Reviewer #1

We appreciate that the reviewer thinks the paper has improved and we thank the reviewer for all time and efforts put into a careful reading of this manuscript. There are many good comments and questions that again have led to improvement of the manuscript. Below we have responded to all reviewer comments (grey) in blue. In the end of this document we have included the manuscript with "track changes" on.

\section*{Summary}
The authors have done a good job in improving the manuscript. It is much more focussed and more clear what the intention is.\\ Thanks
However, although I do acknowledge the importance of understanding the difference between the skin and 2m temperature for the interpretation of satellite products, the majority of the insights presented in this manuscript are still not new. What this manuscript does is bringing these insights together and add an quantitative analyses of the impact of clouds. In that respect it does have merit. But I still miss a clear recommendation. This is not really a statistical analyses. It shows processes and features, but how to apply this knowledge, no hint is given. Based on this paper my conclusion is that you should not interpret the satellite Tskin in terms of T2m because there is a strongly varying surface temperature inversion. This conclusion is not made, nor is a method given of how to apply this so you actually can interpret Tskin in terms of T2m. The added value of this manuscript is therefore still limited. \\
We have made several changes throughout the paper to stress that these results are an important step towards constructing a relationship model between satellite Tskin and T2m. In the follow up paper, we will demonstrate that we can use satellite Tskin observations in a multivariate regression model to estimate the T2m equally good as NWP reanalysis and thus provide an alternative and independent T2m. To include these results in the existing paper would, however, make a long paper even longer and we therefore decided to put these results in a follow up paper.
Furthermore, there are other points that need to be addressed before publication can be considered.\\ \\

The way the surface energy balance is described in Section 3 is still incorrect/unclear. Since you discuss the skin temperature, I assume that you describe the surface energy balance of a skin layer, which is an infinitesimal thin layer without heat capacity. In that case there is an instantaneous balance between the different fluxes, and for each surface that does not change phase M is per definition 0. The warming or cooling of the medium below the surface affects the surface temperature through G. That also includes the effect of latent heat release when refreezing occurs. This affects the temperature of the medium and with that the temperature gradient close to the surface and thus the conductive heat flux at the surface. M can only be non zero when a phase change is possible. In that case the medium is usually almost isothermal and cannot raise in temperature any further being limited to the melting temperature. When the medium is isothermal G is basically 0. The excess heat results in M being positive, indicating melt occurs. M thus cannot be negative.
This is the usual way the surface energy balance is described in this field and in models. This makes it also more transparant to understand since there is a clear difference between M and the ground heat flux G. In your description you seem to mix them up, and that is only possible when the surface layer you describe has a finite thickness and a heat capacity. You have to rephrase this, preferably using the skin layer formulation since that is what you are studying. Furthermore, in your description it is sometimes unclear whether you are looking at the surface (the interface between atmosphere and snow/ice/land) or whether you are looking at the medium below the surface.\\ This part has been rephrased

Furthermore, although the English is not bad, there are numerous statements that are not clear, not specific enough or raise questions, in addition to numerous small mistakes or typos. I have tried to mark them below, but since I am no native speaker as well, I recommend that this manuscript is checked for English language as well before publication.

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Below follows a list of more specific points.

\section*{Specific comments}

P1 L15: Rephrase: 'makes the surface colder than' into 'cools the surface with respect to'\\ Done

P1 L16: Remove: 'often'\\ Not agree, since the two temperatures are not always highly correlated...

P1 L16-17: Remove: 'and the two.... certain conditions'. Is not specific enough, you specify when in the next sentence.\\ Done

P1 L18: I guess that with 'best agreement' you mean with difference of less than 0.5 $^{\circ}$C?\\ By the best agreement we mean the smallest temperature difference. This has been clarified.

P1 L18: How often is T2m $<$ Tskin? Can you give an estimation in \% of time for example?\\ All sites weighted equal T2m is lower than Tskin 13.7 % of the time. It has been added that T2m is larger than Tskin 85% of the time. At the remaining 1.3% of the time, the two temperatures are equal.

P1 L19: Rephrase 'when it is cold' , this is a subjective statement, negative radiative balance with a non melting surface, or temperatures well below 0.\\ Rephrased

P1 L22: Add 'mean overcast T2m-Tskin difference'\\ Done

P1 L24: Is cloud limited the same as clear sky effect (L25)?\\ The result/effect of using cloud-limited observations is typically a clear sky bias due to the combination of large temperature variations and the irregular sampling intervals.

P1 L25: Replace 'assessed' by 'tested' or studied. (in short space 3 times assessed)\\ Done

P1 L25: Replace 'The clear sky effect has been assessed' by 'To this end we test three different...'\\ Done

P1 L28: Why are the smallest biasses found during summer?\\ Sentence added: "... with the smallest bias during summer when the Tskin range is smallest. "

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P2 L6-7: Would be nice if you could mention more than one mechanism responsible for the amplification.\\ Done

P2 L7: Insert 'surface' before 'mass balance', or remove 'atmospheric' before 'warming'. This way you include oceanic warming as well and its impact on the tidewater glaciers.\\ Done

P2 L8: Add that the other part is the result of increased calving rates.\\ Rephrased

P2 L14-15: Add 'increase in projected' between 'the' and 'surface air temperature'\\ Done

P2 L15 remains a vague statement: Add at least one reason how it may contribute. Intensification of weather systems? Change of flow patterns?\\ We have added that the Arctic amplification may contribute to mid latitude weather events through changes in the jet stream.

P2 L20: Replace 'not available everywhere' by 'rare' and add 'available' just before 'time series'\\ Done

P2 L21: with 'ice regions', do you mean land ice and sea ice regions combined?\\ Yes, this has been clarified: "Arctic land ice and sea ice regions"

P2 L23: Replace 'this means that' with 'consequently' \\ Done

P2 L24-25: remove 'due to .... system'. Too much repetition.\\ Done

P2 L28: Add 'clear sky' before 'surface temperature' and 'all sky' before '2 m air temperature'.\\ Done

P2 L30: Add 'and the role of clouds on this relationship' just before 'as we do here'.\\ Done

P2 L32: Formulate more explicite: replace 'an imbalance between the radiative fluxes' with 'a negative net radiative balance'. And replace 'especially' by 'this mostly occurs'\\ Rephrased

P3 L1: remove: 'the inversion continues al the way to the surface' This is a strange statement since you already explained that the inversion is forced at the surface. \\ Done

P3 L2-3: Rephrase: The surface-drive.... snow/air interface. the temperature inversion does not cause the temperature difference but is the temperature difference and the skin temperature is actually the temperature of an infinitesimal thin layer without heat capacity, in this case the snow surface at interface with the air. \\ Removed and rephrased.

P3 L5: the dominating factors? where does this refer to? dominating factors in what?\\ Rephrased
P3 L13: First mention of 'differences' refers to differences between what?\\ Added
P3 L14: Explain for what the T2m in the coupled model was corrected for by using Tskin?\\ Rephrased
P3 L16-19: Nicely formulated. \\ Thanks
P3 L23: Replace: 'an effort has also been made' by 'we'.\\ Rephrased

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P4 L2: I guess you refer to calendar years, not mass balance years? And how do you handle the data which do not cover full years? PROMICE is full years data but ARM, ICEARC, SHEBA, TARA are not.\\ We have added the following: " (see Table 1 for start date and end date for each site).". For all sites we use the data as listed in Table 1 and shown in Fig. 2, which means that we use data for all available days/months/years. For those that do not cover full years the averages are of course biased towards the months with available data. The ARM data is full years (off with less than < 5 days). Over Arctic sea ice, no longer time series are available, so this is the best that it can get.

P4 L4: remove Tskin, or reformulate: Tskin observations are derived from the long wave radiation. You do not have both parameters as observables.\\ This has rephrased
P4 L29: Same question as before: an albedo of 0.3 is already low. In case of an albedo of 0.3, is the surface still fully snow covered? Or is this partly snow covered? My guess is that this might also represent cases with partly snow cover. \\ Yes, it is quite low but ice can have an albedo of 0.3. The albedo threshold is also applied to the PROMICE stations, which was not stated in the paper (added now). Besides the albedo check, all data is also filtered for Tskin temperatures above 0°C to ensure that we only consider ice/snow covered surfaces (this has also been stated in the paper now). Thanks for pointing out the missing information.
P4 L22: Related to the ARM sites, how long is the period of observations per year that you use? Biased to winter spring? Or otherwise?\\ The period of observations generally goes from September/October to May/June, and is therefore clearly biased towards the months Oct-May. This is why the ARM stations have their own category "Seasonal Snow Covered Sites" (SSC sites). All three SSC sites weighted equal the percentage of observations from Sep-May out of all observations is 92%. This has been added to the paper.

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P5 L6: In this case you only have winter/spring data. How do you handle the averaging in this case? Period averages per calendar year? How does this affect the results? \\ See response to comment to P4 L2.
P5 L19: Where does ASFG stand for?\\ Atmospheric Surface Flux Group, as already stated.
P5 L20: Rephrase: 'Five different levels... anemometer.' The mast contains five different levels varying in height..., on which temperature/humidity probes and a sonic anemometers are mounted. \\ Done
P5 L23-25: Rephrase: 'Three surface....2007' e.g. 'Three different methods to measure surface temperature were deployed: a General.....radiometer, for which data is available over the period April to September2007'.\\ Done
P5 L25: How do you handle the differences in available periods when you average?\\ We use a preprocessed data set provided by ASFG. What we describe here is the steps that they have done and described in the reference (Persson, 2002) together with the data documentation. This has been clarified.
P5 L27-28: Rephrase: first state which measurements you use most of the time, then what you use instead in case these are unreliable. e.g. 'which is based on Epply observations, and in cases where epply was known to be wrong.....'\\ In our opinion that is also what we have done: "based on slight corrections to the Eppley temperature and the Barnes temperature when Eppley was known to be wrong"..

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P6 L4-5: Rephrase: Remove reference to the hovercraft here, provide information on the length of the observational period and distance, and how they measured air and surface temperature from the

hovercraft. I guess the weather station was installed on the hovercraft? \\

Removed reference to hovercraft here. We do state the length of the drifting trajectory already in the text and the deployment dates as well. The specific dates are listed in table 1. We have put in a reference to specific start and end dates for all each site in the general introduction to the Data section. We have added the time interval of the section and the mounting on the hovercraft.

P6 L7: Rephrase, obvious that temperature is measured with a temperature sensor.\\ Done
P6 L9: Reprase: 'Build to withstand ...sea ice' Do you mean an ice reenforced ship or an ice breaker?\\
The ship was not build to break ice, but to withstand the forces from the ice, once it was trapped within the ice. This is what is intended with the formulation: "build to withstand".
P6 L11: Remove 'a' befor 'part'.\\ Done
P6 L14: Replace 'had' with 'deployed'.\\ Done
P6 L16: How do you handle the different length observational periods in the averages?\\ When we present monthly averages (e.g. 5, 7, 9, 10, 12 and 14) we average the months that we have and months with no data are left out. I case of the last column of Table 2 it is the average of all the available months that we have (as listed in Table 1).
P6 L22-26: Rephrase: I am not sure I understand what you mean here. I guess the skin temperature you derive using these different sensors will differ, because of the different spectral range they measure in, not covering the whole spectrum in which the surface emits. And you have to correct for that. But what do you mean by 'sky temperature which is reflected'? Why is the sky temperature of importance? You are looking at the surface. My suggestion is to start with a sentence about the different emissivities and spectral ranges resulting in different Tskin. Then state that reflection at the surface of the radiation emitted by the sky affect the observations. And finally explain that the combination of the generally lower temperatures of the sky combined with the lower emissivities of the sky compared to the surface make this a small effect and that you will neglect it.\\
The sentence has been rephrased. The point here is that for surfaces with emissivities < 1 there will always be a component from sky radiation. As the sky temperature tends to be low for cloud free conditions, this component leads to an underestimation of the observed Tskin surface temperature. The section has been rewritten.

P6 L26-27: Do I understand correctly that they looked for emissivities that resulted in the best correspondence of both types of observations?\\ Høyer et al., 2017, modelled the effect that realistic different snow and ice surfaces (with different realistic emissivities) would have on the two types of radiometers used here. They conclude that the effect is small.

P6 L22 - P7 L4: I find this part a bit chaotic. Please try to focus this more, with less repetition of statements.\\ It has been rephrased.

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P7 L1: You present the difference between the two sensors. But which one represents the total surface temperature best? Or is that the third broad band sensor? And how do you translate from a smaller band to a borad band? Or is the point that they provide already reasonable values of Tskin? How do you know what the 'truth' is?\\ A sentence has been added that the KT15/KT19 represents the Tskin the best due to it high emissivity in the spectral window.
P7 L5 Replace 'with' by 'of'. Add behind DMI_Q, showing a good correlation (value) and a small bias(value) when comparing these methods.\\ Numbers added to the text as suggested
P7 L5-6: Remove: 'There is a.....comparison'. This sentence is unclear.\\ The sentence has been rephrased.
P7 L7: Replace 'if' by 'is'.\\ Done
P7 L11: You changed the name of the subsection, but not the text of the section itself. Add Long-wave equivalent befor cloud fraction.\\ Done
P7 L15: It is still not clear to me what you apply on all stations, and what is station dependent. As far as

I understand from your description you apply this equation to all sites and you also apply LWD_cloudy = sigma T^4 to all sites. Thus no station dependent relations for the upper or lower limit of the LWd T2m relation. Kuipers Munneke et al., Int J. Climatol., 2011. describe how you can derive for each station a polynomial function that follows the upper and lower limit of LWd as a function of T2m. This way the functions better represent the observations. Then you determine for every single observation pair LWd T2m the CCF, as you describe. It must be clear in you description what you apply the same way to all stations, and what is station dependent. The way described by Kuipers Munneke is best. But you can also discuss how sensitive the results are for this choice.\\ Yes, the eq. 1 is applied to all sites to define the theoretical clear sky LWd and overcast conditions are assumed to occur when the observed LWd exceeds sigma T^4 (each observation pair (Lwd + T) will have different theoretical clear sky and overcast values of LWd). The CCF is estimated using linear interpolation of the observed LWd, between the theoretical clear sky and overcast LWd estimates for each station. However, it is the same equations that we use for all stations to estimate the CCF. This procedure follows the CCFs already included in the PROMICE data.

P7 L23: To what does characteristics refer to? Characteristics of what?\\ The surface (added)
P7 L24: remove 'net' in front of 'surface energy balance' (also later in the section)\\ Done
P7 L24-25: rephrase 'between the atmosphere..... ocean'. e.g. at the interface of the atmosphere with the snow, ice, land or ocean surface.\\ Rephrased
P7 L25: Add 'as' behind 'written'.\\ Done
P7 L26: Replace 'upwelling' by 'reflected'\\ Done
P7 L28: Add 'defined' between 'are' and 'positive'.\\ Done
P7 L29 - P8 L2: See comment above about the definition of the surface energy balance.\\ Rephrased

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P8 L4-5: This sentence is not clear. What does 'short wave radiation input refer to? The incoming short wave radiation or the net short wave radiation? It is most fair to compare the net short wave with the net long wave flux. Also note that Maykut 1986 describe sea ice conditions, not land ice, nor seasonally snow covered regions. Especially the importance of clouds can differ considerably. \\ Rephrased
P8 L7 (twice): Replace 'non-radiative' by 'turbulent heat' since you do not intent the ground heat flux here. \\ Done
P8 L7: Add before 'On average,' The latter is related to the fact that ....'\\ Done
P8 L8: Replace '. However, because ' by 'and since', and replace 'balance' by flux\\ Done
P8 L10-11: Rephrase this sentence, e.g. 'Note that the surface energy fluxes are strongly related to the surface winds as the turbulent mixing is a function of wind speed.' The link with the previous bit of the paragraph is evident this way.\\ Rephrased
P8 L11-12: Rephrase, this is too simple and not clear. Are you only discussing winter conditions here? In general in the arctic during winter SWD is negligible, irrespective of cloudy or clear sky conditions. I guess you mean: Under clear sky conditions, when SWD is negligible, LWU... (remove the reference to winter, it is SWd that is the objective factor, not time of year) Furthermore, add that this results in a negative radiative balance cooling the surface and driving a positive sensible heat flux. \\ Rephrased
P8 L 13-15: Rephrase, you first mention stable stratification, and then you explain that the surface temperature is lower than the air temperature, Better the other way around. Furthermore, you repeat the reference to stable stratification in L16.\\ Rephrased
P8 L20-21, I prefere consistency within this paper than with other papers. Since katabatic or inversion winds are the same, use only one term in this manuscript and perhaps mention that for a certain region, the other term is often used.\\ We have rephrased this, and decided only to use the term katabatic wind in the paper.
P8 L22: remove 'both'.\\ Done
P8 L26: Replace 'thus the' by 'reduces the'\\ Done
P8 L30-31: Instead of presenting this as length of (polar) night and day, more objective to present this in terms of available incoming shortwave radiation. \\ The available incoming shortwave radiation depends upon e.g. cloud cover, which is not the main focus of this section here. We therefore believe that it is better to use the length of day here.

