analysis from this paper.
c) To avoid confusion, we have removed the concept of positive and negative azimuth sectoring description. Instead, we focus on individual footprint azimuth angles for Ka- and Ku-band frequencies (see last paragraph of section 2.5).
d) Points a) and c) has led to revised interpretation of the backscatter analysis, supported by TLS, radar ranging and snow geophysical data.

- consider to shorten where possible, e.g. the polar plots seem not to reveal too much information;

We do agree the irrelevance of co-pol phase difference analysis in this paper via polar plots and we have removed the entire analysis from the paper. However, we have retained the backscatter analysis using azimuth sectoring as the polar plots clearly show spatial variability in backscatter within the footprint, as a function of incidence angle and polarization, in response to wind-driven snow dynamics and thermodynamic-induced metamorphic changes to snow layering. This analysis distinctly shows the importance of accounting for spatiotemporal variability in snow properties within a satellite footprint which can contribute to the overall measured changes in dominant scattering horizon and backscatter.

In the revised version, we have revised this analysis through improved representation of KuKa radar geometry (see changes and depiction below in the rebuttal).

- results/discussion/conclusion: check for redundant, irrelevant information.

The authors agree with your comment. We have removed the CPD analysis from the paper and discussed only the relevant information related to our primary objectives (ranging and backscatter analysis). We have also revised our interpretation on azimuth sectoring (section 3.3.2) based on changes in the KuKa radar geometry and removal of the 'positive' and 'negative' azimuth sector concept. In the radar backscatter analysis (section 3.3.1), we have refined our interpretations, particularly with respect to non-nadir incidence angles at 15 and 35 degrees.

- Give the main points more weight by improving the graphics showing these results.

We have modified and improved the plots as suggested for Figures 1, 2, 3, 6, 8 and merged Figures 9 and 10 into one single (now Figure 9 based on the revised KuKa radar geometry).

- I really don't understand what is the exact extend and overlap of the observed area with Ku- and Ka band. Different ranges of azimuth angles are given in the text and figures; please clarify this using an observation-setup-sketch showing all relevant geometric parameters.

The reviewer makes a valuable point here. We reviewed the KuKa footprint geometry based on the radar system setup. Although the KuKa azimuth scanning range was set between -45 and +45 degrees (i.e. 90 degree azimuth range), there is ~ 20 degree offset between the individual antennas and the radar positioner axis origin (see revised Figure 1 below). The Ku-band antenna therefore scans between ~ -65 degrees to +25 degree azimuth range (region between purple lines) and from -25 degrees to +65 degrees for Ka-band (region between green lines) (Figure 1(b), (e) and (f)). The region (yellow) between green and purple lines) between -25 degrees and +25 degrees is the overlapping Ku- and Ka-band footprint (Figure 1(b)).

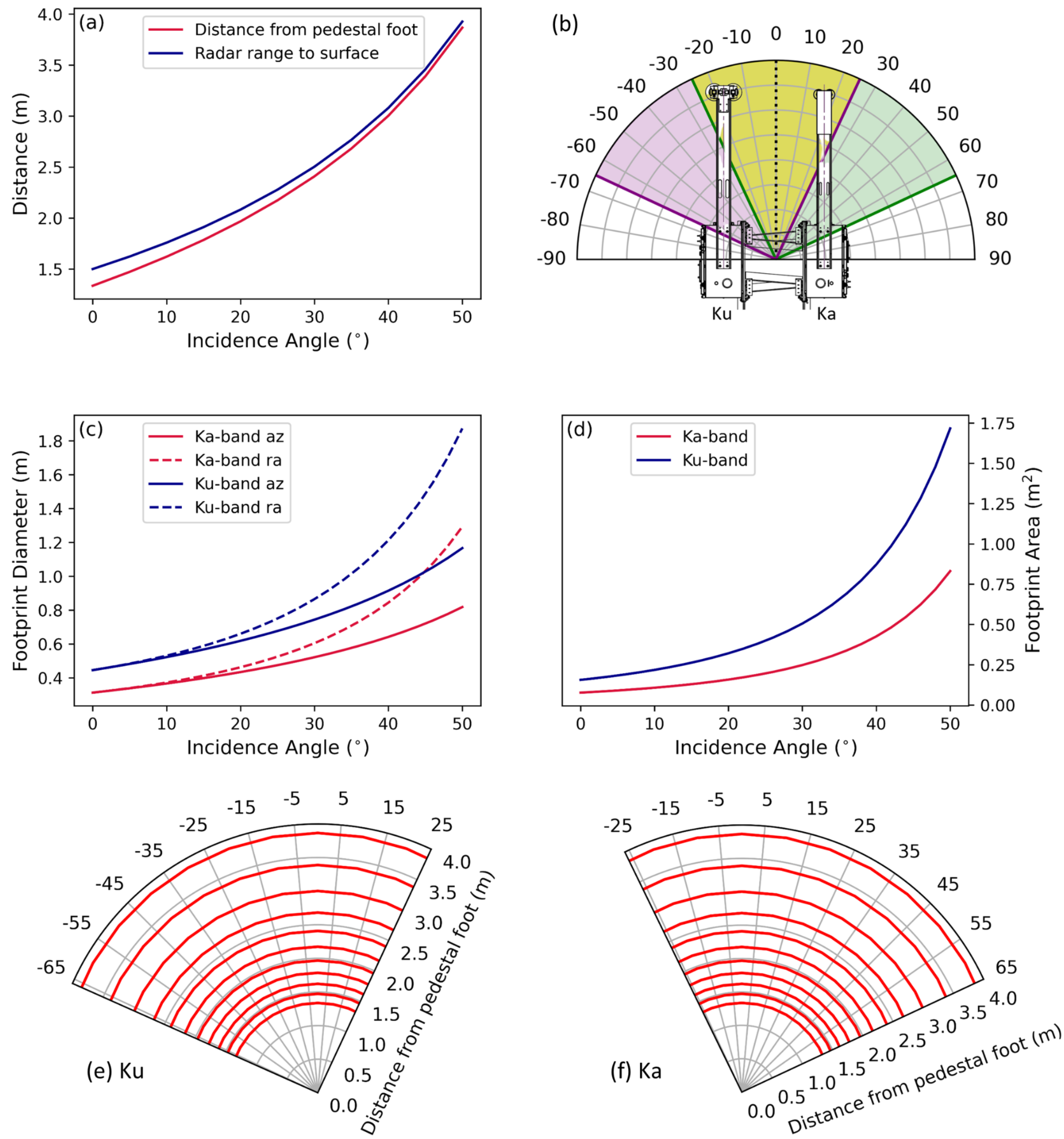


Figure 1: KuKa radar geometry illustrating (a) radial distance and radar range from the pedestal foot; (b) KuKa radar azimuth scan pattern projected based on the positioner axis coordinate system; (c) diameter of radar footprint, measured radially ('ra') and azimuthally ('az'); and (d) area of radar footprint; (e) and (f) depicts the Ku- and Ka-band footprints of the KuKa radar, respectively. In panel (b), the region between purple lines and green lines are the respective Ku- and Ka-band footprints (separately shown in panels (e) and (f), while the yellow region in (b) is the overlapping footprint area for both frequencies.

The revised figures 8-11 are averaged between -25° and +25°, which is the commonly sampled region for Ku- and Ka-band frequencies. In section 2.1, we have provided a detailed description of the overlapping KuKa geometry, as follows:

"During MOSAiC, the KuKa radar scanned over a 90° continuous θ_{az} *range width (between -45° and +45°) for every 5° interval in* θ_{inc} *between 0° and 50°. The KuKa radar takes ~ 16 seconds (i.e. 5.7° per second) over a 90°* θ_{az} *width to acquire data across an incidence angle scan line (e.g. 0°) and ~ 2.5 minutes for one complete scan between* θ_{inc} *= 0° - 50°. However, there is a ~ 20° offset between the individual radar antennas and the radar positioner axis origin. Therefore, the Ku-band antenna scans between -65° to +25°* θ_{az} *range (region between purple lines) from -25° to +65° for Ka-band (region between green lines) (Figure 1(b), (e) and (f)). This also means that the Ka- and Ku-band footprint overlap for a given radar 'shot' is* θ_{inc} *dependent. The yellow region in Figure 1b between -25° and +25° is the overlapping Ku- and Ka-band footprint (Figure 1(b))."*

- Try to provide more convincing conclusions where possibly and try to reduce speculative interpretations throughout the manuscript.

We agree with your comment on condensing the main points. The revised version now focuses only on the ranging and backscatter analysis, supported by TLS, meteorological and geophysical observations. We have removed the phase difference analysis from this paper as we agree it is not relevant to the main message of this paper.

- There are several interpretations/speculations related to surface roughness: consider removing them where not really necessary.

