

**Potential of X-band polarimetric SAR co-polar phase difference for  
Arctic snow depth estimation  
tc-2021-314**

**Revisions**

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Reviewer's comments

Answers to reviewer

**Modification to text**

Dear Reviewer,

Thank you very much for the careful review and suggestions for improving the manuscript. They helped a lot to improve the manuscript. For a better readability of our response, the corrections in the manuscript are shown in orange.

**Reviewer comment 1:** It did take several reads to parse the stats component of the results section – I think it could be explained a bit more clearly. e.g. what exactly is the post-hoc Games-Howell testing for beyond the non-parametric ANOVA? A sentence to explicitly state why you are using them both would be helpful. What does it mean when the ANOVA says there are no differences, but the Games-Howell also reports only some significant differences? (lines 270-273) If you are reporting it to show the overall group stats as a whole, and then breaking them down further using the Games-Howell that would be useful to point out.

Thanks a lot for the comments. The ANOVA is used to test the variance between the groups. We have chosen Welch's ANOVA as it is a non-parametric test without assumptions of equal variances in the groups. ANOVA gives an overall result regarding the statistically significant differences between the groups. Hence, a post-hoc test allowed us to identify significant differences between specific groups.

For a better understanding, we added following explanation (line 245-246):

*"The Shapiro-Wilk test was used to test the normality of distributions for SD and TWI. Since TWI and SD distributions did not respect a normal distribution, the variance in TWI and SD between each group was tested with the non-parametric test Welch ANOVA in conjunction with a post-hoc Games-Howell test. **Welch's ANOVA allows testing at first if the differences between the groups is statistically significant, while the post-hoc Games-Howell test highlights the differences between specific groups. It may be possible that some groups show no statistically significant difference of the means. For instance, we could expect no difference of the means on the SD and TWI between the group Coltsfoot and Shrubs as both vegetation units are located in areas well suited for snow and water accumulation.**"*

**Reviewer comment 2:** How should it be interpreted when results contradict – e.g. the

TWI results contradict significance between the 2 tests run. This could all be my misinterpretation of the writing, but in that case, some clarification will make this much clearer.

In the case of TWI, we found no statistical significance between the groups "Coltsfoot" and "Shrubs" and between "Dryas" and "Lupine" which indicates that no differences in the potential of water accumulation between these groups was observed. These observations are discussed according to their impact on SAR observation in p.18 (lines 396-402).

**Reviewer comment 3:** Section 3.3 snow-SAR correlation – consider revising this wording as you did not do any correlations, you did regressions. Perhaps choose an alternate word like relationship? Or fit, since you did coefficient of determination. Some lines of text also mix correlation with regression (e.g. 325: No significant correlation was found), technicality perhaps, but you didn't test for correlation.

We changed the section title to "**3.3 Snow - SAR relationship**"

**Reviewer comment 4:** Table 2 raised more questions for me than it answered. It is unclear which in situ dates relate to which acquisition. The text says they are within plus/minus 2 days of the acquisition, but what dates are the actual acquisition from?

The reviewer is right, it is not clear which TerraSAR-X acquisitions were used for the linear regression with the snow pit data. We selected the TerraSAR-X data acquired before and after ( $\pm 2$  days) of the snow pit measurements. In order to avoid confusion, we added the acquisition dates of TerraSAR-X data used for the linear regression in parentheses. Dates with snow acquisitions (i.e. TSX passing  $\pm 2$  days) are listed under "In situ data" row and the number of scenes per orbit is now the quantity if scenes used for the paper in Table 2:

Relative orbit	Flight direction	Polarization	Incidence angle	Observation period (yyyy-mm-dd) (Acquisition date used for linear regression)	Number of scenes	In situ data
24	Descending	HH, VV	31°	2014.12.26—2018.03.06 2019.04.17—2019.05.20 (2019.04.17, 2019.04.28)	104	2019.04.18
152	Ascending	HH, VV	24°	2019.04.15—2019.05.18 (2019.04.26)	1	2019.04.26
115	Descending	HH, VV	38°	2019.04.23—2019.05.15 (2019.04.23, 2019.05.04)	3	2019.04.22 2019.05.03 2019.05.04

Modification in the manuscript are done (lines 190-192):

***Snowpits and SD measurements taken before and after ( $\pm 2$  days) each TSX acquisition were included in the analysis as no precipitation occurred and air temperature was stable during the field campaign.***

**Reviewer comment 5:** Observation period covers many days - does each acquisition include data from many days? 24 scenes – how do the snow pits correspond with these? This needs a bit more clarification. It is clear the historical data used for the time series is from Orbit 24, but how many of the 104 scenes are in the 2019 period like the others?