P8 L31-32: Remove 'The temporal...scales.' This sentence more or less repeats the previous sentence. In both sentences you mention variability on different time scales without mentioning what time scales.\\ Done

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P9 L9: I am very surprised that the coldest month is December. Usually the coldest month is February/March, and this also seems the case for most of your sites when looking at Figure 5a. Please check if this is correct, and if the difference with February/March is statistical significant. If not, you cannot make this statement. You also state 'not shown', but you do show this in figure 5. Furthermore, in this sentence and the following, do you refer to KAN_U or all stations?\\ Here, we only refer to KAN_U and the year (2014) as shown in the figure. We see that this can lead to confusing and have clarified this in the text. Figure 5 shows indeed the monthly mean for all sites and all years.
P9 L13-14: Isn't the larger variability also due to the larger Pole equator temperature difference in winter and spring resulting in relative high temperatures in the advected air?\\ We believe this effect is part of the more general statement " .. more frequent and rapid passages of cold and **warm air masses** in contrast to the summer months"
P9 L19: Replace 'exception is' by 'exception are the'\\ Done
P9 L23: Replace 'appear to be' by 'are'\\ Done
P9 L29: Replace 'very likely' by 'mostly'\\ Done
P9 L33: Remove 'tend to'\\ Done
P9 L32-P10 L2: Formulate more direct: This is explained by the LAB sites having surface melt ....' and remove the phrase 'ceiling of variability' but only keep the part about the upper limit of the melting point.\\ Done

\noindent
P10 L3: How can figure 5 present daily variability? You present monthly averages in this figure. I suggest to replace 'daily' by 'monthly' or 'seasonal'.\\ The daily variability is seen in terms of the (monthly averaged) Tskin daily range as shown in Fig. 5b.
P10 L4-5: Formulate more directly: 'Figure 6 illustrates...'\\ Done
P10 L6: Remove 'without gaps'. Not continuous already indicates there are gaps.\\ Done
P10 L11: Where does 'large differences' refer to? differences between individual stations or between ACC and LAB?\\ This has been rephrased to: "...large T2m-Tskin differences.."
P10 L12-13: Where can I see that the Rnet is negative at night? And is this the case for all sites, also the most northern ones?\\ You can see that on average an inversion is established at night for both surface types (Fig. 6a,b), and this is as a result of a negative Rnet. "Typically" has been added to clarify that this is what causes the general pattern observed in Fig.6a,b for the two surface types. The original sentence was suggested by the reviewer during the first review.
P10 L14-15: It is not incorrect, but the length of the melt season is temperature dependent, and thus for sites at lower altitudes and thus higher temperatures, the melt season is longer.\\ Rephrased to: "The reason for the higher temperature difference at the lower altitude sites is the longer time periods with surface melt, which is due to higher temperatures."

P10 L16: Replace 'from' by 'of'\\ Done
P10 L24: Replace 'often katabatic winds' by 'are often of katabatic origin'\\ Done
P10 L29: Remove 'binned'. and add that these are examples for two sites to illustrate the relation.\\ Done and added "... for selected sites"
P10 L29-31: Remove 'The middel .... each bin' this is caption information.\\ Done
P10 L32: Remove 'binned'.\\ Done

\noindent
P11 L12: Remove 'resulting in and inversion wind'. \\ Done
P11 L13: Replace 'inversion' by 'katabatic'. I prefer consistent terminology in this paper over consistency with other papers. You can explain this early in the manuscript. Now it gives the impression that these

are two different things and they are not. \\ This has been rephrased
P11 L14: Remove 'it seems that'. The nature is the same/comparable between Greenland and Antarctica.\\ Done
P11 L17: Replace 'from' by 'of'\\ Done
P11 L19: Replace 'effects' by 'effect'. (also following sentences)\\ Done
P11 L22: Refer to 'next section' instead of number.\\ Done
P11 L27-30: Where can I see the seasonal variations?\\ These are not shown here. But the average daily hours with clear-sky has been shown in Fig. 13 for ACC and LAB sites.
P11: In reference to figure 9, is there for the Greenland ice sheet a pattern in the cloud free and cloud covered frequencies? Lower vs higher ablation zone? Or North vs South or East vs West? \\ As can be seen from the figure the frequency of clear-sky and overcast are quite similar for most of the PROMICE sites with few exceptions. EGP, KAN_U and the TAS sites stand out with >15% more cases with overcast conditions compared to clear-skies, while SCO_U and UPE_U have >10 % more observations with clear-sky compared to overcast. The high altitude GrIS sites tend to have a larger frequency of overcast conditions compared to the lower altitude sites. A comment has been added.
P11 L32: Rephrase sentence. The figure presents cloud cover, not LWd, as this sentence now suggests. \\ Rephrased
P11 L32: Rephrase, 'average slope' of what doe you calculate? \\ The average slope of the fitted linear lines to the graphs in Fig. 10 for each surface type category. Has been rephrased

\noindent
P12 L1-2: present slopes in a small table. And at least describe the results. Does your 95\% confidence interval mean that the slope is significantly different from 0? I think you need to use a different test for that. (same question for the slopes presented later in the manuscript)\\
Clarified that the 95 % confidence intervals are on the computed slope values. This also means that they are significantly different from zero. We have also introduced the R2 values for each of the surface types, to indicate how good our linear fit is.

P12 L15-16: What do you present in column 'all months' in case the is no annual average? Perhaps is makes more sense not to present 'all months' in case no full year is present.\\
All available data is shown in this column (Table 1 lists the period of data that is available for each data site). We think it is good to have the numbers in Table 2 even though they are not representative for a full year and all stations within the SICE and SSC categories. However, we don't think it makes sense to show seasonal variations for categories that do not cover a full season (e.g. Fig. 11 and 13).
P12 L18: Make this section 4.4 instead of 4.3.1.\\ Done
P12 L19: Replace 'that can only be observed during' by 'which are only available under'\\ Rephrased
P12 L20: Replace 'in' by 'during'\\ Rephrased
P12 L21: What do you mean by 'within 1-3 days'? Do you mean 'averages of observations typically over a 1-3 day period'?\\ Yes, this has been rephrased.
P12 L21-23: Rephrase: first say that satellite averages may thus differ, and than how they differ given the results presented in the previous section. Now you repeat the fact that under clear sky conditions the surface is colder twice in one sentence. Also not necessary to repeat when the satellite can and cannot measure, that is already stated the sentence before. For example: However, these satellite averages will differ from the all sky average temperature, since the Tskin is typically lower under clear sky conditions compared to cloudy conditions. This difference is referred to as the clear sky bias. \\
The suggestions from the reviewer have been included in the text – thanks
P12 L24: Add 'from satellites' behind 'observations'.\\ Done
P12 L24: Replace 'therefore' by 'thus'.\\ Done
P12 L25: Replace 'on' by 'off' and add 'on Tskin estimations from satellites' behind 'bias'.\\
Rephrased
P12 L25: Remove: 'by using.... windows'.\\
Rephrased
P12 L28: Add: 'by using.... windows'.\\
Not relevant due to rephrasing
P12 L28: Replace: 'the cloud' by 'a cloud'\\ Done
P12 L30: Replace: 'has been' by 'is'\\ Done
P12 L30-31: Move the part between bracket to between 'observations' and 'with all sky', and move 'for all sites' to the start of the sentence.\\ Done

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P13 L3-6: Rephrase, this sentence is not clear. I don't think I understand what you mean. Furthermore,

you only describe for a specific situation what happens. It does not explain why for so many stations the differences increase for increasing periods. You also do not explain why for some stations the clear sky values are actually higher.\\ This part has been rephrased.
P13 L9: This acn be much better explained than only the range in Tskin. The smaller range is due to the less negative, or even positive radiative balance in summer. That also explains the smaller Tskin range for ACC, and for LAB the Tskin is at melting point and cannot be raised any further. \\ Yes, but this has already been explained in Section 4.1 and we see no reason to repeat why the Tskin range is smallest in summer. The point here is that the clear-sky bias is smaller during summer (compared to other seasons) due to the smaller range in Tskin.
P13 L11: But you can make these figures for the part of the year that you do have observations!! \\ We don't think it makes sense to plot seasonal variations for the sites that only covers part of a season.
P13 L13: Add 'the period' after 'except for'. What is the spread in these figures? Can you present those as an transparant orange band around your observations?\\ Added. The spread in the "daily hours with clear-sky observations" is large due to weather variability where it can be cloudy for days and then clear for days. Adding the variability to these lines therefore does not give much insight in the processes but rather make the figures messy. We therefore decided not to include the spread here.
P13 L13: Replace 'observed' by 'presented' and replace 'an effect' by 'the result'\\ Done
P13 L15: Replace both 'is' by 'are', and add 'for' before 'Jan-Mar.'\\ Done
P13 L16-17: Add 'not shown'\\ Done
P13 L19-20: Rephrase: section 4.3.1 does not present a close relationship between Tskin in absolute sense and CCF. Phrase this as Tskin being affected by clouds.\\ Rephrased
P13 L18: Relationship of what with skin temperature? and remove 'surface'\\ Changed to "Relationship between Tskin and T2m".
P13 L19-27: Why do you present the relation of Tskin with the inversion strength? Since you wish to use Tskin as a proxy for T2m why not present that relation?\\
Because in this study we are assessing the dependencies: In a follow follow-up paper we will present the T2m derived with a relationship model derived using the information obtained here. Presenting, and validating the relationship model thoroughly in this paper will be too much for one paper that is already very long.
P13 L21: Replace 'corroborated' by 'shown'\\ Done
P13 L21: It is difficult to judge the different stations from this plot, and the decrease in inversion strength is not very clear from this figure.\\ The colorbar of the figure has been changed to better distinguish the different surface type categories.
P13 L24-25: Present slopes in a small table. And at least discuss what they show.\\As for comment P12 L1-2: Clarified that the 95 % confidence intervals are on the computed slope values. This also means that they are significantly different from zero. We have also introduced the R2 values for each of the surface types, to indicate how good our linear fit is. A comment on the results have been added.

P13 L25-27: I prefer to have an integrated results and discussion section, but if you do have a discussion section, this sentence should be in the discussion section and not in the results.\\ The discussion section has been removed (separated into the result and conclusion sections).
P13 L29-31: Rephrase, be more specific on when the coldest month occurs. Furthermore, remove the references, I don't see why it is necessary to use these references to confirm that it is colder in winter than summer.\\ This part of the discussion section has been merged with conclusion and this specific part including references has been removed as we attempt only to include the most important findings in the conclusion.
\noindent
P13 L29 - P14 L28: This part only repeats what was already stated in the result section. I am missing a discussion about the bins in occurrence of cloud cover, the slope in the change in inversion strength with cloud cover is also not discussed, their values and the variability in them.\\
This part has been merged with the result and conclusion section. The confidences in the slopes are shown as confidence intervals and r2 values have been computed to indicate how good the fit is. A discussion has been added.
\noindent
P14 L3: Explain what categories do you refer to.\\ Done
P14 L5: When indicating what conditions you refer to with winter, refer to the limited amount of incoming solar radiation instead of low sun and polar night.\\ Here we are looking at the diurnal and seasonal variations. The incoming solar radiation at the surface is dependent on e.g. clouds. To avoid any confusion we prefer to keep the sentence as it is.
P14 L6-7: Around noon and early afternoon in spring and summer? Move 'around noon and early afternoon' to before 'in spring and summer'.\\ Done

P14 L7: Replace 'where' by 'when'.\\ Done
P14 L8: Twice you refer to 'differences ' , but between what? Different sites in the Arctic?\\ T2m-Tskin differences
P14 L9: What do you mean by 'closest coupling'? Rephrase: During summer and local noon the atmosphere is closest to neutral, the inversion is about 0, and then satellite observed Tskin will have the best agreement with T2m.\\ Smallest difference. The sentence has been rephrased
P14 L12: Replace 'downwards' by 'towards the surface'.\\ Done
P14 L12: Replace 'also' by 'especially' or remove.\\ Removed
P14 L12: Replace 'inversion occurs' by 'inversion occur'.\\ Not agree
P14 L13: Rephrase: with increasing wind speed the inversion strength decreases.\\ Done
P14 L14: Remove 'and not at calm winds'\\ Done

P14 L18: Remove sentence ' This is in agreement... ice sheet.' This is already stated in line 15.\\ Done
P14 L20: Categories of what?\\ Surface type categories
P14 L25: Relationship between what?\\ T2m-Tskin
P14 L29: Replace 'at' by 'and'\\ Done

\noindent
P15 L1: What do you mean by screen? Remove the sentence 'we therefore ... PROMICE data. In addition,'\\ By screen we mean only use data measured at a height of 1.9-2.1 m as referred to in the P14 L 32-33.
P15 L2: Remove 'actual' and replace 'on' by 'in'.\\ Done
P15 L2: Add what these uncertainty are. What is the uncertainty in your estimated temperature inversion, what is the uncertainty introduced by not taking height changes into account, what is the uncertainty resulting when you do take it into account?\\

We did put in the uncertainty introduced by this assumption (P14, L32) and showed this effect to be small. As we explained, we therefore did not see the need for a height adjustment and we therefore have no exact number of this effect. Based on our experience working with the data, the variability depends upon many parameters, which is the reason for our expert judgement about the statement of the uncertainty.
P15 L3: Remove: 'and again... sites' Not necessary to repeat this statement\\ Done
P15 L4-5: Reformulate, this sentence is not clear. What do you wish to asses? The uncertainty introduced by using sensors with different spectral specifications? Why do you refer to clear sky here? Did you mean: 'To asses the impact of different spectral characteristics of the used radiometers on the observed clear sky temperature inversion, ...' \\ Rephrased
P15 L7: 'Slope' of what? And here you see a sign change, you have to say something about that. Likely, the trend is not significantly different from 0 in both cases. But you have to show this.\\ Thanks for point this out. There is a minus sign missing. The sentence has been rephrased.
P15 L9: 'Trend' in what? \\ Rephrased
P15 L12: Start new sentence after 'interval', the sentence becomes incomprehensible.\\ Done
P15 L14-16: Reformulate: You have to be more specific on what affects the bias and how that relates to different time windows. This is the only thing new compared to what you already present in the results.\\ This part has been reformulated
P15 L10-16: Again repeat of Results and not much more information. I am missing a proper analyses and explanation of the the differences resulting from the averaging period and between the different stations (see comment about location sites on Greenland in the results part)\\ This part has been merged with the result and conclusion section. The explanation of the results from the averaging period has been clarified in the result section and in conclusions.
P15 L17: You do not show anywhere that IR satellite retrievals usually show a cold bias. Reformulate to introduce this properly. \\ There are several papers that discuss this in detail. We reference three of them here. We have changed the referencing to make it more explicit that we refer to these papers.