We recognise that, though we acknowledge the potential importance of roughness, we do not have quantitative data to investigate its effect. We therefore retain mention of roughness in the manuscript but try to explain this more clearly – we have added several sentences in the second paragraph of the Discussion (section 4.1) to clarify that this is probably important, but not collected in this study, and the need to collect high-temporal resolution surface roughness measurements is paramount (see below).

'In future studies, gathering TLS data on the snow surface roughness at high spatial (radar) and temporal (e.g., daily or hourly) resolution would provide valuable information on the role of roughness. In addition, collecting coincident measurements of snow density would provide information on the role of density affecting radar waveforms. We would therefore recommend collecting these coincident datasets in future similar studies'.

Specific comments:

35/36: It would be good to mention in the abstract what kind of radar is used and for which observation which mode was used: scatterometer or altimeter or both modes of the instrument?

We have revised the text as follows: *"Here, we examine the effects of snow redistribution over Arctic sea ice from radar waveforms and backscatter signatures obtained from a surface-based, fully-polarimetric Ka- and Ku-band radar at incidence angles between 0° (nadir) and 50°."*

37: "waveforms and backscatter": I guess, they were measured in altimeter mode? Please mention.

We have revised the lines as suggested as follows: "*During both events, changes in Ka- and Ku-band radar waveforms and backscatter coefficients at nadir are observed, coincident with surface height changes measured from a terrestrial laser scanner"*

39/40: "...altimeter. The relative ... decreases, ... with increasing incidence angle." For the described observations, it seems like the scatterometer mode was used here? The sentence before ends with altimeter; this sentence mentions "increasing incidence angle" which does not match with altimeter. Please clarify; maybe start with "With increasing incidence angle of the scatterometer, the relative scattering contribution ... ..." if that agrees with what you mean.

To clarify, the KuKa radar operates in altimeter and scatterometer modes. In the altimeter mode, the radar acquires data ONLY at nadir, while in the scatterometer mode, the radar can also acquire data at large incidence angles (including nadir). In this study, we use the scatterometer mode data from nadir to 50° incidence angles. We have avoided terming *altimeter* and *scatterometer* modes in this paper as it slightly conflicts with the instrument terminology for the radar.

We agree with your comment on lines 39-40 and is revised as follows: *"With increasing incidence angles, the relative scattering contribution of the air/snow interface decreases, and the snow/sea ice interface scattering increases."*

124 and Fig. 1b: It would be good to

- 1) refer/use Fig. 1b to better explain/clarify how the "azimuth range" is scanned, at discrete incidence angles. I guess, Fig 1b shows the azimuth-elevation scan pattern of the instrument;

In addition to the revised Figure 1b, we have added information regarding this comment, as follows:

“During MOSAiC, the KuKa radar scanned over a 90° θ_{az} range width (between -45° and +45°) for every 5° interval in θ_{inc} between 0° and 50°. The KuKa radar takes ~ 16 seconds (i.e. 5.7° per second) over a 90° θ_{az} width to acquire data across an incidence angle scan line (e.g. 0°) and ~ 2.5 minutes for one complete scan between θ_{inc} = 0° - 50°.

- 2) this could be mentioned in the caption and as an axis-label on Fig. 1b (at least azimuth).

We have instead provided this information in the main text, as above.

132: How is the beam-width defined? full-width-at-half-maximum (FWHM) equivalent to the "3dB-beam width"? Strove 2020 writes "Antenna 6 dB two-way beamwidth".

Each radar antenna system has a 3 dB half-power beam width of 6°. We have added this information into the manuscript as follows: *‘The radar is beam-limited (3 dB half-power beamwidth of 6° for each antenna system) and, given the 11.9° and 16.9° antenna beamwidths at Ka- and Ku- bands, respectively, the size of the radar footprint on the snow is dependent on frequency, height of the antenna above the snow surface, and θ_{inc}.’*

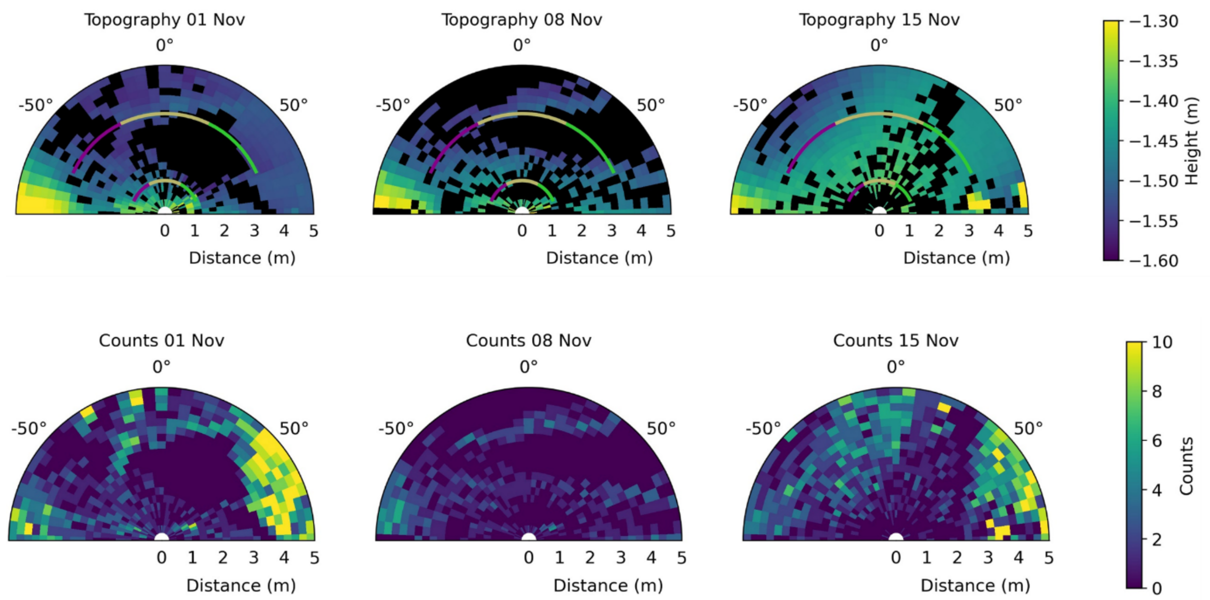
135: "The overlapping footprint is between -5 and +45° for Ku-band, and -45 to +5° for Ka-band": I don't understand this sentence. To me, this seems to contradict the sentence before and the geometric radar setup as shown by Strove 2020. The overlap in % (as given by Strove) of course depends on incidence angle, but why is the azimuth angle mentioned here? Why is the "overlapping footprint" for Ku-band at positive angles and at negative az-angles for Ka-band?

We have revised the description of the scan geometry and the overlapping footprint. The overlapping footprint is between -25 and +25 degrees based on geometry calculation as shown in Figure 1(b) (yellow region). The revised description is as follows:

However, there is a ~ 20° offset between the individual radar antennas and the radar positioner axis origin. Therefore, the Ku-band antenna scans between -65° to +25° θ_{az} range (region between purple lines) and from -25° to +65° for Ka-band (region between green lines) (Figure 1(b), (e) and (f)). This also means that the Ka- and Ku-band footprint overlap for a given radar ‘shot’ is θ_{inc} dependent. The region (yellow region between green and purple lines) between -25° and +25° is the overlapping Ku- and Ka-band footprint (Figure 1(b)).”

Related to that, I don't understand the yellow-orange-red color in Figure 6;

We agree it was not an ideal choice of colours. We have re-coloured Figure 6 following Figure 1, and noted this in the figure caption below



'Figure 6: TLS data (plan view) from 1, 8 and 15 November, from -90° to + 90°, where the angle indicates the azimuth of the radar positioner, and radial horizontal distance measured from the centre of the radar pedestal. The top panels show the topography as measured downwards (increasing negative) from the middle of the radar antenna arms. Black indicates no data recordings in that bin. Projections of the centres of the radar footprints are shown for 0° and 50° radar inclination angles, superimposed on the TLS data in magenta and green for radar observations, respectively, and buff where the two overlap, as per Figure 1. The bottom panels indicate the number of TLS data points within each bin. Surface depressions resulting in 0 counts in the TLS data are due to obscuration by adjacent high areas due to snow/sea ice topography and human-made objects, as viewed from the TLS's oblique viewpoint some distance away.'

I don't understand why Figure 7 shows az-angles of -65..+25° for Ku-band and -25° to +65 for Ka band;

These angles are the azimuth angle ranges for Ku- and Ka-bands, respectively. To avoid confusion, we have revised the portion of the figure caption as follows:

Figure 7: Progression of Ka- and Ku-band radar waveforms at nadir between -65° to +25° (Ku-band) and -25° to +65° (Ka-band) (azimuth ranges following Figure 1(e) and (f)).