Thank you for the comment. TerraSAR-X has a repeat orbit of 11 days. For each orbit, we have a continuous time series during the winter season with acquisitions every 11 days / with data gap from March 6th 2018 to April 17th 2019. A total of five scenes were used for the regression statistics. An average of 10 snowpits for each day were conducted for each day, and two snow depth transects were acquired on May 1st, 2019 (please refer to Transect#2 in Fig.4) and May 4th 2019 (Transect #1). Following modification in the manuscript are added (lines 147-149):

***Additionally, two SD transects were conducted across the catchment to analyze the SD distribution in the study site. Both transects were established from the east side to the west side of the Ice Creek catchment. These transect were acquired on May 1st 2019 (Transect #2) and May 4th 2019 (Transect #1).***

**Reviewer comment 6:** 3.2.1 – two snow pit characterization sampling strategies? Unclear what the second is. the revisited pits vs the ones elsewhere in the catchments?

We apologize for the confusion. The sampling strategy is explained in line 140-147:

“The snowpit locations in the centre of the Ice Creek catchment as well as location at the outlet of the catchment were revisited *after* each TerraSAR-X (TSX, see 3.3.) acquisition so that soil characteristics remain unchanged between snow sampling and satellite measurements. Snow depths were measured using a GPS snow depth probe around the snowpits, ensuring the representativeness of the snowpit location.

[...] Snowpits and SD measurements were then distributed spatially elsewhere in the catchment to refine the characterization of snow within the catchment.”

**Reviewer comment 7:** Lines 303-305: Why the variability in the CPD annual mean? Is that an acceptable range of annual variability to group into an overall 2014-19 mean? Or is there any comparison that can be made. Presumably it's related to different weather conditions year-to-year? But is there anything you can conclusively say about what is driving that? perhaps I missed that, but it would be interesting to know if the range in annual means can be explained by e.g. snow depth. Perhaps not as 14-15 and 17-18 years highlighted as the min and max are also the years missing from the climate data.

Well observed - Sentences on line 303-305 were meant to report seasonal values over each year. The wording seems to confuse the readers so here is the modification:

“For the 2015-2019 period, the mean CPD value during the snow season was  $-8.59^\circ$ . ***The mean of each winter is ranging between  $13.41^\circ$  (2014-2015) and  $-6.42^\circ$  (2017-2018).*** During the snow-free condition, the average CPD over the same period increased to  $-0.87^\circ$  (2015-2019). ***Maximum and minimum values during snow-free conditions ranged between  $-0.44^\circ$  (2015) and  $-1.32^\circ$  (2015-2016).*** ”

**Reviewer comment 8:** Objective 2 – I don't think you fully met this objective. You do show the temperature and precipitation data with the CPD, but is anything else examined? (see comment below about table 1). Nothing is gone into in depth in this section directly relating the meteorological data to the CPD other than the cyclical pattern between snow and non snow times. You should consider making more use of the data to explore the meteorological links or revise the wording of objective 2.

Thank you for the hint. After consideration, we suggest to re-wording the objectives and add a third one (modification at lines 64-67):

(1) investigate SD and DHF variability between different vegetation classes in the Ice Creek catchment (Qikiqtaruk-Herschel Island, Yukon, Canada) using in situ measurement collected over the course of a field campaign in 2019; **(2) evaluate linkages between snow characteristics and CPD distribution over 2019 dataset and (3) Determine CPD seasonality considering meteorological data over 2015-2019 period.**

**Reviewer comment 9:** A few clarifications and very minor typos that caught my eye as I was reading:

Something that would be useful is a sentence early on clarifying that the winter year you report in some places refers to the previous fall and next years spring (e.g. 2018 means 2017-2018)

Thank you for the hint. Yes, the winter refers to the period from mid-September to mid-May, as written at section 4.2.1., lines 298-299:

"The period with presence of snow was set between mid-September and mid-May based on prior observations (Burn and Zhang, 2009; Stettner et al., 2018)."

To avoid any confusion and keep consistency, line 305-306 was changed: The decrease generally started in January, when the average air temperature is at its coldest (-20 °C) **except during the snow season of 2016-2017, where a warming occurred, increasing the average temperature of 5 °C for that year.**

**Reviewer comment 10:** Figure 1: define delta rho

Sorry for the confusion.  $\Delta\rho$  in Figure 1 defines the phase shift. We clarified it in the text and in the figure.