P15 L17-21: As I understand, using satellites you derive Tskin, and based on the impact of clouds, that generally results in a cold bias of Tskin compared to all sky Tskin. Is it correct that this is fully explained by this? \\ This is the largest part. The paragraph has been reformulated to make it more clear.

Rephrase 'another part' because the fact that the satellite Tskin is compared to observations of T2m is another issue. Basically you cannot compare Tskin to T2m because of the varying temperature inversion. Reformulate this last part as well, to make a clear distinction between an issue with how you measure and an issue arising from how you interpret the observations.\\ The paragraph has been reformulated.

Note that several papers report on validation of satellite Tskin products using T2m, which is why it is relevant to mention here.

P15 L23: Replace 'deployments' by 'site' or 'stations'.\\ Done
P15 L23-25: Reformulate sentence into two shorter sentences to improve readability.\\ Done
P15 L29: Reformulate, it is a bit strange that Tskin itself influences Tskin.\\ Reformulated
P15 L30: Remove 'tight', replace 'controls' by 'control'.\\ Done
P15 L32: Start new sentence at 'and the generation' to improve readability.\\ Done
\noindent
P16 L1: Reformulate: with the presented results it is not possible to interpret the satellite derived Tskin in terms of T2m. You first need to make of statistical model that includes all these effects.\\ added: "... through a statistical model"
P16 L2-3: Reformulate: In case you use NWP analyses for the correction of the satellite retrieval, the product is not an independent estimate of the temperature.\\ Reformulated
P16 L3: remove reference to start of satellite era. In terms of climate change assessment it is still a reasonably short period that satellite products are available.\\Removed reference to satellite era.
\nointent
Figure 1: Elevation is in m above sea level.\\ Added
Figure 3: Add correlation coefficient, bias and Root Mean Square Difference. It appears that the broad band is higher than the narrow band. Furthermore, add grid lines and upper axis and axis on the right side. Make the figure of similar design as figure 4. All figures should have the same general design. Check them all!! \\ Figure 3 has been updated and all figures have been checked and updated if necessary.
Figure 4: Reformulate the caption: Add the abbreviations Tskin and T2m, add what regions this stations represents, and also rephrase the part about the orange line. The orange line is the temperature difference T2m - Tskin. Furthermore, add what the standard deviations represent which is the variability in the monthly mean.\\ Done
Figure 5: Add grid lines, similar to figure 4. And add that Tskin is the surface temperature and T2m the air temperature at 2m. Also be consisten with you axis description, Tskin written out or not, T2m written out or not, T2m - Tskin written as temperature difference or not. Check for all figures!!\\ Done. Note the FRAM temperatures were not updated in Fig. 5 after the first revision (as all other figures and numbers were). Now it has been updated as well.
Figure 6: Add the abbreviations Tskin and T2m in the caption. Also be consistent in the use of T2m-Tskin as axes description or Temperature difference (see figure4) Done
Figure 7: Add that these are monthly averages, similar to figure 5.\\ Done
Figure 8: I still do not see the purpose to present the bins in the middle and lower panels. You do not refer to it in the manuscript and to the lower plots not at all. Also present the standard deviations in the upper plot as a band around the signal itself, as in figure 4. Add what regions these stations represent.\\

We have added which regions the stations represent. We have kept the middle and lower panel, as we think there is important information in the figures, e.g. it allows the reader to look at the distribution and gain confidence in the peak at 3-5m/s (since there are observations at low wind speeds as well). We think it is easier to read the standard deviations from the figure as it is.
Figure 11: Remove 'Similar to Figure 7.a but with...' and rephrase into an independent caption. The dotted lines indicate the maximum number of sunlight hours.\\ Done
Figure 13: Reformulate: for each month into seasonal cycle or monthly averages. Add what does the grey band signify. What is the variability in the orange line? You can present this as a transparant orange band around the line.\\ Reformulated to "monthy mean". It has been added that the grey band show the monthly average of the daily standard deviations. For the variability of the orange line see answer to comment: P13 L13.
Figure 14: Add that these are monthly averages. Why not show a scatter plot of Tskin vs T2m with the different stations as different colors?\\ It is not monthly averages but averages of the T2m-Tskin difference for each Tskin bin.

Table 2: Reformulate caption: 'under different circumstances' should be something like 'different seasons'. What does 'all months' refer to? An annual average? And what does SICE .|. DMI_Q mean, describe in caption. Perhaps you should not present all months in case it does not cover a full year.\\
Reformulated. All months refer to the full time series as given by Table 1. It means that DMI_Q has been excluded from these averages. Both parts have been clarified in the caption.

Reviewer #2

In situ observed relationships between snow and ice surface skin temperatures and 2 m air temperatures in the Arctic

Pia Nielsen-Englyst, Jacob L. Høyer, Kristine S. Madsen, Rasmus Tonboe, Gorm Dybkjaer, and Emy Alerskans

Summary

This study compares snow and ice surface temperatures derived from weather station radiometer measurements with air temperature measurements taken at the same locations. The study seeks to establish relationships between skin and surface air temperatures that can be useful for filling in gaps in the satellite record of surface measurements, and finds that the difference between Tskin and T2m varies by location, cloud cover, wind speed, and elevation. The results are potentially useful for improving estimates of arctic surface temperature change derived from satellite measurements.

General Comments

There is a clear motivation for the study, and the study is quite comprehensive in evaluating the effects of various factors on the observed relationships. The findings are important and potentially useful for improving estimates of arctic surface temperature changes. The text is fairly clear, but some improvements could be made in presentation of both figures and text. Some particular suggestions are provided below. I feel the suggested revisions are fairly minor overall.

We thank the reviewer for the time and effort put into this paper. We believe that the reviewer has identified some important areas, where improvements now have been made e.g. in way the figures and results are presented. We believe the manuscript has benefitted from improvements in the overall presentation and clarity. Below we respond to the reviewer comments (black) point by point in blue. In the end of this document we have included the manuscript with "track changes" on.

The authors divide sites into different categories (ACC, UAB, LAB, SSC, and SICE), and these categories are shown in Table 1. These categories are useful and it would be helpful to the reader to be able to distinguish these different types of sites in Figures 1, 2, 5, 7, 10, and 14. For Fig. 1 for example, could the authors use different symbols for different categories of sites? In Fig. 2 sites could be grouped and identified as in Fig. 9. In Figs. 5, 7, 10, and 14, the colors are not particularly useful as it is hard to distinguish between the different sites. However, it would be useful to be able to distinguish between the different categories, possibly by changing the color scheme, so that the different types contrast with each other (e.g. all sea ice sites gradations of red, all SSC sites gradations of green, etc.), or perhaps the line style, line weight or transparency.

We agree with the reviewer on this and have done the following improvements on the figures/table:
Fig. 1: We have written the station names with a different color for each surface type category to distinguish different types. We have not used different symbols, since the Greenland stations of different altitudes are plotted (almost) on top of each other in this figure, due to the large geographical coverage.
Fig. 2: Has been changed as suggested
Fig. 5, 7, 10, 14: Each surface type category has gained its own line style/weight as suggested. Note that the FRAM temperatures were not updated in Fig. 5 after the first revision (as all other figures and numbers

were). Now it has been updated as well.

Table 2 is mentioned fairly late in the manuscript. Numbers from Table 2 could be mentioned earlier along with a citation to the table (e.g. in section 4.1 when discussing T2m – Tskin differences at different types of locations). This would help support the statements made when discussing the seasonal timeseries plots. Thank you for the very good suggestion. Table 2 has now been mentioned in Sect. 4.1.

Section 5 seems to repeat many of the points mentioned in the results section. Perhaps the section can be reduced to avoid too much repetition of details, rather focusing on the general conclusions, and can be merged with the conclusions section, which is currently rather short. Some specific details, such as the discussion of the impact of the spectral range on measurements and the last paragraph of the discussion section might also be more appropriate to include earlier in the manuscript.

The discussion and conclusion sections have been merged and reduced as suggested. Also, the suggested parts of the discussion have been included earlier in the manuscript (in Sect. 4.3, 4.4 and 4.5).

Specific Comments

1. P. 1, Line 17: Add "difference" after "<0.5°C". Done
2. P. 2, Lines 9-13: Perhaps combine into two sentences to avoid shifting away from discussion of surface temperature. Done
3. P. 2, Line 32: Perhaps change "cooling of the surface" to "cooling of the surface relative to the air above it…" for clarity. Done
4. P. 3, Lines 20-22: The end of this sentence is confusing… it could just read "…and to quantify the differences between them." Done
5. P. 3, Line 23: What is meant by "In the response to the latter"? Maybe remove this? Rephrased to "An effort has therefore .."
6. P. 5, Line 26: What is meant by "also reasonable" and "slightly off"? Please be more specific. This part has been rephrased to clarify that we have used the processed data from SHEBA ASFG. What is written here is based on the documentation of the data.
7. P. 5, Line 28: Again, please clarify "known to be wrong". See comment above.
8. P. 6, Line 6: Define "near surface" – a few centimeters?
We have explained in the introduction to the data section (Sect. 2), that near-surface in this context is understood as a few meters (~2 m). This also applies to the FRAM observations.
9. P. 6, Line 22: I think "actual" can be removed from "actual observed" Done
10. P. 7, Lines 1-2: Perhaps here explain to the reader that this section provides some background on the energy balance that is important for interpreting results in the following sections. Otherwise the section seems out of place for the reader. We are a bit confused about this comment. We think the reviewer refers to Sect. 3 (P7, Lines 22-23) on the energy balance, but in that case we also think that we do state why the energy balance is important already: "To perform an analysis of the Tskin and T2m relationship and interpret the following results it is important to consider the surface energy balance and the specific surface characteristics that apply in the Arctic."
11. P. 9, Line 1: It would be good to be a bit more explicit here about why understanding diurnal and seasonal temperature variability helps interpreting satellite measurements.
The sentence has been rephrased to emphasize why the diurnal and seasonal scales of variability are important.
12. P. 9, Line 3: Add "Greenland" after "Kangerlussuaq" for clarity. Done

13. P. 9, Line 7: Add the year range for clarity. Done
14. P. 10, Line 3: Suggest changing “yearly” to “seasonal” for clarity. Done
15. P. 10, Line 29: Add “for selected sites.” after “wind speed”. Done
16. P. 11, Lines 5-7: This sentence is not very clear. I think that the authors mean that a temperature inversion with a slope acts results in winds that reduce the magnitude of the surface temperature gradient, but it is not clear how this leads to the observed peak. The explanation later in the paragraph, that an inversion in conjunction with a slope produces winds seems clearer. In this case because the gradient produces wind, lower wind speeds are less likely at higher gradients. Can the authors clarify the statement here? This part has been reformulated and clarified.
17. P. 11, Line 29: If the SICE sites have a larger frequency of overcast conditions, as stated earlier, how is it that they have only clear-sky observations between April and July? Thank you for pointing this out. The sentence was unclear and has been rephrased. What we mean is that there are almost no clear-sky observations during the other months (but only between April and July).
18. P. 12, Line 12: Reiterate here that DMI_Q measurements are taken at 1 m rather than 2 m as for the other measurements, as this was stated much earlier in the manuscript. Done, but this part has also been moved to section 4.1 as suggested.
19. P. 12, Line 15: Suggest changing “the results” to “the seasonal dependence” to make clear that the seasonal results are being referred to. Done
20. P. 12, Line 30: For what time period does the cloud cover fraction threshold apply? The cloud cover fraction is calculated for all available observations and the threshold is applied on all available observations as well. This should be clearer now. We have added the time interval of measurements for ARM and FRAM data used (in the data section), which was missing. Now the data section contains the information on the measurement intervals for each data source. Thanks for pointing this out.
21. P. 12, Line 31: What is the purpose of using these time intervals? Please briefly mention the reasoning.
The purpose is to assess the effect for averaging intervals used previously (Rasmussen et al., 2018) and when calculating monthly climatological values. This has been added in the text.
22. P. 13, Lines 3-6: This sentence is confusing. It seems that longer periods are more likely to include clouds. Therefore, there is more likely to be a larger difference between “all sky” and “clear sky” conditions because the “all sky” conditions will include clouds.

The sentence has been reformulated: “The larger clear-sky biases for longer temporal averaging windows arise from persistent cloud cover lasting for days. A clear-sky bias cannot be computed when using temporal averaging windows of shorter length than the duration of overcast conditions, due to missing clear sky observations. If however, a longer averaging window is used the Tskin observations during the overcast conditions (which tend to be warmer than during clear-sky) will be included in the all-sky average. The result is a warmer all-sky Tskin for longer temporal averaging windows, and thus a larger clear-sky bias.”

23. P. 13, Lines 13-16: This sentence is also confusing… I think the authors are simply saying that the positive biases at some stations shown in Fig. 12 result from missing data. Please clarify. This part has been reformulated and it should be clear now that it is the timing of clear-sky observations, which is thought to give rise to the positive clear-sky biases seen at a few sites.

24. P. 13, Lines 24-25: If possible, can the r2 values be provided? This will help indicate how close the trends are to being linear. We thank the reviewer for this suggestion. The average r^2 values have now been listed for each surface type.

25. P. 13, Lines 25-27: Given that the slopes at different stations, as well as for different types of stations are very different, how can the authors say that the results are "very encouraging"? While there may be a fairly good relationship between Tskin and T2m locally, it seems that coming up with a general relationship would be a challenge.
The slopes vary from region to region but are similar within each region. We have reformulated and explained that it might be feasible to consider relationship models derived on a regional level.

26. P. 13, Lines 26-27: Cloud cover and longwave radiation. Unfortunately, we do not understand this comment. Please clarify.
27. P. 14, Line 17: Again, as in the results section, the statement that the wind "destroys its own forcing" is unclear. This part has been clarified.
28. P. 15, Lines 29-31: Again, given the difference between different sites, is this really possible?
We have clarified that the similarities are found within each region and explained that it might be feasible to consider relationship models derived on a regional level.
29. P. 16, Lines 1-3: Although the results of this study are very useful and important, it seems that developing new products will require a fair amount of additional work to integrate the many different variables that can influence the relationship between surface temperature and surface air temperature, and account for the uncertainties in the observed relationships. The authors should make this clear here.
We have rearranged the conclusion. We agree that this requires a fair amount of additional work to derive the statistical model, which is why we have chosen to report on this work in an individual follow-up paper.

Technical Corrections

1. P. 1, Line 17: Change "particularly" to "particular" Done
2. P. 1, Line 24: Change "cloud limited Infrared" to "cloud-limited infrared" Done
3. P. 2, Line 18: Change "assessment of the climate change" to "assessment of climate change" Done
4. P. 2, Line 27: Change "due to the good spatial…" to "due to good spatial…" Done
5. P. 2, Line 29: Change "observations in the near…" to "observations and near…" Done
6. P. 3, Line 32: Add "and" before "lower ablation zone (LAB)" Done
7. P. 7, Line 7: Change "if found" to "is found". Done
8. P. 8, Line 31: Suggest removing "in the Arctic" as it has been mentioned already. Done
9. P. 9, Line 23: Change "occur to be" to "are" Done
10. P. 9, Line 24: Change "except from EGP" to "except EGP". Done
11. P. 10, Line 1: Change "but not reaches" to "but does not reach". Done
12. P. 10, Lines 4-6: Suggest changing sentence to read: "Figures 6a-b indicate that the wither months have very little diurnal variability in the T2m-Tskin difference (as is also evident in Fig. 4), with an approximately constant difference…" Done
13. P. 11, Line 1: Add "data from" before THU_U Done
14. P. 12, Line 3: Change "Figure 11a-b" to "Figures 11a-b". Done
15. P. 12, Line 19: Change "only be observed" to "only be utilized" Done
16. P. 12, Line 20: Change "in cloudy conditions" to "resulting from cloud cover" or something similar. Done
17. P. 13, Lines 3-4: Change "For e.g. the 72 hours…" to "For the 72-hour temporal averaging intervals, for example,…" Done
18. P. 13, Lines 11-12: Change "The orange graphs show…" to "Figure 5b also shows…" Done

19. P. 14, Line 9: Change "has the closest coupling" to "is closest to" Done
20. P. 15, Line 32: Spell out NWP. Done

21. Figure 6, caption: Change “Mean 2 m air temperature and skin temperature differences” to “Mean difference between 2 m air temperatures and skin temperatures for…” Done

22. P. 16, Line 3: Change “1980ies” to “1980s”. Done

In situ observed relationships between snow and ice surface skin temperatures and 2 m air temperatures in the Arctic

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Abstract.