I don't understand why Figure 10-12 show azimuth angles for -45 to +45 for both Ku and Ka band.

We have replotted the polar plots based on the corrected Ku- and Ka-band azimuth angle configurations (based on Figure 1(e) and (f)). We have merged Figures 10 and 11 to one single Figure 10 as shown below. There is no CPD analysis in the revised manuscript.

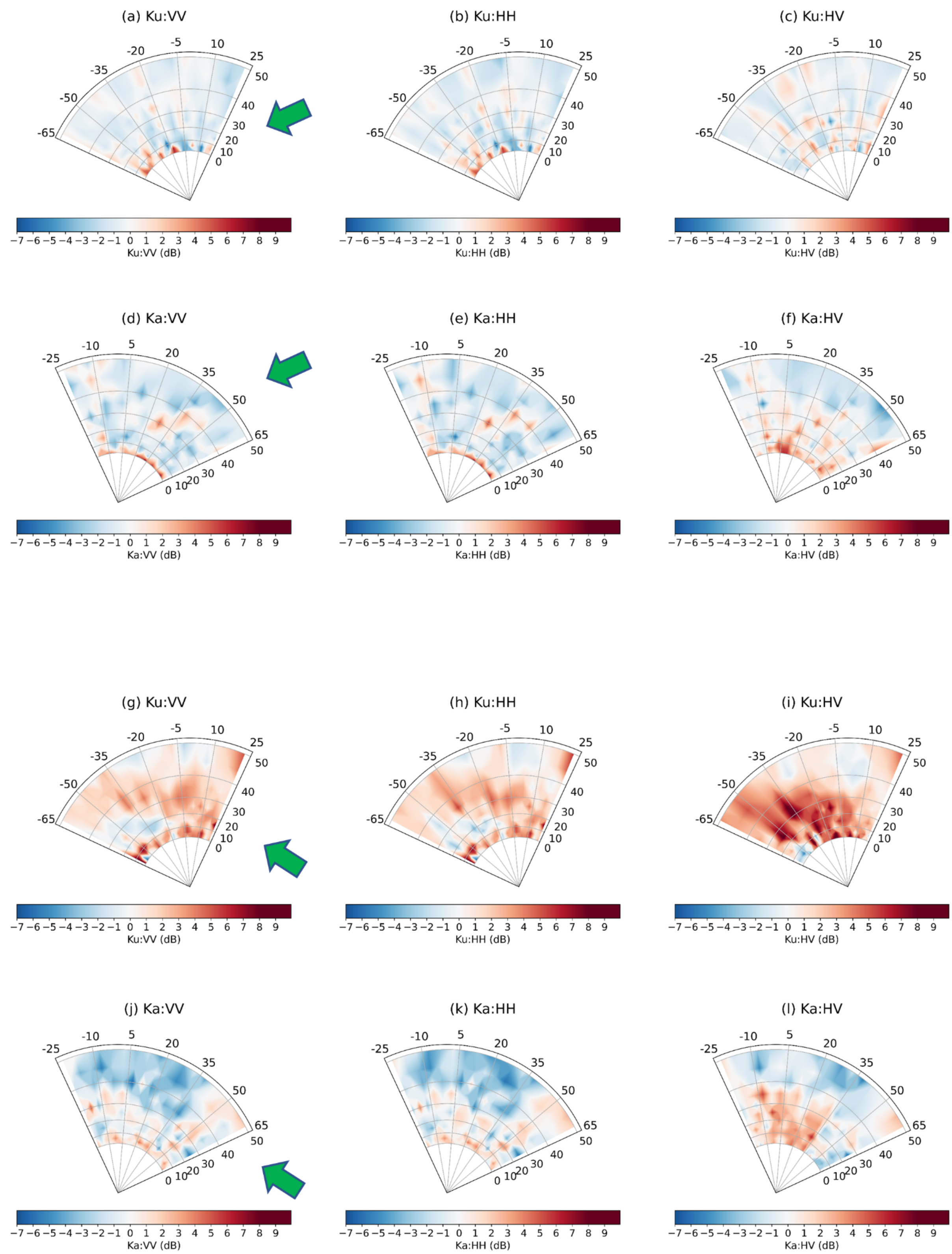
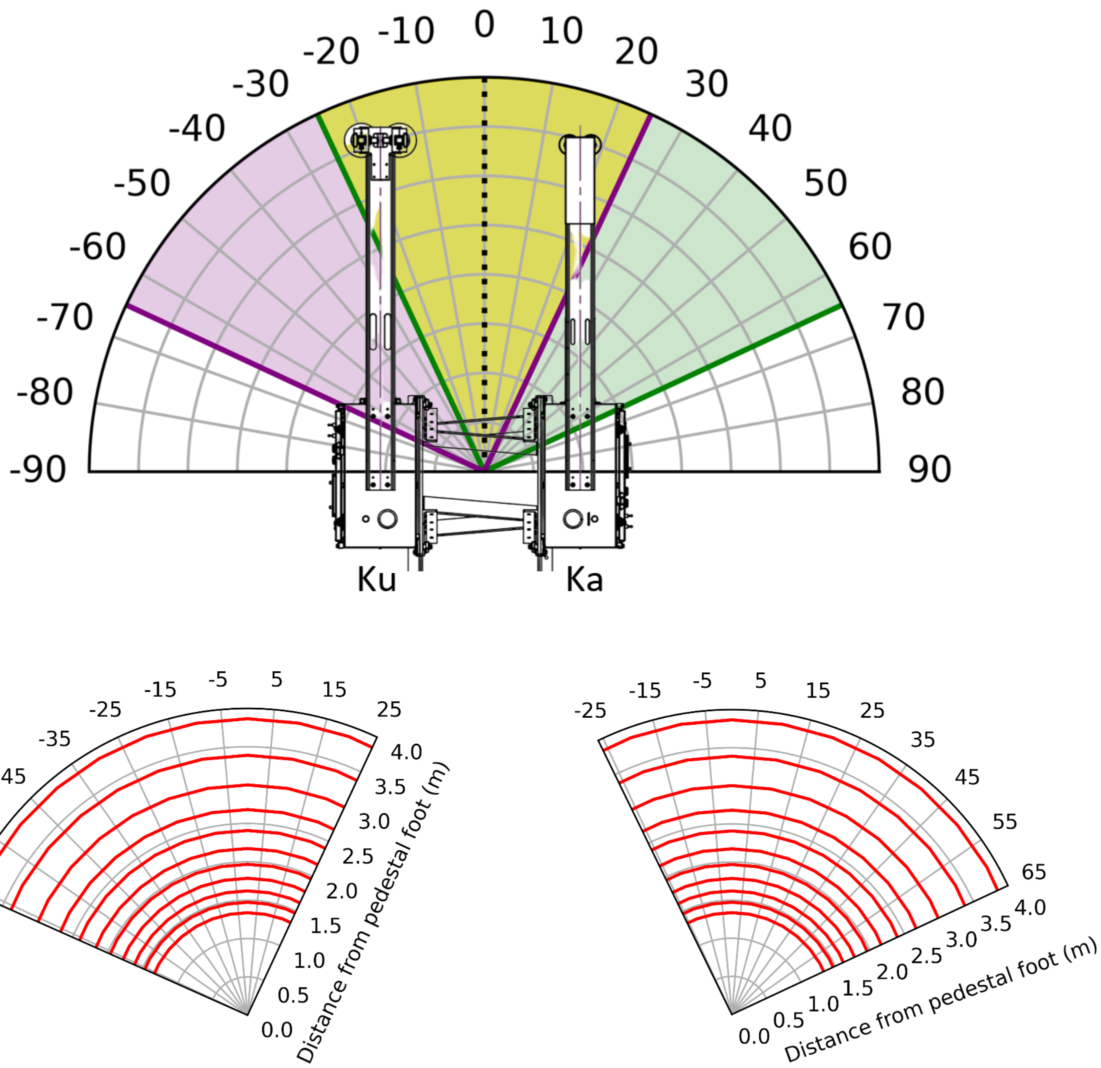


Figure 10: Polar plot panels (a) to (f) show the relative change in averaged Ku- and Ka-band backscatter at 5° azimuth sectors, as a function of θ_{inc} , between WE1 and pre-wind conditions, acquired on 11 (WE1) and 9 November, at 2337 UTC and 0013 UTC, respectively. Panels (g) to (l) show the same between windy conditions, acquired on 15 (WE2) and 11 (WE1) November, at 2338 UTC and 2337 UTC, respectively. Green arrows in (a) and (g) denote the prevailing wind direction on 11 and 15 November, respectively. The scan times also correspond to yellow circles in Figure 9 and CCTV images in Figure 5a & c. Note: The 11 November CCTV image in Figure 5c is acquired at 1736 UTC for image clarity showing blowing snow.