**Reviewer comment 11:** Figure 2: text line 148 says east to west transects, figure shows west to east transect?

We are sorry, that was a typo. We revised the sentence as follows (line 148): "**Both transects were established from the west side to the east side of the Ice Creek catchment.**"

**Reviewer comment 12:** Figure 4: caption, depth shouldn't be capitalized, also you refer to it as depth hoar fraction elsewhere and ratio here

We revised Figure 4 caption and we changed "depth hoar ratio" to "depth hoar fraction" - thank you for the advice.

**Reviewer comment 13:** Figure 5: “is shows” is shown

Thank you. We corrected it.

**Reviewer comment 14:**“Windows pixels size is 1x1 pixel (5x5m)” – explain?

We use the CPD mean value within a window of 5x5 m. We have chosen a smaller window size to better reflect the heterogeneity of the snow surface, which could alter within a few meters. The high heterogeneity of the snowpack and the need for its monitoring at the landscape scale motivate our approach at the finer resolution possible, as discussed in the introduction:

“Current snow modules used in Earth System Models are based on coarse spatial resolution of tens of kilometres (Bokhorst et al., 2016). Coarse spatial resolution hampers our efforts to understand the dynamics driving snowpacks at the landscape scale. Indeed, snow is characterized by a high spatial and temporal heterogeneity (e.g.: Rutter et al., 2014; Thompson et al., 2016; Wilcox et al., 2019). Traditional approaches using *in situ* measurement can provide very detailed spatial information on snow properties, but cannot be deployed over large areas. There is therefore a strong need to bridge these two scales and provide means to monitor the temporal and spatial variability of the snowpack over larger areas.”

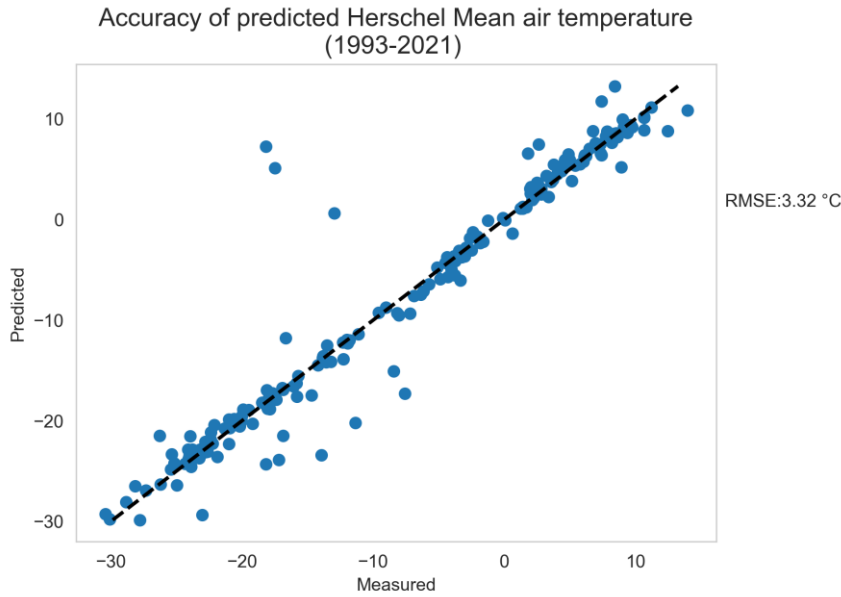
The linear regression analysis showed good results at this scale so we decided to keep this resolution.

**Reviewer comment 15:** Any established relationships between the temp/precip at the Herschel Station and somewhere on the north slope Alaska, or Tuktoyaktuk, That you can use to fill the gaps? Or is the weather too unique to the island? Might be worth a sentence clarifying that the nearby stations are not related, or too far to be used. Alternatively, is there a need to exclude the entire winter from the chart when some months are available? (end of 2017 is missing, but early 2018 is available – or is the data flawed?).

Thank you for the suggestion. We filled the air temperature gap of the meteorological station on Herschel Island using data from Komakuk Beach as performed by Burn and Zhang (2009). Following equation was used to apply on Komakuk dataset:

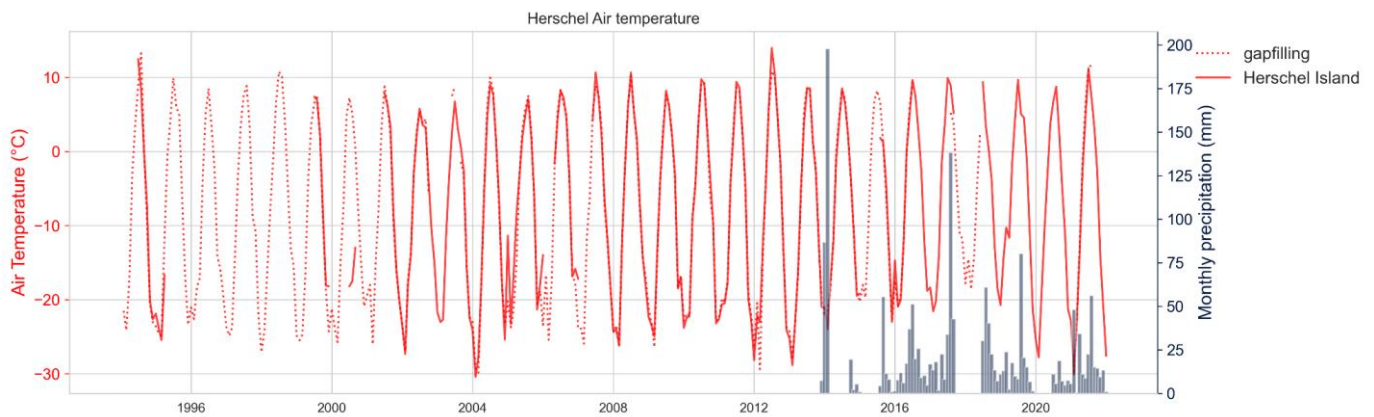
$$T_h = 0.97 \times T_k + 0.75$$

Where  $T_h$  are the monthly mean air temperature at Herschel island and  $T_k$  at Komakuk Beach. Predicted values showed good correlation ( $R^2:0.93$ ,  $p$ -value =  $< 0.001$ ) with RMSE of  $3.32$  °C (Fig.1).



**Fig. 1:** result from linear regression between air temperature measured on Herschel Island and predicted value using Burn and Zhang 2009 equation.

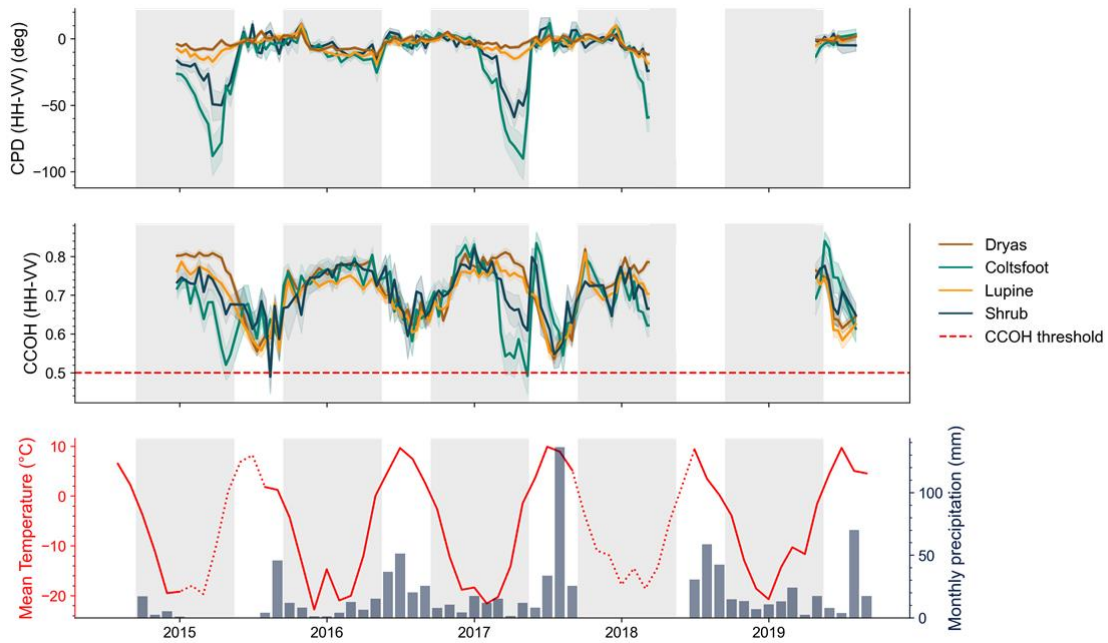
Figure 2 show a visual comparison between the air temperature predicted and measured along the time series. Therefore, the gaps will be filled using this equation. Figure 5 was changed consequently (see Fig. 3) and Fig 1 and 2 from this document are added in the appendix.



**Fig. 2:** Comparison during 1994-2022 air temperature measured on Herschel Island and predicted value using Burn and Zhang 2009 equation.