To facilitate the construction of a satellite derived 2 m air temperature (T2m) product for the snow and ice covered regions in the Arctic, observations from weather stations are used to quantify the relationship between the T2m and skin temperature (Tskin). Multiyear data records of simultaneous Tskin and T2m from 29 different in situ sites have been analysed for five~~5~~ regions, covering the lower and upper ablation zone and the accumulation zone of the Greenland Ice Sheet (GrIS), sea ice in the Arctic Ocean, and seasonal snow covered land in northern Alaska. The diurnal and seasonal temperature variabilities and the impacts from clouds and wind on the T2m-Tskin differences are quantified. Tskin is often (85% of the time, all sites weighted equal) lower than T2m, with the largest differences occurring, when the temperatures are well below 0°C or when the surface is melting. Considering all regions, T2m is on average 0.65-2.65°C higher than Tskin, with the largest differences for the lower ablation area and smallest differences for the sea ice sites. A negative net surface radiation balance generally ~~makes the surface colder than~~cools the surface with respect to the atmosphere, resulting in a surface-driven surface air temperature inversion. However, Tskin and T2m are often highly correlated, and the two temperatures can be~~are~~ almost identical (<0.5°C difference), with the ~~at particularly times of the day and year, and during certain conditions. The data analysed here show the best agreement between Tskin and T2m~~smallest T2-Tskin differences around noon and early afternoon during spring~~, and~~ fall and summer during non-melting conditions. ~~However, Tskin is often lower than T2m by more than 2°C, with the largest differences occurring, when it is cold or when the surface is melting.~~ In general, the inversion strength increases with decreasing wind speeds, ~~except~~ but for the sites on the GrIS ~~where~~ the maximum inversion occurs at wind speeds of about 5 m s^{-1} due to the katabatic winds. Clouds tend to reduce the vertical temperature gradient, by warming the surface, resulting in a mean overcast T2m-Tskin difference ranging from -0.08°C to 1.63°C, with the largest differences for the sites in the low ablation zone ~~sites~~ and the smallest differences for the seasonal snow covered sites. To assess the effect of using cloud~~-~~limited i~~I~~nfrared satellite observations, the influence of clouds on temporally averaged Tskin has been ~~assessed~~ studied by comparing averaged clear-sky Tskin with averaged all-sky Tskin. ~~The clear-sky effect has been assessed for~~To this end, we test three different temporal averaging windows~~ of~~: 24 h, 72 h and 1 month. The largest clear-sky biases are generally found when 1 month averages are used and smallest for 24 h. In most cases, all-sky averages are warmer than clear-sky averages, with the smallest bias during summer when the Tskin range is smallest.

1 Introduction

The Arctic region is warming about twice as much as the global average because of Arctic amplification (Graversen et al., 2008). Greenland meteorological data show that the last decade (2000s) is the warmest since meteorological measurements of surface air temperatures started in the 1780s (Cappelen, 2016; Masson-Delmotte et al., 2012) and the period 1996-2014 yields an above average warming trend compared to the past six decades (Abermann et al., 2017). The reason for the Arctic amplification is a number of positive feedback mechanisms, e.g. the lapse rate feedback, which is positive in high latitudes (Manabe and Wetherald, 1975) and the ~~-~~ice-albedo feedback (e.g. Arrhenius, 1896; Curry et al., 1995), which is driven by the retreat of Arctic sea ice, glaciers, and terrestrial snow cover. The ~~atmospheric~~ warming leads to a declining mass balance of the Greenland Ice Sheet (GrIS), contributing to global sea level rise. The increased mass loss of the GrIS partly comes from increased calving rates, while the other part is a result of increased surface melt (Rignot, 2006), which is driven by changes in the surface energy balance. Several studies have focussed on the assessment of current albedo trends and their possible further enhancement of the impact of atmospheric warming on the GrIS (e.g. Box et al., 2012; Stroeve et al., 2013; Tedesco et al., 2011)~~. However,~~ but recent studies have shown that uncorrected sensor degradation in MODIS Collection 5 data was contributing falsely to the albedo decline in the dry snow areas, while the decline in wet snow and ice areas ~~remain~~ is confirmed but at lower magnitude than initially estimated~~thought~~ (Casey et al., 2017). Future projections of the GrIS mass balance show that the surface melt is exponentially increasing as a function of the increase in projected surface air temperature (Franco et al., 2013). Further, the Arctic warming may contribute to mid latitude weather events e.g. through its effects on the configuration of the jet stream (Cohen et al., 2014; Overland et al., 2015; Vihma, 2014; Walsh, 2014). It is therefore important to monitor the temperature of the Arctic to understand and predict the local as well as global effects of climate change. Current global surface temperature products are fundamental for the assessment of ~~the~~ climate change (Stocker et al., 2014) but in the Arctic these data traditionally include only near surface air temperatures from buoys and automatic weather stations (AWSs; Hansen et al., 2010; Jones et al., 2012; Rayner, 2003). However, in situ observations are ~~not available everywhere~~rare and the available time series have gaps and/or limited duration. In particular, the Arctic land ice and sea ice regions are sparsely covered with in situ measurements, due to the extreme weather conditions and low population density (Reeves Eyre and Zeng, 2017). The global surface temperature products are thus based on a limited number of observations in this very sensitive region. ~~This means that~~Consequently, crucial climatic signals and trends could be missed in the assessment of the Arctic climate changes~~ due to poor coverage of the observational system~~.

Satellite observations in the thermal infrared (IR) have a large potential for improving ~~upon~~ the surface temperature products in the Arctic due to ~~the~~ good spatial and temporal coverage. However, the variable retrieved from ~~infrared~~ IR satellite observations is the clear-sky surface skin temperature (Tskin), whereas current global surface temperature products estimate the all-sky 2 m air temperature (T2m; Hansen et al., 2010; Jones et al., 2012). An important step towards integrating the satellite observations ~~in~~ and ~~the~~ near surface air temperature products is thus to assess the relationships between Tskin and T2m and the role of clouds on this relationship as we do here.

A surface-based air temperature inversion is a common feature of the Arctic winter (Serreze et al., 1992; Zhang et al., 2011). The inversion exists because of ~~an imbalance between the radiative fluxes~~a negative net radiation balance, leading to a cooling of the surface relative to the air above it, ~~especially~~ which mostly occurs when the absorbed incoming solar radiation is small (during winter and night). ~~An analysis based on observations from the Antarctic Plateau showed that the inversion continues all the way to the surface with the largest gradient between the surface and 20 cm above it (Hudson and Brandt, 2005). The surface-driven temperature inversion causes a difference between the T2m and the actual skin temperature at the snow/air interface.~~ A few studies have investigated the temperature inversion in the ice regions for the lowest 2 m of the atmosphere, focusing on limited time periods and single locations e.g. Summit, Greenland (Adolph et al., 2018; Hall et al., 2008), the South Pole (Hudson and Brandt, 2005) and the Arctic sea ice (Vihma and Pirazzini, 2005). Previously, work has been done to characterize the relationship between the T2m and land surface temperatures observed from satellites and identified land cover, vegetation fraction and elevation as the dominating factors impacting this relationship (Good et al., 2017). ~~A few studies have investigated the temperature inversion in the ice regions for the lowest 2 m of the atmosphere focusing on limited time periods and single locations e.g. Summit, Greenland (Adolph et al., 2018; Hall et al., 2008), the South Pole (Hudson and Brandt, 2005) and the Arctic sea ice (Vihma and Pirazzini, 2005).~~ Until now, no systematic studies have yet been made for the high latitude ice sheets and over sea ice.

The difference between the T2m and Tskin is very important in validation studies of remotely sensed temperatures. Several studies have used T2m observations for validating satellite Tskin products on the GrIS (Dybkjær et al., 2012; Hall et al., 2008; Koenig and Hall, 2010; Shuman et al., 2014) and over the Arctic sea ice (Dybkjær et al., 2012) and found that a significant part of the satellite versus in situ differences could be attributed to the difference between the Tskin and T2m. Conversely, Rasmussen et al. (2018) used satellite Tskin observations in a simple way to correct the T2m, which was used to force ~~in~~ a coupled ocean and sea ice model, and obtained an improved snow cover.

In order to facilitate the integrated use of Tskin and T2m from in situ observations, satellite observations and models, there is a need for a better understanding and characterization of the observed relationship. The aim of this paper is to bring further insight into this relationship, using in situ observations. This study extends the previous analyses to include multiyear observational records from 29 different sites located on~~at~~ the GrIS, Arctic sea ice, and at the coastal region of northern Alaska. The aim is to identify the key parameters influencing the temperature difference between the surface and 2 m height and to assess under which conditions Tskin is, or is not, a good proxy for the T2m and to quantify the differences~~, using Tskin as a proxy for T2m~~. The findings are intended to aid the users of satellite data and to support the derivation of T2m using satellite Tskin observations. ~~In the response to the latter, a~~An effort has therefore also been made to estimate a clear-sky bias of Tskin based on in situ observations. The paper is structured such that Sect. 2 describes the in situ data. Section 3 gives an introduction to the near surface boundary conditions. The results are presented in Sect. 4 and ~~discussion and discussed in Sect. 5. C~~conclusions are given in Sect. 5~~6~~.

2 Data

In situ observations have been collected from various sources and campaigns covering ice and snow surfaces in the Arctic. The focus has been on collecting in situ data with simultaneous observations of Tskin, derived from ~~infrared~~ IR radiometers and T2m measured with a shielded and ventilated thermometer about 2 m above the surface. Table 1 gives an overview of the data and the abbreviations used in this paper. The data has been divided into five different categories based on surface characteristics and location: accumulation area (ACC), upper/middle ablation zone (UAB)~~,~~ and lower ablation zone (LAB) of the GrIS, seasonal snow covered (SSC) sites in northern Alaska~~,~~ and Arctic sea ice sites (SICE). All time series which cover multiple full years have been cut to cover an integer number of years (within 5 days), in order to avoid seasonal biases (see Table 1 for start date and end date for each site). The geographical distribution and elevations of all sites are shown in Fig. 1, while Fig. 2 shows the temporal data coverage. Observations from the sites in Table 1 include T2m, ~~Tskin,~~ wind speed and~~,~~ shortwave- and longwave radiation. Measurement heights vary depending on the site and snow depth, but for this paper near-surface air temperatures are referred to as 2 m air temperature despite these variations. The impact of these height variations are discussed in Sect. 4.1~~5~~. For all sites, Tskin has been derived from the longwave radiation measurements and the data has afterwards been filtered to exclude observations with Tskin>0°C. Further details are provided for each data source in Sect. 2.1-2.6.

2.1 PROMICE

Data have been obtained from the Programme for Monitoring of the Greenland Ice Sheet (PROMICE) provided by the Geological Survey of Denmark and Greenland (GEUS). PROMICE was initiated in 2007 by the Danish Ministry of Climate and Energy, and operated by GEUS in collaboration with the National Space Institute at the Technical University of Denmark and Asiaq (Greenland Survey; e.g. Ahlstrøm et al., 2008). PROMICE collects in situ observations from a number of AWSs mostly located along the margin of the GrIS (Fig. 1). Each observational site has one or more stations; typically one located in the lower ablation zone close to the ice sheet margin, and one or two located in the middle/upper ablation zone near the equilibrium line altitude. Exceptions are KAN_U and KPC_U located in the lower accumulation area and EGP, which is located in the upper accumulation area. All 22 PROMICE AWSs located on the GrIS have been used in this study. PROMICE Tskin has been calculated from up-welling longwave radiation, measured by Kipp & Zonen CNR1 or CNR4 radiometer, assuming a surface longwave emissivity of 0.97 (van As, 2011). The air temperature is measured by a thermometer at a height of 2.7 m, while the wind speed is measured at about 3.1 m height, if no snow is present. Snow accumulation during winter reduces the measurement height. Data where the surface albedo is less than 0.3 indicate that the snow and ice have disappeared and these data have been excluded to ensure that we only consider snow/ice covered surfaces. In this study, we use hourly averages of the data, provided by PROMICE.

2.2 ARM

The Atmospheric Radiation Measurement (ARM) Program (Ackerman and Stokes, 2003; Stamnes et al., 1999) was established in 1989 and it provides data on the cloud and radiative processes at high latitudes. Three ARM sites from the North Slope of Alaska (NSA) are used in this study: Atqasuk (ATQ), Barrows (BAR), and Oliktok Point (OLI). The stations provide surface snow ~~infrared~~IR ~~(IR)~~ temperature measured using a Heitronics KT19.85 IR Radiation Pyrometer (Moris, 2006) and air temperature measured at 2 m height. Wind speed is measured at 10 m height. All measurements are provided with a sampling interval of 1 min. The ARM stations have seasonal snow coverage, i.e. the snow melts away in summer. As for the PROMICE stations, ~~D~~data ~~where the surface~~ with a surface albedo ~~is~~ less than 0.3~~0~~ ~~indicate that the snow has disappeared and these~~ have been excluded. The data used here is thus biased towards autumn, winter and spring with 92% of all observations being measured during the months Sep.-May (all three SSC sites weighted equal). ~~to ensure that we only consider snow/ice covered surfaces.~~

2.3 ICEARC

We use the ICEARC sea ice temperature and radiation data set from the Danish Meteorological Institute (DMI) field campaign in Qaanaaq. The DMI AWS is deployed on first-year sea ice in Qaanaaq and is funded by the European climate research project, ICE-ARC. The AWS was deployed for the first time in late January 2015 at the north side of the fjord Inglefield Bredning and recovered in early June before break-up of the fjord ice. The campaign has been repeated every year since then and the data used in this study is procured by fieldwork done in the periods Jan.-Jun., 2015-2017. The AWS is equipped to measure snow surface IR temperature and air temperature at 1 and 2 m heights. In this study, the 1 m air temperature is used instead of the 2 m air temperature, as careful analysis of the 2 m air observations revealed anomalies that could arise from a systematic temperature dependent error. Using the 1 m instead of 2 m air temperatures observations will have an impact on the strength of the relationship with the Tskin observations, but the observations are included here as the dependency with other parameters, such as cloud cover and wind, is still important to assess. The data used here are snapshot measurements every 10 minute ~~snapshots~~ (Høyer et al., 2017) and are referenced as~~:~~ DMI_Q in this paper.

2.4 SHEBA

The Surface Heat Budget of the Arctic (SHEBA) experiment was a multiagency program led by the National Science Foundation and the Office of Naval Research. The data used in this study originates from deployment of a Canadian icebreaker, DesGroseilliers, in the Arctic ice pack 570 km northeast of Prudhoe Bay, Alaska in 1997 (Uttal et al., 2002). During its year-long deployment, SHEBA provided atmospheric and sea ice measurements from the icebreaker and the surrounding frozen ice floe. The data used here contain hourly averaged data collected by the SHEBA Atmospheric Surface Flux Group (ASFG) and Dr. J. Liljegren from the ARM project. The SHEBA ASFG installed a 20 m tall tower, which was used to obtain measurements of the surface energy budget, focusing on the turbulent heat fluxes and the near surface boundary layer structure (Bretherton et al., 2000; Persson, 2002). The mast contains ~~F~~five different levels, varying in height from 2.2-18.2 m, on which ~~had mounted a~~ temperature/humidity probes and a sonic anemometer are mounted. ~~We use~~The air temperature and wind data used here originates from the lowest mounted instruments (2.2 m), which vary in height from 1.9 to 3 m depending on snow accumulation and snow melt. Three different methods to measure surface temperature ~~measurements~~ were deployed: ~~measured from~~ a General Eastern thermometer, an Eppley radiometer and a Barnes radiometer, for which data is available over the period from April to September 2007. According to ASFG, ~~T~~the Eppley radiometer is the most reliable, though there are periods when the other two are also reasonable, and one period (May), when the Eppley data may be slightly off (Persson, 2002). ~~We~~ They ~~use~~ provide an~~the best~~ estimate of Tskin, which is based on slight corrections to the Eppley temperatures and the Barnes temperatures when Eppley was known to be wrong (Persson, 2002). We use the processed data from the SHEBA ASFG (Persson, 2002).