Consider drawing a measurement-setup figure indicating all relevant geometric parameters like footprints, scan areas, etc. for both, Ku and Ka band.

We show the measurement-setup in figure 1(b), (e) and (f) as shown below:



'Figure 1: KuKa radar geometry illustrating (a) radial distance and radar range from the pedestal foot; (b) KuKa radar azimuth scan pattern projected based on the positioner axis coordinate system (b) scan pattern of radar projected onto a level surface; (c) diameter of radar footprint, measured radially ('ra') and azimuthally ('az'); (d) area of radar footprint; (e) and (f) depicts the Ku- and Ka-band footprints of the KuKa radar, respectively. In panel (b), the region between purple lines and green lines are the respective Ku- and Ka-band footprints (separately shown in panels (e) and (f), while the yellow region in the middle is the overlapping footprint area for both frequencies.'

137: what are the scan-increments (in degree) in the azimuth direction? For incidence angle it seems to be 5°.

The azimuth scan is continuous and not discrete. We have added the word 'continuous' in section 2.1 as follows:

"During MOSAiC, the KuKa radar scanned over a 90° continuous θ_{az} range width (between -45° and +45°) for every 5° interval in θ_{inc} between 0° and 50°.

Section 2 or 2.2: I miss here an overview map figure (e.g. the blue sub-figure in Fig. 4 could be used) showing the location of instruments. Such a figure is very helpful for the reader to imagine where which instrument is installed and where which sampling/measurement was done.

Map on Figure 4 (with scale) clearly shows the location of the remote sensing site and its approximate distance to the snow pit locations. Therefore, we intend to use the map in Figure 4 as the overview figure and refrain from using another map since they would be seen as redundant to the maps shown in Stroeve et al. (2020).

196-202: I don't understand the azimuth sectoring method:

- why are negative and positive theta_az sectors mentioned separately? Is there any special relation between negative and positive angles?

We have thought about this comment and agree with the reviewer. With the updated geometry of the radar antennas, there is no special relation between negative and positive sector angles. Therefore, we have deleted this aspect throughout the paper and focus only on azimuth sectoring rather than distinguishing them as negative and positive sectors.

- How is the number of independent samples calculated? I would expect something like azimuth-angle-width / antenna-beamwidth * analyzed-range / range_resolution. What is "theta_az width"? Why do you devide the antenna beam-width? Why half of it? What are the range-gates? It this the range-sample spacing or the range-resolution? (note: increasing the sampling of a band-limited signal does not increas the number of *independent* samples).

We calculate the number of independent samples based on the following steps:

1. We first determine the 6-dB range swath, i.e., the distance between the 6 dB points below the peak on either side of the peak.

2. Then we divide the 6-dB range swath by the range resolution. The range resolution is 1.5 cm for Ka-band and 2.5 cm for Ku-band (full bandwidth). This is a measure of the number of independent samples in range.

3. Now we divide the azimuth width (90 and 5 degrees in our study) by the azimuth beamwidth and multiply by 2. This is a conservative estimate of the number of independent samples in azimuth.

4. The total number of independent samples would then be the number of independent samples in range multiplied by the number of independent samples in azimuth.

We have corrected the statement in the revised manuscript as follows:

'The number of independent samples is estimated based on the following steps: a) determine the 6 dB range swath, i.e., the distance between the 6 dB points below the peak on either side of the peak; b) divide the 6 dB range by the range resolution (1.5 cm for Ka-band and 2.5 cm for Ku-band). This is a measure of the number of independent samples in range; c) divide the azimuth width (90° and 5° in our study) by the azimuth beamwidth and multiply by 2, and d) the total number of independent samples would be then the number of independent samples in range multiplied by the number of independent samples in azimuth (Doviak & Zrnić, 1984)'

Doviak, R. J., & Zrnić, D (1984). Doppler Radar and Weather Observations. Academic Press, 458 pp.

Table 1: Why does the number of independent samples change with θ_az at Nadir? Is is $theta_az$ a range of azimuth angles or does θ_az describe a specific angle? Or are the numbers in the table given for a 5° theta_az bin?

The numbers given in the table are for a 5° azimuth bin. We have revised the table caption as follows:

Number of independent samples at Ka- and Ku-band frequencies at nadir and θ_{inc} = *50° at* θ_{az} *= 90° and along a 5° bin*

207-216: Definition of the CPD: Note, that in Leinss 2016, the CPD is derrived from S_VV * S_HH* while here it is derrived from S_HH * S_VV*, resulting in a sign change. The definition in Leinss 2016 is motivated by the desire for a positive change for increasing snow, while your definition makes more sense in terms of radar terminology. Make sure, you describe the increase/decrease of the CPD in agreement with the used definition (HH * VV* vs. VV * HH*).

We have carefully reviewed your overall comment on the utility and reliability of CPD analysis in this study and have decided to remove the entire analysis from this paper.

Figure 2: I understand that the daily wind-rose plots might be important but I miss temporally-resolved plots indicating hourly or sub-hourly resolved wind speeds. This could be plotted together with either temperature or air-pressure.

Thank you for the great suggestion. We have included the 10-min averaged air temperature (based on your next comment) and wind speed to Figure 3 as shown below.