Unfortunately, no precipitation datasets were available at Komakuk Beach station between 2014-2019. The final figure is shown below, where the red dotted line shows the gap filled data. Modification in the legend is also showed:





**Figure 5.** (a) Average CPD and (b) Average CCOH by vegetation class with interval of confidence (95%) for orbit 24 (31°, descending). Pixels values were extracted from GPS dataset (see Fig. 2c), where  $N_{Coltsfoot} = 33$ ,  $N_{Dryas} = 140$ ,  $N_{Lupine} = 118$ ,  $N_{Shrub} = 29$ . Winter period (mid-September to mid-May) is shown in shaded area. Windows pixels size is 1x1 pixel (5x5m). (c) Meteorological data from Qikiqtaruk Herschel Island station (dataset from Environment Canada (2021)). The meteorological station is not equipped with a telemetry system and since the island is inaccessible during the winter, the lack of data during the winters 2014-2015 and 2017-2018 was caused by a malfunction of the station. **Air temperature during these periods were gap filled using Komakuk Beach meteorological station and shown by the red dotted line.. Please refer to appendix A for further details on the method.**

**Reviewer comment 16:** Figure 6: snow depth on the x axis should be 2 words based on how its written elsewhere in the manuscript

Corrected.

**Reviewer comment 17:** Table 1: are you using the ECCC wind and humidity data for anything? Why list just those variables from the tower (and does the datalogger really matter)? If they are used, considering adding a column to the table for what they are used for.

You are right. As this information is not relevant for the understanding of the work, we deleted it.

**Reviewer comment 18:** Line 33: snow depth trend[s] (s missing)

We corrected it.

**Reviewer comment 19:** Line 44: spatial (says special)

Thank you! We corrected it accordingly.

**Reviewer comment 20:** Line 49: (possible elsewhere?) Spaceborne is typically one word

Corrected.

**Reviewer comment 21:** Line 73: just terminology here, consider explaining kinetic metamorphic regime for the more general reader? Presumably, most readers will be snow scientists or related fields and understand this, but a few sentences to clarify would be helpful for those who are not.

Thank you for the suggestion. We revised the sentence as followed (line 74):

***"Kinetic growth refers to formation of depth hoar within the snowpacks induced by a strong thermal gradient".***

**Reviewer comment 22:** Line 83: "...vertical direction after their setting up in the snowpack". While I understand what you mean here, the wording reads a little odd to me. Is 'setting up' in the snowpack common terminology? Consider a more formal explanation here?

You are right. We modified the sentence as follows (line 82-83):

***"As such, over the time, snow crystals become elongated to a vertical direction **after and during the constructive snow metamorphosis in the snowpack**"***

**Reviewer comment 23:** Line 87-88: "such as used in this study or below as dry snow can be" – I think this sentence needs a comma, I believe you are referring to shorter wavelengths, but I did have to reread this one a few times.

Thank you for the correction. We added the comma (line 87-88):

***"Given the dry nature of the arctic snowpack, the main source of backscattering should occur at the snow-ground interface for frequencies in X-band ( $\lambda = 3.1$  cm), such as used in this study, or below as dry snow can be considered as a homogeneous, "non-scattering" and non-absorbing volume (Leinss et al., 2014). "***

**Reviewer comment 24:** Line 93: random? vs. randomly

We corrected it to "random phase shift".

**Reviewer comment 25:** Line 131: you probably need the full citation for ArcticDEM here as well as other online data sets mention later

ArticDEM is cited and referred as Porter et al., 2018. The reference below respects the journal's guideline:

***" Porter, C., Morin, P., Howat, I., Noh, M.-J., Bates, B., Peterman, K., Keeseey, S., Schlenk, M., Gardiner, J., Tomko, K., Willis, M., Kelleher, C., Cloutier, M., Husby, E., Foga, S., Nakamura, H., Platson, M., Wethington Michael, J., Williamson, C., Bauer, G., Enos, J., Arnold, G., Kramer, W., Becker, P., Doshi, A., D'Souza, C., Cummens, P., Laurier, F. and Bojesen, M.: ArcticDEM [data set], doi:10.7910/DVN/OHHUKH, 2018."***

**Reviewer comment 26:** Line 158: snow depth [and] mean density

Corrected

**Reviewer comment 27:** Line 256: SD decreased significantly? It was tested? Or this is just a word choice here? If I'm missing somewhere her with the stats test, no problem,



but otherwise pick something that does not imply a stats test since you have several stats tests also being talked about. Substantially, or greatly, or ...

Thank you for the correction. We modified the sentence as followed:

***"Further west, SD values decreased substantially on the slope with values between 20 and 50 cm."***

**Reviewer comment 28:** Line 258: "Along transect #2 (Fig. 4), and snow cover" remove , and

Corrected. Thank you for your contribution.