2.5 FRAM2014/15

The scientific program of the FRAM2014/15 expedition is carried out by the Nansen Center (NERSC) in co-operation with Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Germany, University of Bergen, Bjerknes Center for Climate Research and Norwegian Meteorological Institute. FRAM2014/15 is a Norwegian ice drift station deployed near the North Pole in August 2014 using a ~~medium-sized~~ hovercraft as logistic and scientific platform (Kristoffersen and Hall, 2014). This type of mission allows exploration of the Arctic Ocean not accessible to icebreakers, and enables scientific field experiments, which require physical presence. ~~The hovercraft was operated by two people and b~~By the end of March 2015 they had drifted 1.450 km. During the drift with sea ice they obtained Tskin measurements by Campbell Scientific IR120 (later corrected for sky temperature and surface emissivity) mounted on the hovercraft and near surface air temperature measurements-, with a sampling interval of 1 min. ~~from a temperature sensor.~~

2.6 TARA

TARA is a French polar schooner that was built to withstand the forces from the Arctic sea ice. In late August 2006 TARA sailed to the Arctic Ocean, where she drifted for fifteen months frozen into the sea ice. The TARA multidisciplinary experiment was ~~a~~ part of the international polar year DAMOCLES (Developing Arctic Modelling and Observing Capabilities for Long-term Environmental Studies) program (Gascard et al., 2008; Vihma et al., 2008). Air temperature and wind speed were measured from a 10 m tall Aanderaa weather mast at the heights of 1, 2, 5, and 10 m and wind direction was measured at 10 m height. We use the air temperatures and wind speed measured at 2 m height. They also ~~had~~ deployed an Eppley broadband radiation mast with two sensors for longwave fluxes and two sensors for shortwave fluxes (upward and downward looking). The downward looking IR sensor also provided Tskin from April to September 2007. The data used in this study are 10 minute averages.

2.7 Radiometric observations of Tskin

The Tskin observations used in this study are all derived from radiometric observations, but with spectral characteristics that range from the Heitronics KT19.85 with a spectral response function from 9.5-11.5 µm over Campbell Scientific IR120 with a 8-14 µm spectral window to broadband longwave observations from ~4-40 µm. The emissivity of the ice surface varies for the different spectral windows for the radiometers and this will lead ~~leads~~ to a difference in ~~actual~~ observed Tskin as radiation from surfaces with emissivities < 1 will include (1-emissivity) reflected radiation from the s~~S~~ky. The radiation emitted from e.g. a cold sky during cloud free conditions will thus result in a colder Tskin observation for surfaces with lower emissivities, compared to high emissivity surfaces and this may introduce a Tskin difference between radiometers with different spectral windows. However,~~ as the sky temperature, which is reflected, tends to be much colder than the ice surface in the infrared, in particular during cloud free conditions. The contribution from the reflected sky is thus included in the radiometric observations but the~~ ice and snow surfaces have generally very high emissivities, which reduce the effects from the reflected sky radiation. In Høyer et al. (2017), the difference in emissivity between the KT15.85 and the IR120 was modelled using an IR snow emissivity model with the spectral response functions for the two types of instruments (e.g. Dozier and Warren, 1982). This resulted in averaged emissivities of 0.998 for the KT15.85 and 0.996 for the IR120 spectral windows for a typical snow surface and an incidence angle of 25 degrees. Using the same ~~type of model~~ approach for a broadband 4-40 µm spectrum resulted in an emissivity of 0.997. The high emissivities for all three instruments mean that the contributions from the sky are small. ~~F~~For realistic conditions in the Arctic, this e.g. introduces an average difference of 0.06°C between the IR120 and the KT15.85 radiometer (which has a similar spectral response function as the KT19.85), with the IR120 being colder than the KT15.85 (Høyer et al., 2017). It is thus clear that the KT15.85 is closest to the true Tskin due to the high emissivity, but also that these Tskin variations due to different spectral windows can be neglected. Several of the stations (ATQ, BAR, OLI, DMI_Q, SHEBA and FRAM) used here observed both narrow band and wide band IR observations of the ice surface. The two types of Tskin have been calculated and compared for each of the stations. Figure 3 shows an example ~~with~~ of a comparison of the two Tskin estimates from DMI_Q, showing a correlation of 0.99 and a bias of 0.69°C when comparing the two Tskin estimates. There is ~~close~~ a good ~~to a 1:1~~ relation between the two observations for the full range of temperatures, meaning that there are no ~~systematic~~ temperature dependencies in the comparison. Considering all sites, a good agreement i~~f~~s found with a small mean difference between the two Tskin types of 0.06°C and a mean root mean squared value of 0.96°C. In the following we use the narrow band Tskin observations when available and the broadband at the other stations and assume that all the Tskin derived observations have the same characteristics.

2.8 Longwave-equivalent cloud cover fraction

For ~~each site~~all observation pairs,~~,~~ the longwave-equivalent cloud cover fraction (CCF) has been estimated based on the relationship between T2m and down-welling longwave radiation (LW_d), following the cloud cover estimation already included in the PROMICE data sets (van As, 2011; van As et al., 2005). It is based on Swinbank (1963), who ~~presented~~

developed a ~~very~~ simple approach for estimation of clear-sky (CCF=0) atmospheric longwave radiation as a function of T2m:

$$LW_{d\_clear} = 9.365 \cdot 10^{-6} \cdot \mathrm{T2m}^2 \cdot \sigma \cdot \mathrm{T2m}^4, \qquad (1)$$

where σ is Stefan-Boltzmann's constant. Overcast conditions (CCF=1) are assumed to occur when the observed LW_d exceeds the blackbody radiation emitted from the surface, which is calculated using T2m. The CCF for any observed T2m and LW_d pair from all individual observation sites is then calculated by linear interpolation of the observed LW_d, between the theoretical clear-sky (from Equation 1) and the overcast estimates. See van As (2011) for more details on the CCF calculation.

3. Introduction to the near surface boundary conditions

To perform an analysis of the Tskin and T2m relationship and interpret the following results it is important to consider the surface energy balance and the specific surface characteristics that apply in the Arctic. The surface temperature and surface melt are driven by the surface energy balance. The ~~net~~ surface energy balance is ~~defined by the fluxes of~~the sum of the energy fluxes between the atmosphere, and the snow/ice surface and the ~~underlying~~ sub-surface land, snow/ice, or ocean. The surface energy balance can be written as

$$SW_d - SW_u + LW_d - LW_u + SH + LH + G = M,$$

where M is the net energy flux at the surface and SW_d, SW_u, LW_d, LW_u, SH, LH, and G represent the downwelling~~-~~ and ~~upwelling~~ reflected (at the surface) shortwave radiation, down- and upwelling longwave radiation, sensible and latent heat flux~~,~~ and subsurface conductive heat flux, respectively. The energy fluxes have the unit W m^{-2}. All fluxes are defined positive when energy is added to the surface. The surface is a skin layer, which is an infinitesimal thin layer without heat capacity and there is an instantaneous balance between the different fluxes. This means that the elements in the surface energy balance are balanced and M equals 0 if there is no phase change (melt or refreeze). The warming or cooling of the medium below the surface affects the surface temperature through the conductive heat flux (G) and latent heat (LH) release when refreezing occurs. This affects the temperature of the medium and with that the temperature gradient close to the surface and thus the conductive heat flux (G) at the surface. ~~A positive net surface energy balance results in warming of the surface, if the temperature is lower than the freezing point of water, or in melting of snow and ice (latent heat) if the temperature is at the freezing point. When the surface energy balance is negative the snow/ice will cool thus driving the conductive heat flux from warmer layers below. If the surface is melting, a negative energy balance results in freezing of liquid water.~~

The radiative budget of ~~the polar regions~~sea ice is dominated by net longwave radiation flux during much of the year.~~and~~ E~~e~~ven during summer the net shortwave radiation ~~input~~ flux is in the same order of magnitude as the ~~incoming~~ net longwave radiation flux because of extensive cloud cover, especially during late summer, and the high surface albedo of the snow (Maykut, 1986). However, SW_d is the dominating source for ice melt in Greenland (van den Broeke et al., 2008; Box et al., 2012; van As et al., 2012), even though ~~non-radiative~~turbulent energy fluxes can dominate during shorter periods (Fausto et al., 2016). The latter is related to the fact that ~~O~~on average, the ~~non-radiative~~turbulent fluxes are an order of magnitude smaller than the radiation fluxes~~. However, because~~ and since the net radiation flux~~balance~~ is small compared to the individual radiation fluxes the variations in SH and LH fluxes are important for the total surface energy balance and thus the surface temperature. ~~Surface winds interact strongly with the surface energy fluxes as the t~~The turbulent mixing of the lower atmosphere increases as a function of wind speed (van As et al., 2005).

During ~~winter and clear skies~~clear-sky conditions, ~~-~~ when SW_d is negligible, LW_u is higher than ~~the~~ LW_d. This results in a negative radiative balance cooling the surface and this drives a positive sensible heat flux.~~ and it results in a stable stratification of the lower atmospheric boundary layer (Maykut, 1986).~~ When the heat conduction flux from below the surface is limited on thick sea ice and on continental ice sheets the negative radiation ~~budget~~ balance at the surface makes the surface temperature colder than the surface air temperature, resulting in a surface-based temperature inversion (Maykut, 1986). At low to moderate wind-speeds, when turbulent mixing is limited, this creates a very stable stratification of the lower atmosphere. On a sloping surface, the surface air starts to flow downslope, driven by the existence of a horizontal temperature gradient and gravity. The generated winds are called inversion or katabatic winds, and are characterised by stronger winds at more negative surface net radiation and a strong correlation between slope and wind direction (Lettau and Schwerdtfeger, 1967). In this paper, these winds will be referred to as katabatic winds. ~~In the case of PROMICE sites on GrIS, we will refer to these winds as katabatic winds and in the case of interior Antarctic studies these winds are referred to as inversion winds for consistency with referenced studies.~~

Formateret: Sænket skrift

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Clouds play a complex role in the Arctic surface energy budget e.g. they ~~both~~ reflect SW_d, leading to a cloud shortwave cooling effect, and absorb LW_u and emit LW_d, which tend to have a warming effect. In the Arctic, clouds have a predominantly warming effect on the surface (Intrieri, 2002; Walsh and Chapman, 1998) as the dry atmosphere, with lower emissivity and with that absorptivity to LW radiation, enhances the cloud longwave warming effect, while the high surface albedo and the high solar zenith angles ~~thus~~ reduces the impact of the cloud shortwave cooling effect (Curry et al., 1996; Curry and Herman, 1985; Zygmuntowska et al., 2012).

4 Results

4.1 Diurnal and seasonal temperature variability

The local air and surface temperature conditions in the Arctic are to a large extent influenced by the length of the day or night~~ in the Arctic~~, with extreme variations depending on latitude and time of the year. ~~The temperature variability has several important temporal scales.~~ In this study we will focus on the diurnal and seasonal temperature variations, as these ~~which~~ are key temporal scales of variability and therefore important to understand when ~~, considering~~ the aim is ~~of~~ to derive ~~deriving~~ T2m from satellite observations. As an example of the large seasonal variations, Fig. 4 shows the 2014 monthly mean diurnal temperature variation of Tskin and T2m at the upper PROMICE site in Kangerlussuaq, Greenland~~,~~ (KAN_U)~~,~~

during January, April, July and October. The seasonal variability in the diurnal temperature at KAN_U is representative of the conditions at the other stations, except for the general temperature level at each station, which changes with latitude and altitude. ~~Considering all months individually, there is high correlation between Tskin and T2m ranging from an average value of 0.92 in January to an average of 0.99 in July considering the entire time series of KAN_U. The high correlations arise from hourly variability and daily cycles in temperatures that are seen in both temperature records. The correlation decreases for stations which have occasional surface melt, where Tskin is constrained to the freezing point of water.~~ At KAN_U b~~B~~oth Tskin and T2m reach a maximum in July, while the coldest month is December (not shown) during 2014. During winter and polar night, ~~there~~ Fig. 4 ~~is~~shows no clear diurnal cycle in ~~either~~ T2m or Tskin, and T2m is higher than Tskin. However, during spring there is a strong diurnal cycle, with Tskin lower than T2m at night and small T2m-Tskin differences during daytime. The shadings indicate the standard deviations in T2m and Tskin, respectively. The largest variability is found in spring and winter as a result of more frequent and rapid passages of cold and warm air masses in contrast to the summer months (Steffen, 1995). The summer temperature variability is moreover limited by the upper limit of 0°C on Tskin during surface melt.~~when the surface melting begins.~~ Considering all months individually, there is high correlation between Tskin and T2m ranging from an average value of 0.92 in January to an average of 0.99 in July considering the entire time series of KAN_U, 2008-2018. The high correlations arise from hourly variability and daily cycles in temperatures that are seen in both temperature records. The correlation decreases for stations which have occasional surface melt, where Tskin is constrained to the freezing point of water. The presence of a lower Tskin compared to T2m is a general ~~phenonema~~phenomenon found for all stations. Tskin is thus lower than T2m 85% of the time, when all sites are weighted equally, whereas the opposite is true for only 13.7% of the observation times.

The large seasonal variations in Fig. 4 and the relationship between T2m and Tskin are typical for all sites. Figure 5a shows the monthly mean Tskin for all sites and all years. EGP is by far the coldest site due to its high elevation, with a monthly mean Tskin of -42°C in January and a maximum of -11°C in July. All sites reach a maximum in Tskin in July, regardless of latitude. July is also the month with least variation in temperature among sites, where melt at most stations (exceptions ~~is~~ are the ACC sites) constrains Tskin, while the winter months show a larger variance in Tskin among sites since local conditions are dominating Tskin. The AWS data from the GrIS show the effect of altitude and latitude on Tskin, with the high altitude sites being the coldest (EGP, KAN_U and KAN_M) together with the most northern sites (THU_U and KPC_U). The southern (e.g. QAS_A and QAS_U) and low altitude sites (most LAB sites, TAS_U and~~,~~ TAS_A) ~~occur to be~~are the warmest. The SICE sites are comparable in temperature with the coldest sites on the GrIS (except ~~from~~ EGP), but are slightly warmer in summer and fall.

Figure 5b shows the mean daily range (daily max – daily min difference) of Tskin as a function of month for all sites and all years. Again, the observations show a similar pattern across the diverse geographical locations. During summer, the high elevation sites tend to have the largest daily range in Tskin, while the observations from LAB and SICE sites show the smallest daily range. This is ~~is very likely~~mostly an effect of the warmer temperatures and the Tskin upper temperature limit at 0°C, the melting point for ice. This constraint is seen during summer at almost all data records included in this study (exceptions are the ACC sites). Figure 5c shows the monthly mean difference between T2m and Tskin for all observation sites as a function of time of year. The T2m-Tskin differences observed in Fig. 5c have been averaged for each surface type category in Table 2, divided into summer months (Jun.-Aug.), winter months (Dec.-Feb.) and all available months. Note that DMI_Q is withheld from the averaging for the SICE sites to avoid systematic impacts from the 1 m height observations used from DMI_Q. In general, the ACC, SSC and SICE sites show the weakest inversion, while the UAB and LAB sites show the strongest inversion. For the ACC sites the weakest inversion is found during summer, while the UAB and LAB sites have the strongest inversion during summer. This is explained by the UAB and LAB sites having surface melt in contrast to the high elevation ACC sites, where the surface warms but does not reach the upper limit at the melting point.