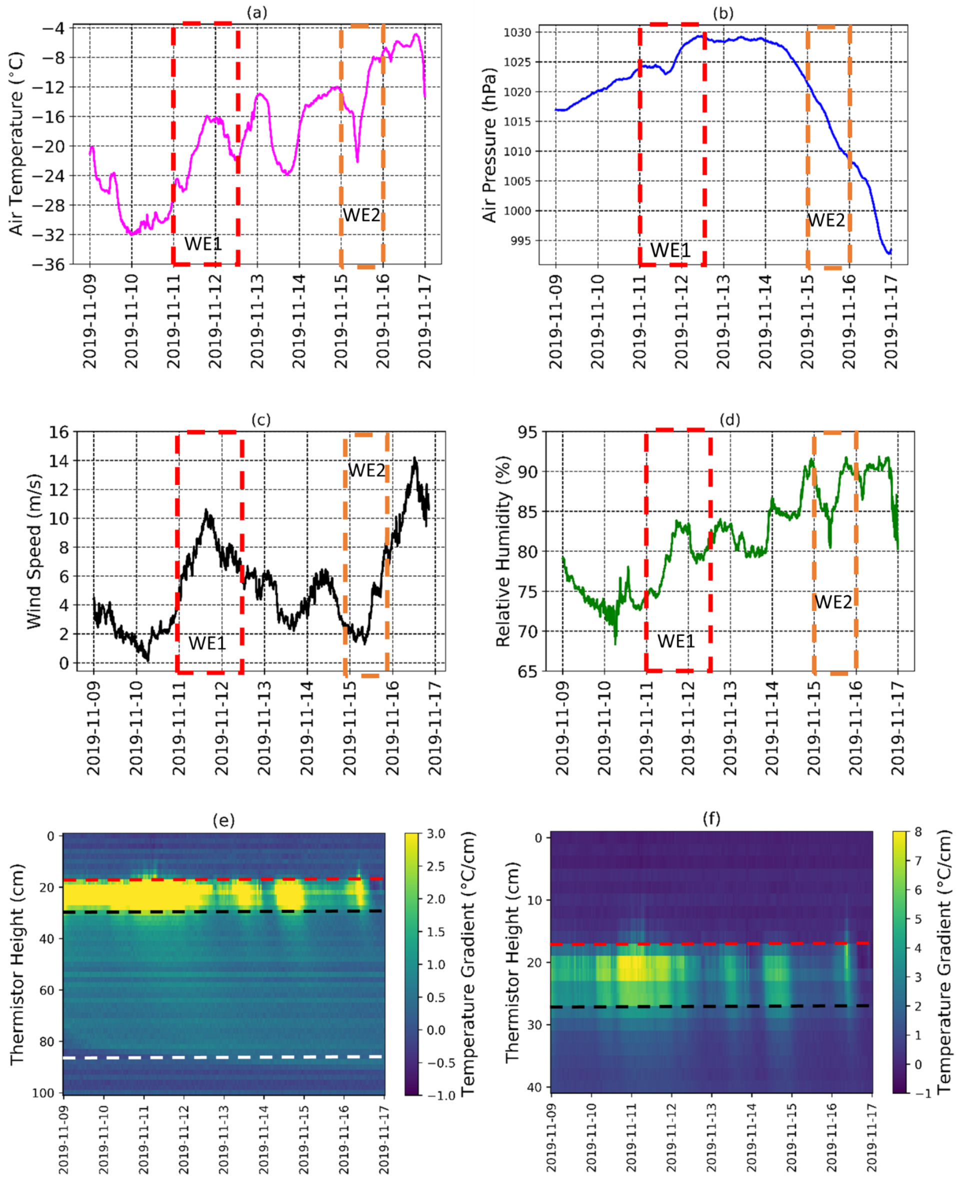
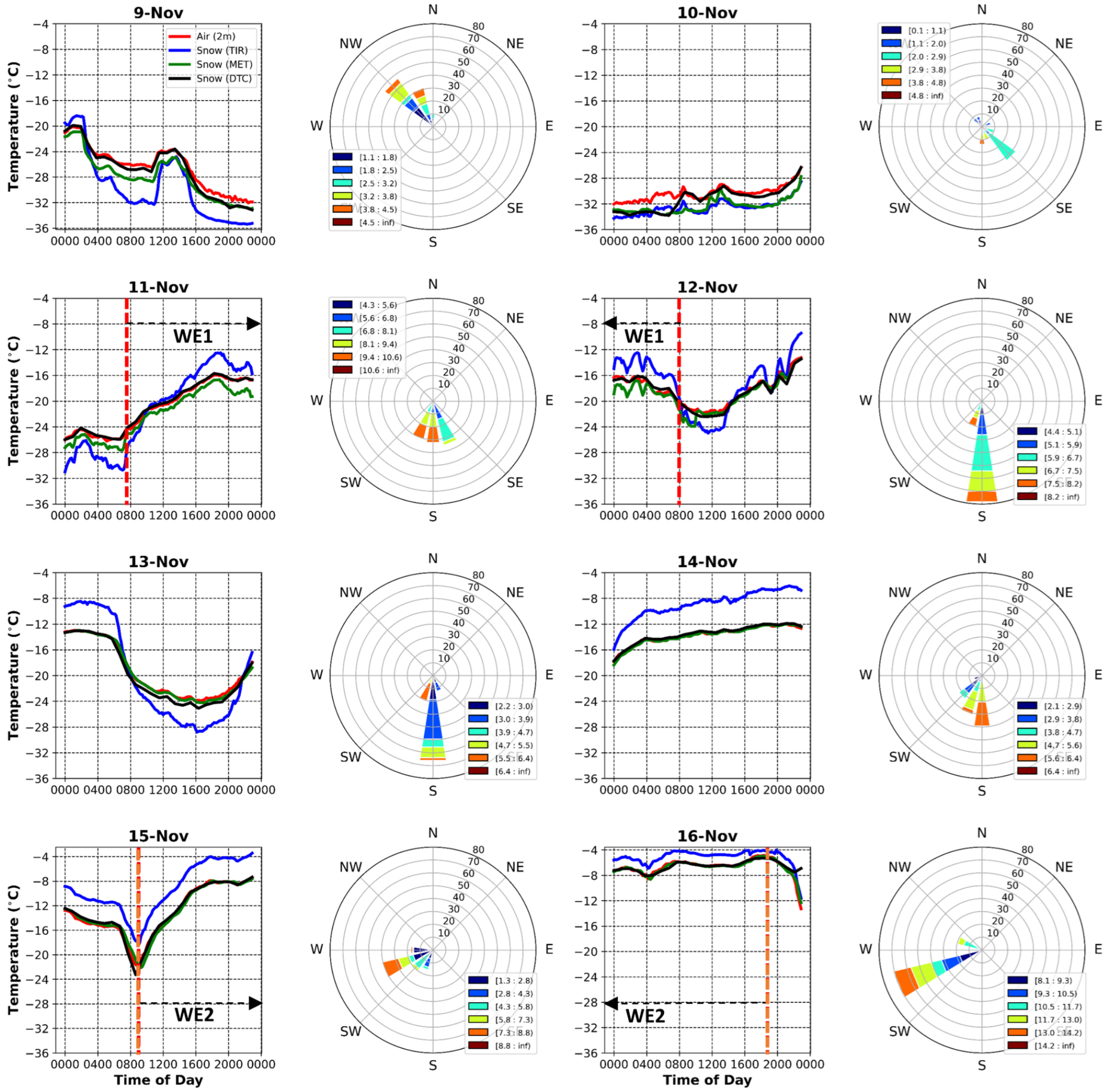


Figure 2: Could you indicate in the plots, similar to Fig. 3, when the wind-events occured? This would simplify the understanding. To save space you could also plot temperature as a continuous time series (one plot, like Fig. 3a and b) with the series of daily wind-roses above or below.



235, Caption:

- Surface plots -> I would say this is a 2D color plot, it does not show any 2D surface in 3D space (what I would expect for a "surface plot" in visualization-terminology. I would also avoid the word surface here, as the plot shows a time-series not a snow(or other physical)-surface.).

Thank you for the suggestion. We have changed the caption as suggested, as follows:

Figure 3: Line plots show daily, 10-min averaged 2-m (a) air temperature, (b) air pressure, (c) wind speed and (d) relative humidity, recorded by the MET tower between 9 and 16 November. 2D color plots show DTC-derived hourly-averaged temperature gradient of (e) near-surface, snow, sea ice and ocean; and (f) sub-section of panel (e) showing the snow volume from the RSS. Yellow represents strong temperature gradients within the snowpack. Dotted red, black and white lines represent approximate locations of air/snow, snow/sea ice and sea ice/ocean interfaces. DTC temperature sensors are spaced by 2 cm, with the top 20 cm representing the height above the air/snow interface. Red and orange boxes in (a) to (d) indicate WE1 and WE2 windows. Note the different temperature gradient scales for (e) and (f).'

- "Yellow pixels represent snow volume": I know what you mean, but this statement does not make sense. Better indicate by a box or line where the snow volume is (see comment below). Yellow represents strong temperature gradients (within the snow pack).

Thank you for the suggestion. We have added dotted lines of different colours showing the estimated air/snow, snow/sea ice and sea ice/ocean interfaces. See revised Figure 3 above.

- with the top 20 cm representing the distance between the first sensor located above... and at...: I don't understand this sentence. How many sensors are above the air/snow interface? Do the top-20cm represent the height above the air/snow interface, i.e. everything above 20cm is air? How did the snow height change within the shown 8 days? Could you draw the (possibly estimated) air/snow interface into the plot?

The top 20 cm represents the height above the air/snow interface. We have corrected this in the revised caption as above.

235, Figure: Could you indicate in the plot what you consider as near-surface, snow/snow volume, sea-ice, and ocean? Could you also indicate that Fig. 3d is (I think it is) a zoom/subsection of Fig- 3c? You could indicate this by drawing the outline of the zoom into Figure 3c.

We have added lines to indicate interfaces. Also added in the caption that (f) is a zoomed in version of (e). Drawing an outline clutters the whole plot by having lines overlapping through the plot legends. The caption instead makes it clearer.

220: At which time did WE1 start?

WE1 started approximately 0745 UTC on 11 November. We have included the timing in the revised manuscript as follows: *'WE1 started ~ 0745 UTC on 11 November and* *lasted until ~ 0800 UTC on 12 November when winds ~12 m/s originated from the SW to SE (Figure 2).'*

252 - 253: From figure 3d there seem to be temperature gradients up to 7 or 8 K/cm during WE1, in the text I read 3 °C/cm for WE1. For WE2 fig. 3d indicates gradients of around 2-3 K/cm. Please check consistency.

We have cross checked and the temperature gradient is ~ 7°C/cm during WE1 and reducing to ~ 3°C/cm during WE2. We have revised the sentence as follows: *'A large temperature gradient of ~ 7°C/cm was observed during WE1, whereas the gradient decreased by half to ~ 3°C/cm during WE2 (Figure 3(f)).'*

254: 0.25 °C/m: do you mean 2.5 °C / cm?

Corrected to 2.5°C/cm

257: uppermost: could you provide a number like e.g.: uppermost ... cm?