The SSC sites also experience melt, but the snow melts away in summer, which limits the time where Tskin is constrained to the melting point. It is difficult to interpret the seasonal dependencies for the SICE sites, as none of the individual sites cover an entire year. ~~In general, the SICE sites show the weakest inversion, while the LAB sites show the strongest inversion. For the ACC sites the weakest inversion is found during summer, while the LAB sites tend to have the strongest inversion during summer. This is explained by differences in surface conditions during summer, where the LAB sites have surface melt in contrast to the high elevation ACC sites, where the surface warms but not reaches the ceiling of variability (the melting point).~~

Figure 5 indicates both ~~yearly~~ seasonal and daily variations in the observed Tskin and T2m relationship. ~~A detailed analysis of these variations can be seen in~~ Figures 6a-b~~, which~~ illustrate the mean diurnal and seasonal T2m-Tskin differences for the ACC and LAB sites, respectively. The SSC and SICE sites have not been included as none of the individual sites have a continuous data record throughout the year~~ without gaps~~. Figures 6a-b indicate that the winter months have very little diurnal variability in the T2m-Tskin difference (as is also evident in Fig. 4), with an ~~As also noticed in Fig. 4, the winter months have very little diurnal variability in the T2m-Tskin difference, with an~~ approximately constant difference of about 1.5-2.5°C for the LAB sites and 0.5-1.5 °C for the ACC sites. During spring and summer the differences decrease at the ACC sites and the weakest vertical stratification is found around noon or early afternoon, where Tskin may even exceed T2m slightly, resulting in an unstable stratification of the surface air column. For the LAB sites, the weakest stratification is found in spring and fall, around noon and early afternoon. The summer months show large T2m-Tskin differences due to the constrain of Tskin for melting surfaces, which is common to all LAB sites. At night the net radiation is typically negative, thus cooling the surface and resulting in a surface-based inversion for both surface types. The T2m-Tskin differences are higher (especially in summer) at the LAB sites compared to the ACC sites, and the UAB sites have temperature differences in between. The reason for the higher temperature difference at the lower altitude sites is the longer time periods with surface melt, which is due to higher temperatures.

As mentioned in Sect. 2, the measurement height changes with snowfall and snow melt and with that the strength of the inversion measured. The PROMICE data includes a height of the sensor boom, which can be used to determine the impact of using different measurement height on our results. We reproduced the numbers in Table 2, based upon observations measured at a height of 1.9-2.1 m only and found overall all-sky, all-months differences less than 0.22°C for all the different

PROMICE regions. In addition, the screening did not change the conclusions regarding the impact of clouds and the seasonal behaviour of the T2m-Tskin differences. Data from the other sites do not all include such information on the measurement height. For consistency, we therefore chose not to screen the PROMICE data. In addition, we chose not to perform an adjustment of the observations, as we estimate the uncertainty of such an adjustment to be equal to or larger than the uncertainty in the results obtained here.

4.2 Impact ~~from~~ by wind

The surface wind speed is an important component in the near surface thermal stratification since the turbulent mixing increases as a function of wind speed (Monin and Obukhov, 1954). Figure 7 shows how the wind regimes differ among the observation sites used in this study. In general, winds on the GrIS are strongest in winter and reach a minimum around July (see also Steffen and Box, 2001). The surface radiative cooling and the terrain play the primary role in the generation of the surface winds. The direction and strength of the prevailing surface winds are closely related to the direction and steepness of the slope and the strength of the inversion.~~–~~ Surface winds at the PROMICE sites generally have a high directional persistence (see Fig. 4 in van As et al., 2014), commonly blowing from inland, which is an indication that local winds are often of katabatic ~~winds~~origin. High elevation sites experience stronger winds due to the larger radiative cooling of the surface (provided a comparable surface slope is present; Fig. 8; van As et al., 2014). The SSC and SICE sites show less variability in wind speed on annual basis. At these sites the wind is determined by large scale synoptic conditions combined with local topography.

The expectation is that stronger inversions can develop in low wind speed conditions because of reduced turbulent mixing. Figure 8a-b shows the T2m-Tskin difference as a function of ~~binned~~ wind speed for selected sites. ~~The middle plots show the binned distribution of the T2m-Tskin difference (with bin size of 1 K) as a function of binned wind speed, where the colour bar is the number of members in each bin.~~ The top plots show the mean (solid lines) and standard deviation (dashed lines) of the T2m-Tskin difference as a function of ~~the binned~~ wind speed~~s~~. Figure 8a shows data from the DMI_Q AWS on sea ice. As expected, the strongest temperature inversion occurs at low wind speeds and larger wind speeds have larger turbulent mixing and thus smaller vertical temperature differences between Tskin and T2m. However, data from THU_U (Fig. 8b) shows that this relationship is more complex. The maximum inversion is reached at wind speeds from 3-5 m s^{-1}, whereas the mean and standard deviation decrease for calm winds (<2.5 m s^{-1})

The wind dependencies shown in Fig. 8 are representative for all the stations in this paper, where the SICE and the SSC sites resemble Fig 8a and all the PROMICE stations have a wind dependency similar to Fig. 8b. The pattern of the PROMICE stations is explained by the combination of inversion ~~combined with~~and a surface slope that results in a flow, which ~~actually destroys~~reduces the strength of the inversion (its own forcing). For large wind speeds the inversion will be destroyed and calm winds can only occur when the inversion is close to zero (as the presence of inversion on sloping surfaces forces a wind). ~~a~~As a result there is an optimum in inversion strength and wind speed, which in this case is at wind speeds of 3-5 m s^{-1}. ~~The PROMICE~~This behaviour is also found by Adolph et al. (2018) at the Summit station on the GrIS. Miller et al. (2013)

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also found that the surface based inversion intensity peaks at wind speeds ranging from 3 to 10 m s^{-1} at Summit based on microwave radiometer retrieved profiles. Furthermore, Hudson and Brandt (2005) show that at the South Pole the maximum inversion strength occurs at wind speeds of 3-5 m s^{-1}. They investigated this using the model by Mahrt and Schwerdtfeger (1970) and their results supported the idea that the inversion forces an air flow, which ~~They suggest that it is not the weak wind of 3-5 m s^{-1} that promotes the strong inversion, but the inversion which forces the air flow resulting in an inversion wind. They investigated this using the model by Mahrt and Schwerdtfeger (1970), which relates the slope of the terrain and the strength of the inversion to the inversion wind. Their results supported the idea that the inversion wind~~ can explain the "unexpected" location of the maximum in inversion strength. T~~It seems that t~~he nature of the surface winds and the directional constancy are highly comparable between the sloping surfaces of Antarctica and Greenland (van den Broeke et al., 1994; King and Turner, 1997) and in both cases the maximum inversion occurs at non-zero wind speeds.

4.3 Impact ~~from~~ by clouds

The difference in LW_d radiation between clear-sky and overcast conditions can result in large differences in both T2m and Tskin due to the cloud effect~~s~~ on the surface radiation budget. As IR satellite Tskin can only be retrieved during clear-sky conditions, the assessment of the cloud effect~~s~~ on the average conditions is essential to facilitate the combination of satellite and in situ observations. In this section, we therefore assess the inversion strength as a function of the cloud cover and in ~~Sect. 4.3.1~~the next section the clear-sky bias is estimated for all sites.

Clear-sky conditions are defined to be cases where CCF<0.3, while overcast conditions are defined to have CCF>0.7. The frequency of clear-sky (overcast) observations is defined as the number of clear-sky (overcast) observations compared to the total number of observations. Figure 9 shows the frequency of clear-sky and overcast observations for each of the observation sites used in this study. The SSC and~~,~~ SICE sites~~,~~ and EGP all show a much larger frequency of overcast conditions compared to the frequency of clear-sky conditions. Also, the TAS_U, TAS_A and TAS_L sites located in the high accumulation area (Ohmura and Reeh, 1991) of the south-eastern part of the GrIS tend to have more overcast observations compared to clear-sky observations. There is a general tendency with more frequent overcast observations for increasing altitudes for the PROMICE sites. The ACC sites ~~show~~ have a strong seasonal dependence with more clear-sky observations during summer and more overcast conditions during winter (not shown). A similar but much weaker seasonal cycle is seen for UAB. The LAB and SSC sites show limited seasonal variability, while the SICE sites have almost ~~only~~ no clear-sky observations ~~from~~ during the months from August to March (not shown).~~April to July.~~

The relation between the inversion strength and CCF is shown in Fig 10 for all sites. As expected, the inversion strength decreases for larger~~with increasing~~ cloud cover fractions due to increasing LW_d radiation ~~due to a more extensive cloud cover~~. For each surface type category ~~T~~the average slope ~~is~~ has been calculated ~~for each category~~based on linear fits to the graphs in Fig. 10: ACC=-0.011±0.0037 °C/%, UAB = -0.019±0.0012 °C/%, LAB = -0.021±0.0016 °C/%, SSC = -0.016±0.0026 °C/%, SICE = -0.017±0.0048 °C/% where the uncertainties are given as 95% confidence intervals on the slope values. The average r^2 fit values for each surface type category are: 0.25 (ACC sites), 0.76 (UAB sites), 0.83 (LAB sites), 0.55 (SSC sites), and 0.40 (SICE sites). Excluding ATQ and EGP (with very low r^2 values of 0.013 and 0.0014, respectively) increases the average r^2 to 0.83 and 0.38 for SSC and ACC sites, respectively. These results indicate that a linear approximation is a good assumption for UAB, LAB and SSC (excluding ATQ), whereas the ACC and SICE dependencies are further away from linear.

Figures 11a-b show how the temperature differences at the ACC sites vary as a function of season and local time for clear-sky and overcast conditions, respectively. Clear-sky conditions show the largest stratification with temperature differences up to 2-3°C during winter and night time. Overcast conditions reduce the temperature gradient at all times, with the maximum temperature differences of about 1°C. During summer around noon, overcast conditions usually lead to an unstable stratification of the order of -1°C. An unstable stratification may also occur during clear-sky conditions and large solar insolation. This behaviour is common for all sites included in this study, but the strength of the inversion varies among the different sites. Table 2 also summarizes the impact of clouds on the T2m-Tskin differences for each surface type category.

~~The impact of season and sky conditions on the T2m-Tskin differences is quantified in Table 2. The table summarizes the findings of the dependencies of cloud/clear and summer/winter on the T2m-Tskin difference for all 5 categories. Note that DMI_Q is withheld from the averaging for the SICE sites to avoid systematic impacts from the 1 m height observations. The categories which experience summer surface melt (UAB + ACC) tend to have larger T2m-Tskin differences during summer than winter. The SSC sites also experience melt, but the snow melts away in summer, which limits the time where Tskin is constrained to the melting point. It is difficult to interpret the results for the SICE sites, as none of the individual sites cover an entire year.~~ For all surface types and for all times of the year, cloud cover tends to decrease the inversion strength.

To assess the impact of the different spectral characteristics of the used radiometers (broad band versus narrow band, as discussed in Sect. 2.7) on the observed Tskin, the T2m-Tskin differences were calculated as a function of CCF for both narrow and broad band Tskin for the sites containing both instruments (ATQ, BAR, OLI, DMI_Q, SHEBA, and FRAM). The average slope for above sites was estimated in both cases and resulted in a small difference in the slope from -0.017°C/% to -0.020°C/% for narrow band and broad band Tskin estimates, respectively.

4.4~~3.1~~ Clear-sky bias

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The most accurate surface temperature satellite observations are thermal IR observations that can only be ~~observed~~ utilized during clear-sky conditions. ~~-~~As the satellite IR observations thus have gaps ~~in cloudy conditions~~resulting from cloud cover, the satellite Tskin products are often averages of the available satellite observations ~~within~~ over a 1-3 day periods~~s~~ (see e.g. Rasmussen et al., 2018). However, these satellite averages will differ from the all~~-~~-sky average temperature, since the Tskin is typically lower ~~under~~during clear~~-~~-sky conditions compared to cloudy conditions. This difference is referred to as ~~the~~ clear

-sky bias~~However, these satellite averages can be colder than the all-sky average temperature due to a clear-sky bias arising from the fact that Tskin is typically colder in clear-sky conditions compared to the cloudy conditions where the satellite cannot observe~~. When using the averaged Tskin observations from satellites for monitoring or in combination with ocean, sea ice or atmospheric models, it is ~~therefore~~ thus important to assess the impact off the different temporal averaging windows on the clear-sky bias~~, by using different temporal averaging windows~~. Hall et al. (2012) show monthly temperature maps from MODIS and discuss the fact that the monthly average temperatures (from satellites) are likely lower tha~~t~~n the all-sky monthly average temperatures. Here, we use the in situ observations to estimate the clear-sky effects that satellite observations would introduce. We use ~~the~~ a cloud mask derived from the longwave-equivalent cloud cover fraction and assume that it is equivalent to the cloud masks used for IR satellite processing. The clear-sky bias ~~has been~~is assessed by comparing all available clear-sky Tskin observations (where clear-sky has been defined as a CCF < 0.3) with all available all-sky Tskin ~~(where clear-sky has been defined as a CCF < 0.3)~~ observations, averaged for different time windows: 24 h, 72 h and 1 month, for all sites. The three averaging windows were chosen to examine the clear-sky effect for previously used averaging windows in Rasmussen et al. (2018) (72 h) and when calculating monthly climatological values. ~~-~~The results are shown in Fig. 12. For most stations all-sky observations are warmer than clear-sky observations for all time windows and the difference tends to increase with increasing length of temporal averaging window. The larger clear-sky biases for longer temporal averaging windows arise from persistent cloud cover lasting for days. ~~The~~ A clear-sky bias cannot be computed when using temporal averaging windows of shorter length than the duration of overcast conditions, due to missing clear-sky observations. If however, a longer temporal averaging window is used the Tskin observations during the overcast conditions (which tend to be warmer than during clear-sky) will be included in the all-sky average. The result is a warmer all-sky Tskin for longer temporal averaging windows, and thus a larger clear-sky bias.~~. However, t~~ There is large variability among the stations and at a few stations e.g. EGP, KPC_U, ATQ, OLI and DMI_Q the all-sky observations are colder than clear-sky observations using one or more of the ~~-~~temporal averaging ~~-time~~ windows. These positive clears-sky biases are very likely a result of seasonal differences in cloud cover.

~~The larger clear-sky biases for longer temporal averaging windows arise from persistent cloud cover lasting for days. For e.g. the 72 hours temporal averaging intervals, observations from periods with >1 day persistent cloud cover (and higher Tskin) are included, which are otherwise missing in the 24 hour clear-sky averages, resulting in a warmer all-sky averaged Tskin, compared to the average clear-sky Tskin.~~

Figure 13a-b show~~s~~ the monthly mean difference in the 24 h averaged clear-sky and all-sky Tskin for the ACC stations (a) and the LAB stations (b), together with the average number of hours with clear sky per day. For both groups of stations it is found that the 24 h averaged clear-sky bias is closest to zero during summer, which can partly be explained by the smaller daily Tskin range in summer (Fig. 5b). The UAB sites (not shown) look very similar to the LAB sites, but with a slightly more pronounced seasonal cycle in the clear-sky bias. The figures have not been produced for the SSC and SICE sites as none of the individual sites included in these categories cover an entire season. Figure 13 also shows~~The orange graphs show the mean number of hours with clear-sky per day, which illustrate~~ more hours with clear-skies for LAB stations compared to

ACC stations except for the period May-July, where both surface groups on average have about 12 hours with clear sky per day. For the ACC sites the number of hours with clear sky decreases to about 4 hours per day during Sep.-Mar. ~~.~~ ~~The positive clears-sky biases observed in Fig. 12 are very likely an effect of seasonal differences in cloud cover e.g. i~~It is found that EGP has no clear-sky observations in Dec.-Feb. and at DMI_Q there are~~is~~ no clear-sky observations available for Jan-Mar., which means that the results in Fig. 12 are~~is~~ biased towards the months where a zero or positive clear-sky bias is observed. This very likely explains the positive clear-sky biases observed (in Fig. 12) for these stations. The 72 h and 1 month averaged clear-sky biases show the same seasonal variation as in Fig. 13, with the smallest biases in summer and largest biases in winter (not shown).