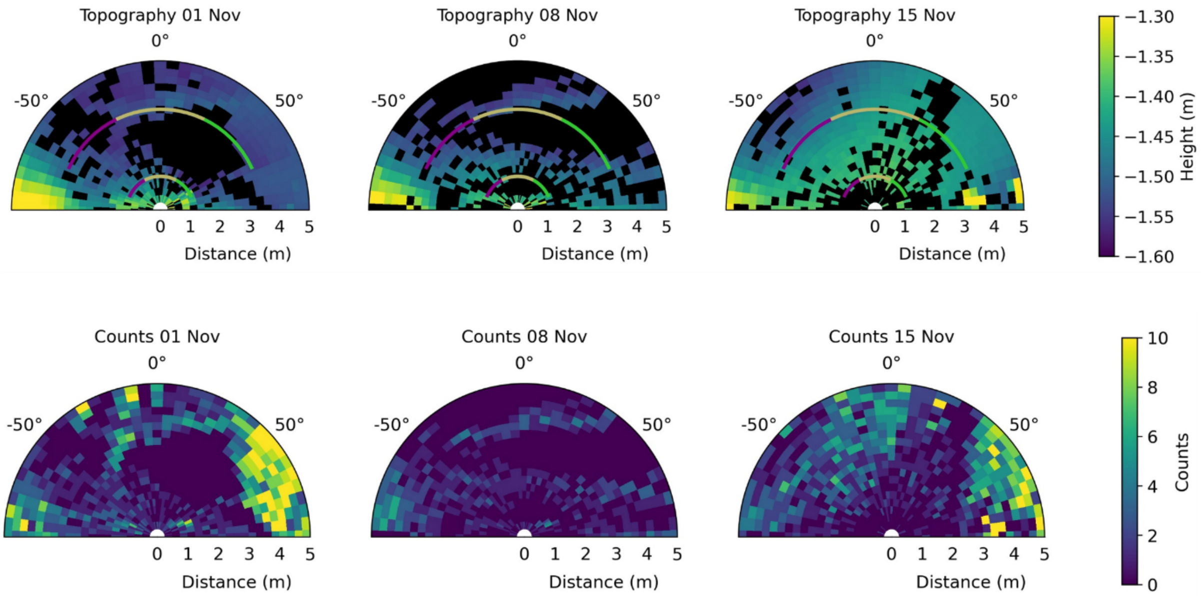
Uppermost 2 cm snow layers. Corrected in the revised manuscript.

274: I doubt that breakup of snow particles decreases the SSA. No matter how SSA is defined, as surface area per volume or kg, breaking up crystals would increase the SSA because the grain size get's smaller by the breaking events. King 2020 describes the SSA decrease in wind slaps rather as a "product of mechanical wind rounding and subsequent sintering".

We agree with the reviewer and have revised the sentence as follows: *'An SSA decrease indicates the reduction in surface area, caused by rounding of snow grains, followed by sintering during wind transport (King et al., 2020).'*

305: "superimposed on the TLS data in yellow ... and orange where the two overlap": I understand the yellow-to-blue colors in Figure 6 so that black indicates no TLS data (count=0). Why are there then a yellow or orange colored radar footprints or TLS data that are located on black pixels? Or does yellow and red indicate two different radar observations? Please clarify in the caption what is yellow, orange and red. As mentioned earlier, I did not understand the difference in radar observations in the positive and negative azimuth angles theta_az.

Thank you and we agree that the choice of colours was not good. We have changed Figure 6 and the caption, as follows.



'Figure 6: TLS data (plan view) from 1, 8 and 15 November, from -90° to + 90°, where the angle indicates the azimuth of the radar positioner, and radial horizontal distance measured from the centre of the radar pedestal. The top panels show the topography as measured downwards (increasing negative) from the middle of the radar antenna arms. Black indicates no data recordings in that bin. Projections of the centres of the radar footprints are shown for 0° and 50° radar incidence angles between -65° to + 65° azimuth range*, superimposed on the TLS data in magenta and green for radar observations, respectively, and buff where the two overlap, as per Figure 1. The bottom panels indicate the number of TLS data points within each bin. Surface depressions resulting in 0 counts in the TLS data are due to obscuration by adjacent high areas due to snow/sea ice topography and human-made objects, as viewed from the TLS's oblique viewpoint some distance away.'*

Figure 6 and Figure 7: The TLS data and the radar-Nadir data indicate a possibly considerable slope within the observation area. Looking at both figures, I can estimates slopes of 2-5°. Would it be possible to make any statement about changes of the local slope in the observation area? As observed later, in Figure 9, the incidence angle has a very significant effect on the radar waveform, hence the local incidence angle must also have an significant effect. I can't tell of 2-5° are already significant, but I belive they are.

Thank you for the observation. Yes, the local incidence angle is particularly important at nadir or near-nadir backscatter. Sloped surfaces of 2-5° will significantly affect the total backscatter magnitude. However, since surface scattering is the dominant scattering mechanism at nadir and steep incidence angles, slightly sloped surfaces that we observe in this study likely do not affect the relative distribution of scattering between the air/snow and the snow/ice interface scattering.

We have added this observation in section 3.2 as follows:

'The TLS and radar waveforms also indicate an ~ 2-5° slope in the radar footprint especially at nadir (See figures 6 and 7). Sloped surfaces of 2-5° will significantly affect the total backscatter magnitude. However, since surface scattering is the dominant scattering mechanism at nadir, slightly sloped surfaces that we observe from the radar footprint likely do not affect the relative distribution of scattering between the air/snow and the snow/ice interface scattering.'

Figure 7: I find it quite confusing that Figure 7 shows TLS profiles from different dates in every figure. Why not showing the TLS profile from 08 Nov (and possibly 01 Nov) for the radar data from Nov 09 , 11, and possibly 11 and the TLS data from Nov 15 ontop of the radar data from Nov 15? If you perfer to keep all three TLS profiles, then please mention why different TLS profiles are shown ontop of the radar data for each date.

TLS data were gathered weekly so the 8 and 15 November are the only available TLS datasets within the study period. The 8 November has considerable missing data due to the positioning of the TLS scanner and we therefore use the 1 November as a similar dataset (pre wind event) with more data points, as noted in the text. We also show the 15 November on the same plots so that the before and after elevations of the air/snow interface are present, to aid comparison with the KuKa radar data for all dates.

378, caption 8:

- "red, yellow, black": I do not see a yellow line in the figure. Consider refering only to the dashed red and black lines.

We have rephrased to clarify.

- But keep the sketched yellow arrows in the figure (very interesting!) and the sentence refering to them.

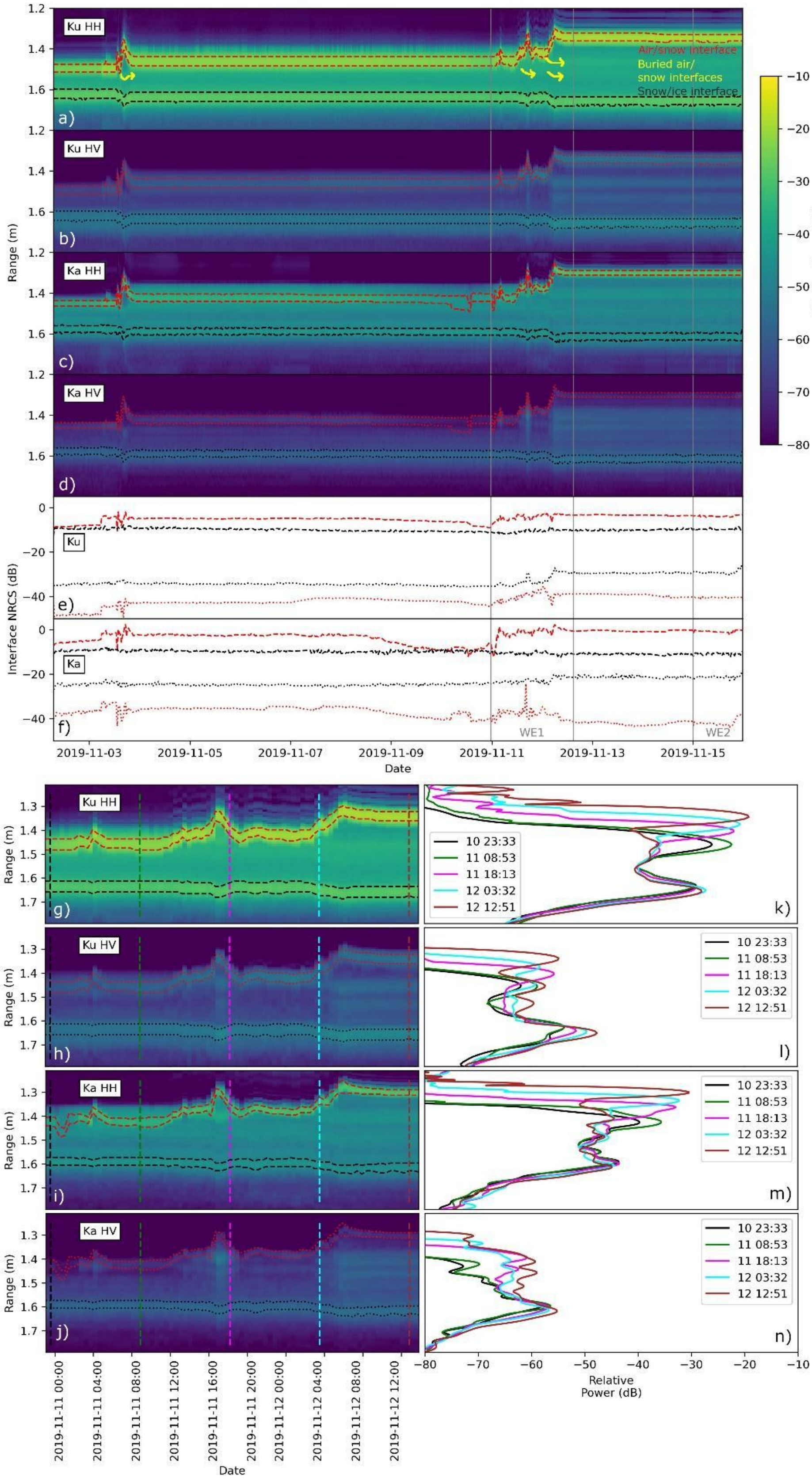
Thank you. These are kept.