The observed clear-sky bias explains part of the cold bias observed in IR satellite retrievals of skin surface temperature compared to in situ skin surface temperatures as seen in Høyer et al. (2017) and Rasmussen et al. (2018) ~~(Høyer et al., 2017; Rasmussen et al., 2018; Shuman et al., 2014)~~. Another contribution to a satellite versus in situ cold bias ~~part of the explanation~~ is related to the fact that the satellite skin observations are compared to in situ observations measured at typically 2 m height (Shuman et al., 2014). T~~, where the t~~emperature ~~gradients~~inversions in the lowest 2 m of the atmosphere will thus result in the satellite retrievals of surface temperature being colder than the in situ measurements at 2 m height.

4.5~~4~~ Relationship between Tskin and T2m~~with skin surface temperature~~

Section 4.3 showed how clouds impact the T2m and Tskin relationship, and Sect. 4.4~~3.1~~ revealed how satellite Tskin is affected by clouds~~a close relationship between Tskin and the CCF~~. With the aim of deriving T2m based upon satellite Tskin observations, it is important to examine how the T2m-Tskin difference is related to the skin temperature itself. The relationship with Tskin is ~~corroborated~~ shown in Fig. 14 where the strength of the surface-based inversion is shown as a function of Tskin. All PROMICE sites show an almost linear trend towards weaker inversion strength for higher skin temperatures with the steepest slope of the curve for low elevation sites. The average slopes of the linear fits of the graphs in Fig. 14 for all categories are found to: ACC=-0.030±0.003, UAB =-0.066±0.004, LAB=-0.101±0.004, SSC = -0.044±0.005, SICE = -0.043±0.007, where the uncertainty estimates are given as 95 % confidence intervals on the slopes. The average r^2 fit values for each surface type category are: 0.76 (ACC sites), 0.77 (UAB sites), 0.86 (LAB sites), 0.54 (SSC sites), and 0.51 (SICE sites). The numbers demonstrate that the linear relationship is a better assumption when using Tskin ~~rather~~compared to ~~than~~ cloud cover fraction. ~~T~~The results of this section show that the slopes are similar within each region but tend to vary from region to region. ~~These results thus~~This indicate that Tskin and T2m relationship models can be derived on a regional level ~~are very encouraging in a situation where we would like to relate Tskin to T2m~~using Tskin for situations where~~, but~~ the cloud cover and longwave radiation are not available, such as the case with satellite observations.

As in Sect. 4.3, the impact of the different spectral characteristics of the radiometers on above results has been assessed. The T2m-Tskin differences were calculated for both types of radiometers as a function of Tskin for the sites containing both

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~~5 Discussion~~

~~The T2m and Tskin variability shows that the coldest month ranges from December to March, whereas the warmest month is July for all sites considering both Tskin and T2m. This is in agreement with mean air temperatures found in Steffen and Box (2001) for Greenland GC-Net AWSs, Persson (2002) for Arctic sea ice and Rigor et al. (2000) for North Pole stations and land stations in Alaska. The monthly mean daily temperature range is largest in April–May and reaches a minimum in July, related to the upper temperature limit when the ice or snow is melting. Surface temperature inversions are very common for the Arctic region. Considering all categories the mean temperature difference between T2m and Tskin is on average 0.65–2.65°C with the strongest inversion for the sites located in the lower part of the ablation zone and the weakest inversion for the sea ice sites. Inversions are predominantly found during winter (low sun and polar night periods), which allows for a strong radiative cooling at the surface. Smaller temperature differences are dominating in spring and summer, around noon and early afternoon, where the sun is warming the surface. This is in agreement with Adolph et al. (2018) who found large T2m-Tskin differences during night time and small differences during the peak solar irradiance (see Fig. 5 in Adolph et al., 2018). During summer and local noon Tskin has the closest coupling to T2m and the satellite observed Tskin observations will therefore have the best agreement with the T2m at these times.~~

~~Increasing wind speeds are expected to decrease the inversion strength through increased turbulence, and mixing warmer air downwards. This is also seen at the ARM sites and Arctic sea ice sites, where the strongest inversion occurs at calm winds and weaker inversions occur with increasing wind speed. The relationship is more complicated over a sloping terrain with the maximum inversion strength at winds of about 5 m s~~$^{-1}$ ~~and not at calm winds. This feature has previously been identified by others for Antarctica (Hudson and Brandt, 2005) and at Summit, GrIS (Adolph et al., 2018; Miller et al., 2013) and can be explained by the presence of a katabatic wind driven by the surface temperature inversion over a sloping terrain. The katabatic wind destroys part of its own forcing and as a result there exist an optimum in inversion strength and wind speed. This is in agreement with what Hudson and Brandt (2005) found for the Antarctic ice sheet.~~

~~The analysis of the impact of clouds showed an almost linear relationship between cloud cover and the T2m-Tskin difference, with a trend towards zero with increasing CCF (Fig. 10). Considering all categories the T2m-Tskin difference decreases from an all sky mean value ranging from 0.65–2.65°C to a difference ranging from -0.08–1.63°C considering observations with a CCF above 0.7. On the other hand, the difference increases to the range of 1.05–3.44°C by only considering observations with CCFs below 0.3. The smaller inversion strength under cloudy conditions is explained by the fact that clouds have a predominantly warming effect on the surface in the Arctic (Intrieri, 2002; Walsh and Chapman, 1998). In cases where the cloud cover and longwave radiation are not available, the relationship can be quantified by using the Tskin. We have found an almost linear relationship between the inversion strength and the skin temperatures, with~~

~~weaker inversions for higher Tskin. This is in agreement with Adolph et al. (2018) who found larger T2m-Tskin differences at lower temperatures at the Summit station, during summer.~~

~~As mentioned earlier, the measurement height changes with snowfall and snow melt at with that the strength of the inversion measured. The PROMICE data includes a height of the sensor boom, which can be used to determine the impact of using different measurement height on our results. We reproduced the numbers in Table 2, based upon observations measured at a height of 1.9-2.1 m only and found overall all-sky, all-months differences less than 0.22°C for all the different PROMICE regions. In addition, the screening did not change the conclusions regarding the impact of clouds and the seasonal behaviour of the T2m-Tskin differences. Data from the other sites do not all include such information on the measurement height. For consistency, we therefore chose not to screen the PROMICE data. In addition, we chose not to perform an adjustment of the observations, as we estimate the uncertainty of such an adjustment to be equal to or larger than the actual uncertainty on the results obtained here and again, it would not be possible to make such a correction for all sites.~~

~~To assess if there is any impact of clear sky observations on the radiometer observations due to the different spectral characteristics (broad band versus narrow band, as discussed in Sect. 2.7), the T2m-Tskin differences as a function of CCF were calculated for narrow band Tskin and broad band Tskin for the stations containing both instruments (ATQ, BAR, OLI, DMI_Q, SHEBA, and FRAM). This resulted in a small change in the slope from -0.017 to 0.020°C/% for narrow band and broad band Tskin estimates, respectively. Similarly, the T2m-Tskin differences were calculated for both types of radiometers as a function of Tskin. Again, the change in trend was small from -0.046 to -0.055.~~

~~The influence of clouds on Tskin has been assessed by comparing clear-sky Tskin observations with all-sky Tskin observations averaged for different time intervals: 24 h, 72 h and 1 month, for all sites. In general, the clear-sky average is colder than the all-sky average with increasing bias with the length of the averaging time interval and the clear-sky bias is smaller during summer than winter for all averaging windows. This is also reported by Comiso (2000), who finds a monthly mean clear-sky bias of about -0.3°C during summer (Jan.) and -0.5°C during winter (Jul.) at Antarctic stations. The range in temperature over the averaging window as well as the frequency and timing of clear-sky observations are factors partly explaining the clear-sky bias variations observed among the stations.~~

~~The observed clear-sky bias explains part of the cold bias observed in IR satellite retrievals of skin surface temperature compared to in situ surface temperatures (Høyer et al., 2017; Rasmussen et al., 2018; Shuman et al., 2014). Another part of the explanation is related to the fact that the satellite skin observations are compared to in situ measured at typically 2 m height, where the temperature gradients in the lowest 2 m of the atmosphere will result in the satellite retrievals of surface temperature being colder than the in situ measurements at 2 m height.~~

5~~6~~ Cc~~C~~onclusions

Coincident in situ skin temperature (Tskin) and 2 m air temperatures (T2m) from 29 ~~deployments~~ sites in the Arctic region have been analysed to assess the variability and the factors controlling the Tskin and T2m variations. The aim is to ~~in order~~

~~to~~ facilitate the combined use of satellite observed Tskin and traditional observations of T2m. The extensive data set used in this study represents a wide range of conditions including all-year observations from Arctic sea ice, land ice in northern Alaska as well as low and high altitude land ice covering the lower, middle and upper ablation zones and the accumulation region of the Greenland Ice Sheet (GrIS). It has been found that for each region, there is a good correspondence between the Tskin and T2m and that the main factors influencing the relationship between Tskin and T2m are seasonal variations, wind speed, and cloud cover.

Considering all surface type categories the mean T2m-Tskin difference is on average 0.65-2.65°C with the strongest inversion at the sites located in the lower ablation zone and the weakest inversion at the sea ice sites. Inversions are predominantly found during winter (low-sun and polar night periods), which allows for a strong radiative cooling at the surface. Smaller T2m-Tskin differences are dominating around noon and early afternoon in spring and summer, when the sun is warming the surface but no melting occurs. This is in agreement with Adolph et al. (2018) who found large T2m-Tskin differences during night time and small differences during the peak solar irradiance at Summit, GrIS (see Fig. 5 in Adolph et al., 2018). During local noon in spring, fall and summer (during non-melting conditions), satellite observed skin temperatures will therefore have the best agreement with the T2m.

Increasing wind speeds are expected to decrease the inversion strength through increased turbulence and mixing of warmer air towards the surface. This is seen at the ARM sites and the Arctic sea ice sites, where the strongest inversion occurs at calm winds. Conversely, the ~~and with increasing wind speed~~ inversion strength decreases with increasing wind speed. The relationship is more complicated over a sloping terrain with the maximum inversion strength at winds of 3-5 $m\ s^{-1}$ for all the GrIS sites. This feature has previously been identified by others for Antarctica (Hudson and Brandt, 2005) and at Summit, GrIS (Adolph et al., 2018; Miller et al., 2013) and can be explained by the presence of a katabatic wind driven by the surface temperature inversion over a sloping terrain. The katabatic wind reduces the inversion strength and as a result there exist an optimum in inversion strength and wind speed.

The analysis of the impact of clouds showed an almost linear relationship between cloud cover fraction (CCF) and the T2m-Tskin difference, with a trend towards zero with increasing CCF, for most sites (Fig. 10). Considering all surface type categories, the T2m-Tskin difference decreases from an all-sky mean value ranging from 0.65-2.65°C to a difference ranging from -0.08-1.63°C for observations with a CCF above 0.7. On the other hand, the T2m Tskin difference increases to the range of 1.05-3.44°C by only considering observations with CCFs below 0.3. The smaller inversion strength under cloudy conditions is explained by the fact that clouds have a predominantly warming effect on the surface in the Arctic (Intrieri, 2002; Walsh and Chapman, 1998). In ~~cases~~situations where the cloud cover and longwave radiation are not available, the T2m-Tskin relationship can be quantified by using the Tskin. We have found an almost linear relationship between the inversion strength and the skin temperatures, with weaker inversions for higher Tskin. This is in agreement with Adolph et al. (2018) who found larger T2m-Tskin differences at lower temperatures at the Summit station, during summer.

In order to facilitate the construction of a satellite derived T2m product the influence of clouds on temporally averaged Tskin has been assessed. This has been done by comparing clear-sky Tskin observations with all-sky Tskin observations averaged over different time intervals: 24 h, 72 h and 1 month. In general, the clear-sky average is colder than the all-sky average with increasing bias with the length of the averaging time interval.

The clear-sky bias is smaller during summer than winter for all averaging windows. This is also reported by Comiso (2000), who finds a monthly mean clear-sky bias of about -0.3°C during summer (Jan.) and -0.5°C during winter (Jul.) at Antarctic stations.
The seasonal variation in clear-sky bias in combination with differences in frequency and timing of clear-~~-~~sky observations lead to ~~the~~ differences among the stations. The average positive clear-~~-~~sky bias at e.g. EGP is thus a result of persistent cloud cover during winter months and predominantly clear sky in summer months, where the clear-~~-~~sky ~~-~~bias is small or positive.
~~The range in temperature over the averaging window as well as the frequency and timing of clear-sky observations are factors partly explaining the clear-sky bias variations observed among the stations.~~

~~It has been found that there is a good correspondence between the Tskin and T2m and that the main factors influencing the relationship are seasonal variations, wind speed, cloud cover and the Tskin of the surface.~~ The assessment of the ~~tight~~ T2m-Tskin ~~relationship~~ differences and the identification of the main variables that control~~s~~ the variability are important findings when developing a statistical model to estimate the T2m from satellite Tskin observations. In addition, the findings in the diurnal and seasonal variations in the T2m-Tskin differences are valuable when validating the satellite Tskin against T2m observations. ~~that can convert satellite Tskin observations to T2m.~~ All the identified parameters can be derived from either the satellite retrievals themselves or from numerical weather prediction (NWP) analysis~~ and~~. T~~t~~he generation of a daily satellite derived T2m product for the Polar Regions using a statistical model is thus facilitated ~~made possible~~ with these results, which is the focus of current developments~~ through a statistical model~~. Such a satellite derived product ~~that only uses parameters derived from the satellite retrievals themselves~~ can~~will~~ be independent of other existing surface temperature products and NWP reanalysis and can therefore contribute significantly to improvements in the Arctic climate change ~~assessment since the satellite era started in the early 1980'ies~~monitoring and assessment.

6~~7~~ Author contribution

Pia Nielsen-Englyst, Kristine S. Madsen, Rasmus Tonboe, Gorm Dybkjær and Emy Alerskans compiled the in situ data. Pia Nielsen-Englyst, Jacob L. Høyer and Kristine S. Madsen designed the experiments and Pia Nielsen-Englyst carried them out. Pia Nielsen-Englyst prepared the manuscript with contributions from all authors.

7~~8~~ Competing interests

The authors declare that they have no conflict of interest.

8~~9~~ Acknowledgements

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Table 1 Observation sites used in this study covering the following surface types: Accumulation zone (ACC), upper/middle ablation zone (UAB), lower ablation zone (LAB), seasonal snow cover (SSC), sea ice (SICE).