- Mention the meaning of the vertical gray lines in the caption, I guess they constrain WE1. You could also add a label "WE1" to the figure.

We have added this label and in the caption it is also mentioned

- "Time series of the interfaces NRCS values are snown below the echograms" -> "NRCS time series of the two interfaces (red, black) are snown below the echograms for HH and HV (dashed/dotted)". Also add a legend to the timeseries indicating the colors and line-styles.

We already have a legend showing this and adding legends for colors and linestyles could clutter the already busy plot. Therefore, we wish to retain the presently used legend in the plot.



- Figure 8 has many sub-panels. Consider labeling them with (a, b, c...). Is figure 8, bottom right mentioned in the text? If not, it seems not to be too important and could be removed.

We have labelled the panels. We would prefer not to remove any of the panels as these form the complete set of co- and cross-pol data for the reader's reference.

- Figure 8 (and other figures): Consider labeling the time-axis according to the shown tick labels, e.g. "Date (YYYY-MM-DD)" or "Date / time (MM-DD HH:mm)"

We have adjusted the labels to what we hope is a clearer format.

356: "It is interesting ...can still be seen ... 10 November, .." add a reference to "yellow arrows, Figure 8".

Added.

359-360: "During WE2, ... the air/snow interface moved upwards... (bottom right of Figure ... and 8)": I do not see any effect of WE2 in Figure 8. The x-axis of Fig. 8 ends likely at end of the day 2019-11-15. Could you indicate, similar to WE1 by gray vertical bars, where WE2 is located in Figure 8?

We have added this.

393 and 394: Both sentences: Add reference to the corresponding panels in Figure 8.

Included.

415-416: "... at all theta_inc. VV and HH backscatter primarily originates as surface scattering at the air/snow interface" I think this might be an inadmissible generalization. The fact, that Nadir observations indicate the strongest return at the air/snow interface cannot be generalized to all incidence angles. On the contrary, the backscatter at the air/snow interface might even be reduced for non-zero incidence angles due to specular reflection away from the radar.

We agree with the reviewer and have removed this generalisation, as follows:
'During pre-wind conditions, both Ka- and Ku-band backscatter are relatively stable (Figure 9a & b). At nadir, VV and HH backscatter primarily originate as surface scattering at the air/snow interface. As θ_{inc} *increases, air/snow interface scattering reduces due to strong specular scattering away from the radar and is dominated by snow volume scattering and surface scattering at the snow/sea ice interface.'*

420-429: This seems more an interpretation of the Nadir observations in Figure 7 and 8 rather and seems less relevant or even misleading for the interpretation of off-Nadir observations. Consider moving to the interpretation of figure 7 and 8 and refer only briefly to this interpretation when discussing the non-nadir angles in Figure 9.

We disagree with the reviewer on this comment. Our objective in this section is to link the changes in azimuthally averaged NRCS at nadir, 15, 35 and 50 incidence angles to what we see from the waveform analysis. Moving the nadir section to section 3.2 will isolate nadir NRCS observations and focus ONLY on the non-nadir incidence angles.

436-439: I think observation of different layers at non-zero incidence angles is difficult due to the slant imaging geometry. In the slant geometry each slant-range bin samples the backscatter from all targets located at the same range (bin). This includes contributions from the air/snow surface, the volume and the snow/ice interface. As for each slant-range distance a slant cross section through the scattering volume is measured, the measured profile is rather a representation of the beam-pattern weighted by the incidence-angle dependent backscatter intensity from the different surfaces illuminated by the beam.

Similar to Figure 9 and 10 in [Leinss et al. EUSAR 2014] I interpret the strong near-range return in Figure 9c (at theta_inc=15°), possibly also 9d (30 deg) as a Nadir-return from the air/snow interface (consider the beam-width of 12-17°). However, the increasing slant-range distance to the strongest return is a good indicator that the snow above the ice delays the radar signal.

439/440: "The waveform analysis shows": Please be more specific. Similar to the observations with the SnowScat instrument, where dry arctic snow up to 1m depth appeared almost transparent at incidence angles between 30 and 60° and X to Ku-band frequencies [https://doi.org/10.1109/JSTARS.2015.2432031], I interpret the increasing range to the strongest return caused by 1) increased delay to to increased accumulation and 2) caused by the snow/ice interface. See also Figure 9 and 10 in [Leinss et al. EUSAR 2014] where the snow/soil interface is detected. This interface appears further away from the sensor (due to increasing delay) with increasing snow depth.

Thank you for the above 3 comments. We agree with the reviewer as to how increased snow accumulation can delay the propagation speed leading to increased ranges at shallow angles. We have corrected our interpretation as follows (answering all three comments above into one):

'The effect is less at θ_{inc} = 35° due to the snow volume scattering becoming more dominant compared to surface/interface scattering at the slanting cross section at

more oblique angles. The waveform analysis shows that the relative contribution of the snow/sea ice interface, snow volume scattering and increased radar propagation delay due to increased snow accumulation becomes more important at shallow angles (Leinss et al., 2014) and the air/snow interface becomes relatively less prominent due to lower surface roughness after WE1.'

Leinss, S., Lemmetyinen, J., Wiesmann, A., & Hajnsek, I. (2014, June). Snow Structure Evolution Measured by Ground Based Polarimetric Phase Differences. In *EUSAR 2014; 10th European Conference on Synthetic Aperture Radar* (pp. 1-4). VDE.

Reference: Leinss, Silvan and Lemmetyinen, Juha and Wiesmann, Andreas and Hajnsek, I.. (2014). Snow Structure Evolution measured by Ground Based Polarimetric Phase Differences. in Proceedings of European Conference on Synthetic Aperture Radar (EUSAR)] https://www.researchgate.net/publication/312171448_Snow_Structure_Evolution_measured_by_Ground_Based_Polarimetric_Phase_Differences

We have added this reference in the revised manuscript.

Figure 10, 11, 12: These figures take up a lot of space but seem to reveal little information. Consider removing them (and the associated discussion) if you agree that they are not crucial for the main points of the manuscript.

We do agree with the irrelevance of co-pol phase difference analysis (Figure 12) in this paper using the polar plots thus we have removed the entire analysis from the paper.

However, we have retained the backscatter analysis using azimuth sectoring as the polar plots (we have merged Figures 10 and 11 into one single Figure 10) clearly show spatial variability in backscatter within the footprint, as a function of incidence angle and polarization, in response to wind-driven snow dynamics and thermodynamic-induced metamorphic changes to snow layering. This analysis shows the importance of accounting of spatiotemporal variability in snow properties within a satellite footprint that can induce associated changes in dominant scattering horizon and backscatter. In the revised version, we have revised this analysis through improved representation of KuKa radar geometry.

451: "Next, we show..." Sentence should be used as introductory sentence for section 3.3.2 and not at the end of section 3.3.1.

Sentence moved to the beginning of section 3.3.2 as suggested.

482: "stable snow metamorphism": metamorphism is a dynamic process. Do you mean "stable snow conditions with little metamorphism" or "continuous metamorphism"?. Variations of the CPD indicate metamorphism, however a single observation of the CPD does not provide any information about the dynamics of the snow pack. Nevertheless, it can give an idea about the history of methamorphism of the snow pack.

This sentence belongs to the CPD analysis. The whole analysis is removed in the revised version.

499: What is "phase reversal"? Do you mean "phase wrapping"?

CPD analysis removed from the revised version

480-502: I have some doubts on the results and interpretation of the CPD.

CPD analysis removed from the revised version

- First of all, the backscatter results in the previous sections are most convincing when averaged over azimuth (but not over incidence angle!) and plotted with temporal resolution (like Figure 8 and 9). Why not showing such plots for the CPD first (at different incidence angles, because the CPD is strongly incidence angle dependent)? If temperature-gradient-metamorphism induces variations of the structural anisotropy then these variations should be well visible during the extreme temperature gradients up to 800 K/m shown in Figure 3.

CPD analysis removed from the revised version

- Could the authors ensure that they use the same definition of the CPD as in Leinss 2016? See comment above: Currently, there might be a sign error. The sign of the CPD might also dependent on the data processing and chosen side-bands in the electronics of the instrument.

CPD analysis removed from the revised version

- Did the authors ensure that the CPD of the instrument was well calibrated? Snow-free data and open water should have zero CPD.

CPD analysis removed from the revised version

- An analysis of CPD time series, averaged over the whole area might also indicate calibration issues.

CPD analysis removed from the revised version

- The instrument seems to allow processing of the data at user-defined bandwidth and central frequencies. Phase wraps can be easily detected by using two slightly different frequencies. See approach in [https://doi.org/10.1109/JSTARS.2015.2432031].

CPD analysis removed from the revised version

- At Ka-band, there seem to be large phase differences at Nadir. It could be speculated that this could be caused by an wind-induced anisotropy in the x-y-plane (horizontal) rather than processes that act in the vertical direction (settling, metamorphism). However, a non-zero CPD at Nadir might also indicate a not well calibrated instrument. Please check.

CPD analysis removed from the revised version

504: "The dominant radar scattering surface": add: "at nadir and for both Ku- and Ka-band"

Added as suggested.

513-514: "provide contextual information for reliable interpretation": this is a very vague statement. Try to draw more specific conclusions. One point I see is: The fact that the dominant radar return for incidence angles > 15 degree, possibly even smaller, is not the air/snow interface anymore has an important impact for Altimeter-observations on snow-covered slopes. For such slopes, the surface height is likely to be underestimated. If you agree, please mention it in the discussion.

Thank you for the suggestion. We have revised the sentence as follows:

'At satellite scales, this can likely overestimate sea ice freeboard when assuming that the snow/sea ice interface is the dominant scattering surface, and therefore, warrants careful interpretation of waveforms and backscatter at nadir. At non-nadir incidence angles, the relative scattering contribution of the snow/sea ice interface compared to the air/snow interface increases, and the air/snow interface gradually becomes invisible (Figure 9), as a result of the snow surface smoothening.'

517: "which indicates that snow density and surface roughness contrasts (Figure 4) existing prior to ..." -> "which indicates that snow layers existing prior to ...": I don't understand why surface roughness is mentioned here. The manuscript shows no data on surface roughness; Especially not in Figure 4. What does the word contrasts refer to? I don't understand. Consider revising this sentence.

It is unfortunate that surface roughness data are not available for this study, and as noted above we have added context for this in both the discussion and conclusion: based on previous studies, roughness is an important parameter to quantify and that this data should be collected in future studies.

523: "The relatively small backscatter indicates ..." I think, the relatively small backscatter is a consequence from the specular reflections away from the sensor at non-nadir angles. It's rather the increasing delay (slant-range) to the observed echo that indicates that most scattering is associated with the snow/ice interface. See comment above (436-439).

We have revised the statement as follows: *'The relatively small backscatter observed from the snowpack at θ_{inc} = 15° and 35° (Figure 9c & d) indicates dominant scattering away from the radar. Additionally, at these angles, most of the backscatter is associated with the snow/sea ice interface, and that deeper snow is causing an increasing slant-range delay.'*

524: what are "shallow theta_inc"? Incidence angles close to zero or close to 90°?

We meant non-nadir incidence angles and have changed accordingly in the revised manuscript.

524/525: What does "change" mean here? What changes under which conditions?

We refer to this change in snow volume scattering to changes in microstructure in response to wind-driven thermodynamics and its impact on the snow pack. We have revised the statement to:

'This absence of volume scattering change (due to wind-driven snow microstructural changes) at non-nadir θ_{inc}, in combination with the observed nadir sensitivity, suggests that surface scattering is the dominant scattering mechanism at nadir.'

535: "a two-scale function of the microscale surface roughness" what do you mean? What is a two-scale function?

The 'two-scale' function refers to the RMS and correlation length components of the surface roughness. To avoid confusion, we have removed this phrase.

569/570: I doubt that "strong contributions from snow grain volume scattering at C-band" exists.

If the storm has a thermodynamic effect on snow-covered first-year sea ice, then C-band volume scattering contributions from brine inclusions within the snowpack cannot be ruled out. We have noticed this effect during calm conditions over saline snow on first-year sea ice from Ku, X and C-band scatterometry (e.g. Nandan et al., 2016)

Nandan, V., Geldsetzer, T., Islam, T., Yackel, J. J., Gill, J. P., Fuller, M. C., ... & Duguay, C. (2016). Ku-, X-and C-band measured and modeled microwave backscatter from a highly saline snow cover on first-year sea ice. *Remote Sensing of Environment*, *187*, 62-75.

584: why would the anisotropy induce "scale-dependent" properties? I think scale-dependent should be removed here.

CPD analysis removed from the revised version

585: Why would the anisotropy alter surface and interface roughness? I would rather agree that snow metamorphism can alter interface roughness.

CPD analysis removed from the revised version

586-596: Revise according to the outcomes resulting from adressing comment 480-502.

CPD analysis removed from the revised version

599: "the first-ever recording of" a matter of taste if you need that or not. As publications should naturally contain new and original data all main results should be first-ever anyway. I would remove this statement.

We have removed this statement.

603-604: Revise sentence to make it accurate.

- As observed in Figure 9, the air/snow interface can be hardly detectable with non-zero incidence angles. I even presume that the air/snow signal at 15° is a Nadir-return of the 12-17° beam-width (6 dB two-way beamwidth according to Strove 2020). As the beam-width does not have sharp edges it is certain that a Nadir-return can be observed.

- "buried air/snow interface remains detectable" well, yes, this is shown in the nadir-looking data in Figure 8. However, this figure also shows that the intensity of the buried air/snow interface seems to be 10-20 dB below the intensity of the air/snow interface.

Yes, we agree with this and have used the term ‘detectable’ to indicate that, although at far lower power, the KuKa radar is still capable of detecting these features.

613: "strong spatial variability in backscatter": The figures 10 and 11 indicate temporal changes of less than 3 dB for WE1, and around 5 dB for WE2 with an decrease in Ka and an increase in Ku band. However as change and no absolute backscatter is shown one cannot speak about a strong spatial variability, rather than about a temporal variability of 3-5 dB at least for the second wind event.

We somewhat disagree with the reviewer’s comment here. In our azimuth sectoring analysis, we show the relative change in backscatter as a difference between two instances of a) difference between WE1 and calm conditions (old Figure 10) and, b) difference between WE2 and WE1 (old Figure 11). In these analyses, we show the differences in backscatter at all incidence angles and polarizations, across the 5 degree azimuthal sector bins. Our point is that when we average backscatter across the entire azimuth, the variability in geophysical change is also averaged. Or in other words, the variability in the dominant scattering surface is also masked. We have modified the sentence as follows in the revised manuscript:

'Compared to pre-wind conditions, nadir backscatter across the full radar azimuth increased by up to 8 dB (Ka-band) and by up to 5 dB (Ku-band) during the wind events. This was caused by the formation of snow bedforms within the radar footprint, which increased the snow surface roughness and/or density. Azimuth sectoring at 5° bins reveals the spatial variability in backscatter across the radar footprint, in response to formation of snow bedforms caused by increasing wind speeds and changing wind direction.'

614-617: Revise according to the outcomes resulting from adressing comment 480-502.

We have removed CPD analysis from this manuscript.

Technical comment:

36/37: "changes in ...backscatter coincident with ... are observed": The sentence is correct, however, I had to read it a few times to make sure that really "backscatter coincident with..." is meant and not "backscatter coefficient". You might want to move the verb before coincident: "changes in ...backscatter (coefficients) are observed, coincident with ... "

Corrected

39: detect -> detected

Changed as suggested

47: "Our results reveal the imprtance of wind, through its geophysical impact on Ka- and Ku-band (...) and has implications..." I'd suggest: "Our results reveal the impact of wind on Ka- and Ku-band (...) which has implications..."

Changed as suggested

68: I'd suggest: -> will result in the formation of heterogenities on different scales, from cm-scale ripple marks to snow bedforms ...

Corrected as suggested

131: from "nadir to theta_inc = 50°" maybe, from "theta_inc = 0 - 50°"

Corrected as suggested

142: "denote d" -> "denoted \textit{d}" (italic d) corrected

175 "across the theta_az range" -> "across theta_az" (here and other places: Even though linguistically correct, I would avoid using the word "range" together with "azimuth" to describe a span/interval/sector to avoid confusion with slant-range of the radar)

Corrected throughout the manuscript

234: "are spaced every 2 cm" -> "are placed every 2 cm" or more accurate: "are spaced by 2 cm".

corrected

256: increase and decrease in density and SSA -> increase in density and decrease in SSA

corrected

525: "dominant changing scattering mechanism" add: "at nadir".

Added.

527: "changed by more " -> "increased by more"

Corrected.