Project	Site	Station	Surface Type	Latitude (°N)	Longitude (°W)	Elevation (m)	Start date	End date
PROMICE	East Grip	EGP	ACC	75.62	35.97	2660	01/05/2016	30/04/2018
PROMICE	Kangerlussuaq	KAN_U	ACC	67.00	47.03	1840	04/04/2009	03/04/2018
PROMICE	Crown Prince Christian Land	KPC_U	ACC	79.83	25.17	870	17/07/2008	16/07/2018
PROMICE	Kangerlussuaq	KAN_M	UAB	67.07	48.84	1270	02/09/2008	01/09/2018
PROMICE	Nuuk	NUK_N	UAB	64.95	49.89	920	25/07/2010	24/07/2014
PROMICE	Nuuk	NUK_U	UAB	64.51	49.27	1120	20/08/2007	19/08/2018
PROMICE	Qassimiut	QAS_A	UAB	61.24	46.73	1000	20/08/2012	19/08/2015
PROMICE	Qassimiut	QAS_M	UAB	61.10	46.83	630	11/08/2016	10/08/2018
PROMICE	Qassimiut	QAS_U	UAB	61.18	46.82	900	07/08/2008	06/08/2018
PROMICE	Scoresbysund	SCO_U	UAB	72.39	27.23	970	21/07/2008	20/07/2018
PROMICE	Tasiilaq	TAS_A	UAB	65.78	38.90	890	28/08/2013	27/08/2018
PROMICE	Tasiilaq	TAS_U	UAB	65.67	38.87	570	11/03/2008	10/03/2015
PROMICE	Thule	THU_U	UAB	76.42	68.15	760	09/08/2010	08/08/2018
PROMICE	Upernavik	UPE_U	UAB	72.89	53.58	940	18/08/2009	17/08/2018
PROMICE	Kangerlussuaq	KAN_L	LAB	67.10	49.95	670	01/09/2008	31/08/2018
PROMICE	Crown Prince Christian Land	KPC_L	LAB	79.91	24.08	370	17/07/2008	16/07/2018
PROMICE	Nuuk	NUK_L	LAB	64.48	49.54	530	20/08/2007	19/08/2018
PROMICE	Qassimiut	QAS_L	LAB	61.03	46.85	280	24/08/2007	23/08/2018
PROMICE	Scoresbysund	SCO_L	LAB	72.22	26.82	460	22/07/2008	21/07/2018
PROMICE	Tasiilaq	TAS_L	LAB	65.64	38.90	250	23/08/2007	22/08/2018
PROMICE	Thule	THU_L	LAB	76.40	68.27	570	09/08/2010	08/08/2018
PROMICE	Upernavik	UPE_L	LAB	72.90	54.30	220	17/08/2009	16/08/2018
ARM	Atqasuk	ATQ	SSC	70.47	149.89	2	07/11/2003	06/11/2010

ARM	Barrow	BAR	SSC	71.32	156.62	8	31/10/2003	28/10/2018
ARM	Oliktok Point	OLI	SSC	70.50	157.41	20	18/10/2013	13/10/2018
ICEARC	Qaanaaq	DMI_Q	SICE	77.43	69.14	Sea level	31/01/2015	08/06/2017
FRAM2014/15	Arctic Ocean	FRAM	SICE	82.22-89.35	-180.00-180.00	Sea level	05/09/2014	3/07/2015
SHEBA	Arctic Ocean	SHEBA	SICE	74.62-80.37	143.92-168.15	Sea level	01/11/1997	26/09/1998
TARA	Arctic Ocean	TARA	SICE	71.41-88.54	0.01-148.28	Sea level	01/04/2007	20/09/2007

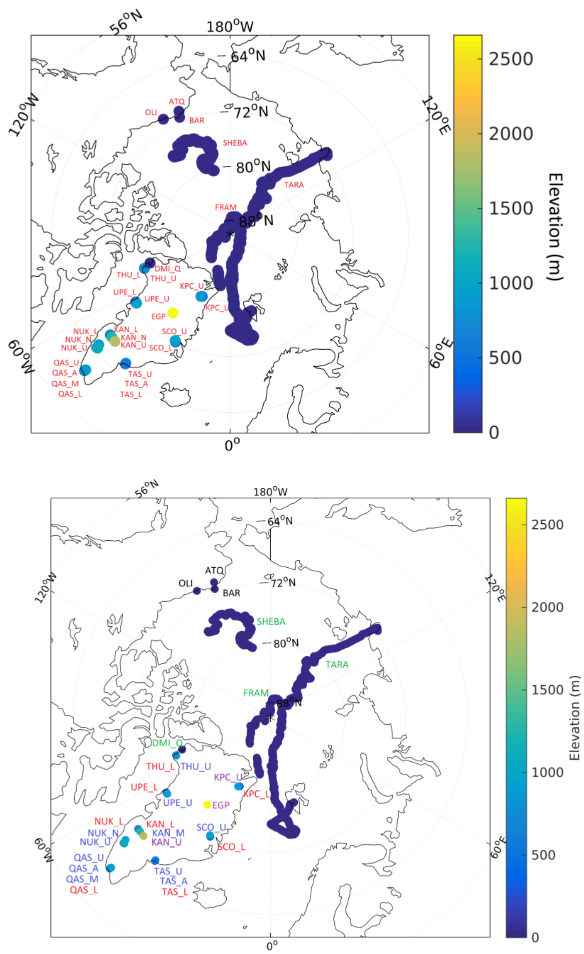


Figure 1: Spatial coverage and elevation for each site included in this study. Each surface type group has been labelled with a different colour: ACC sites are purple, UAB sites are blue, LAB sites are red, SSC are black and SICE sites are green. The colour bar is elevation above sea level in meters.

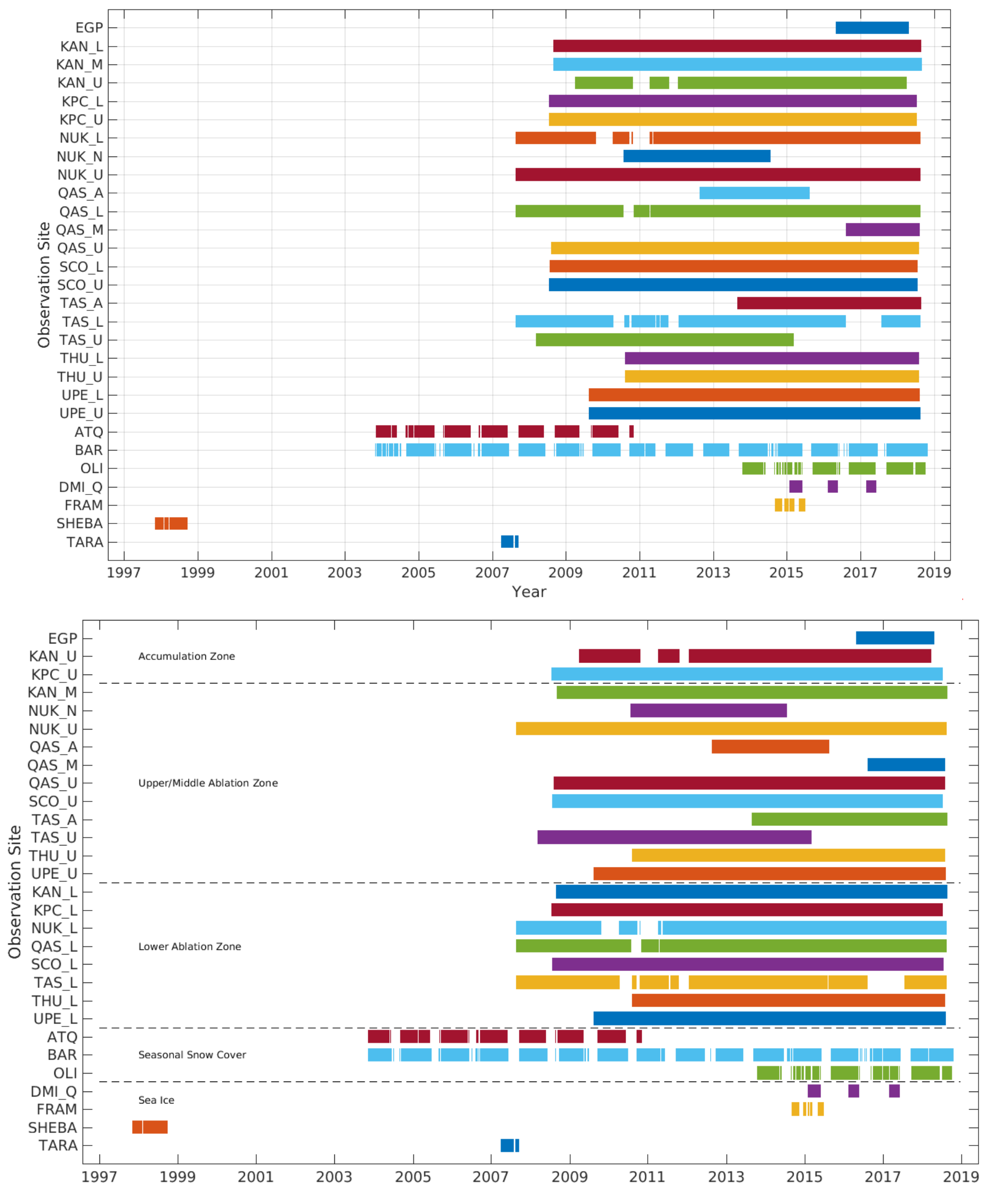


Figure 2: Temporal coverage for each observation site included in this study.

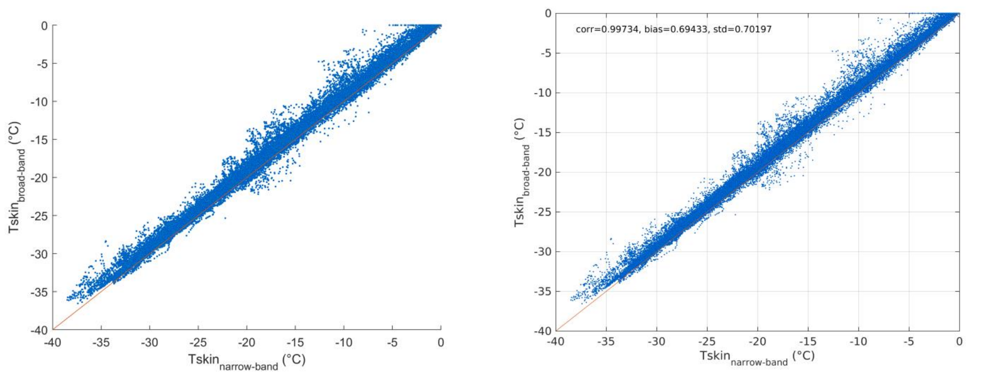


Figure 3: Scatterplot of Tskin estimated from narrow-band IR observations versus Tskin estimated from broad-band IR observations for DMI_Q.

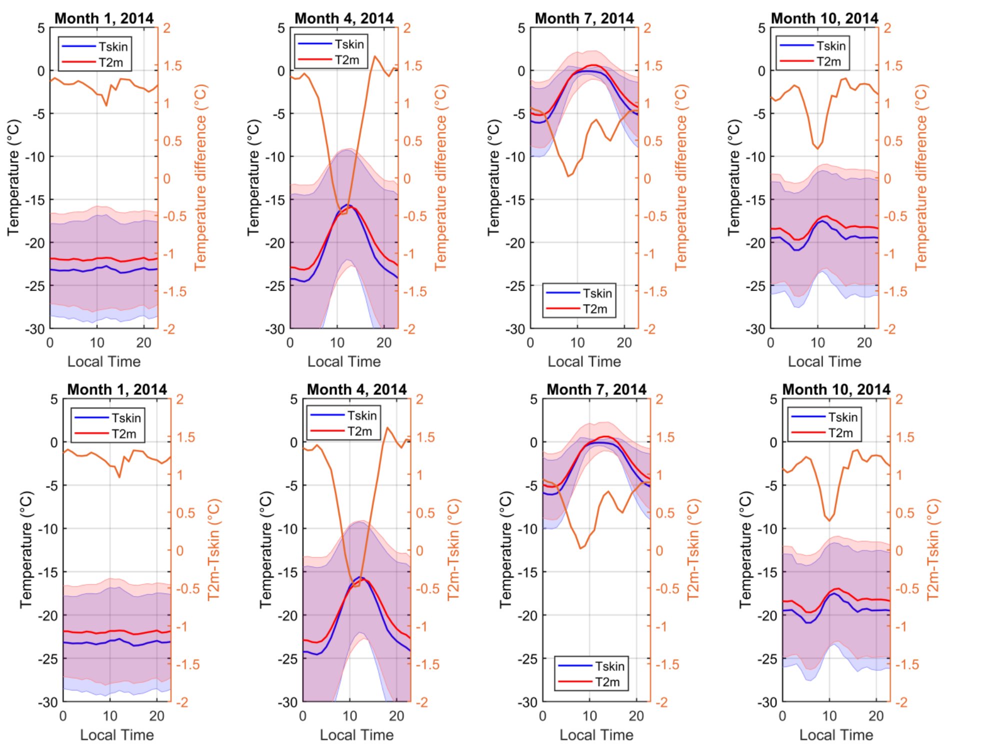
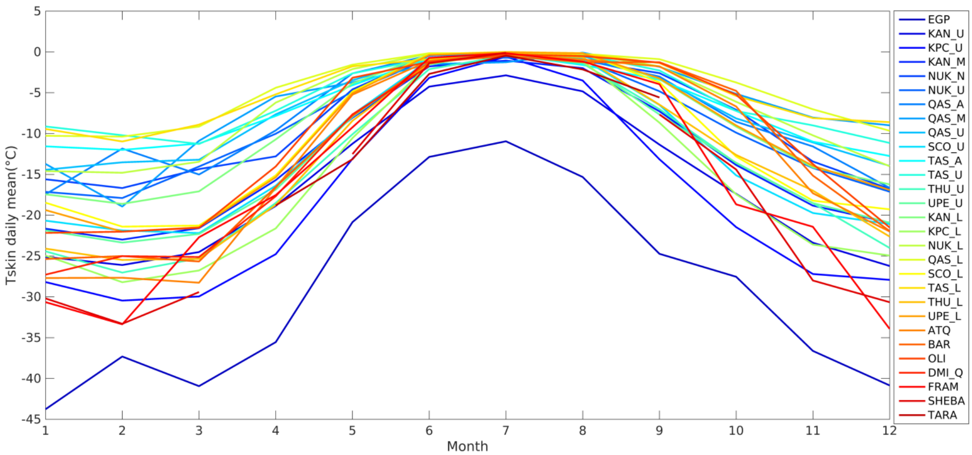
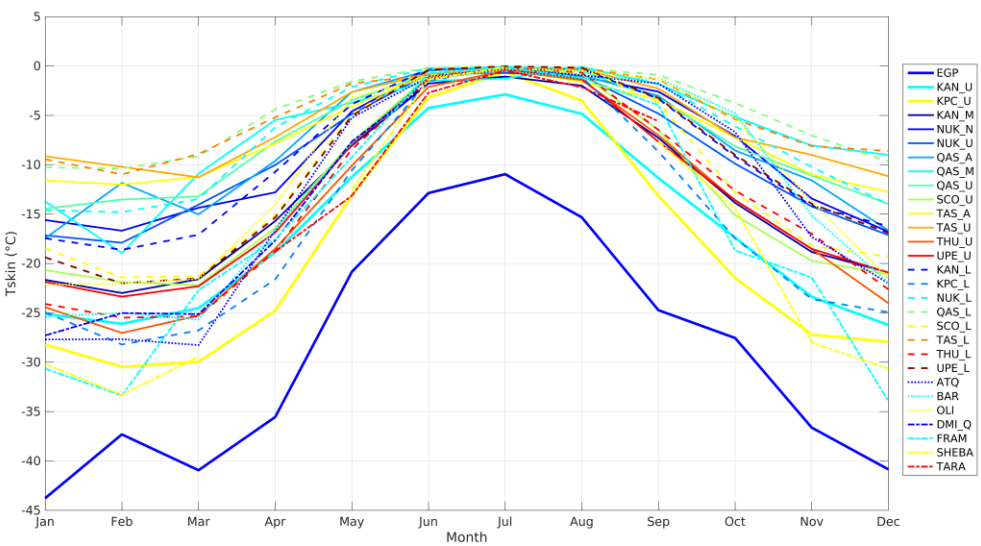


Figure 4: Mean ~~Monthly d~~diurnal variability of 2 m air temperature (~~red~~T2m) and skin temperature (~~blue~~Tskin) at KAN_ U during the months: January, April, July and October, 2014. The orange lines ~~curves~~ are the temperature difference T2m-Tskin~~between the red and blue curves~~. The shadings indicate the standard deviations, which represent the variability in the monthly mean.



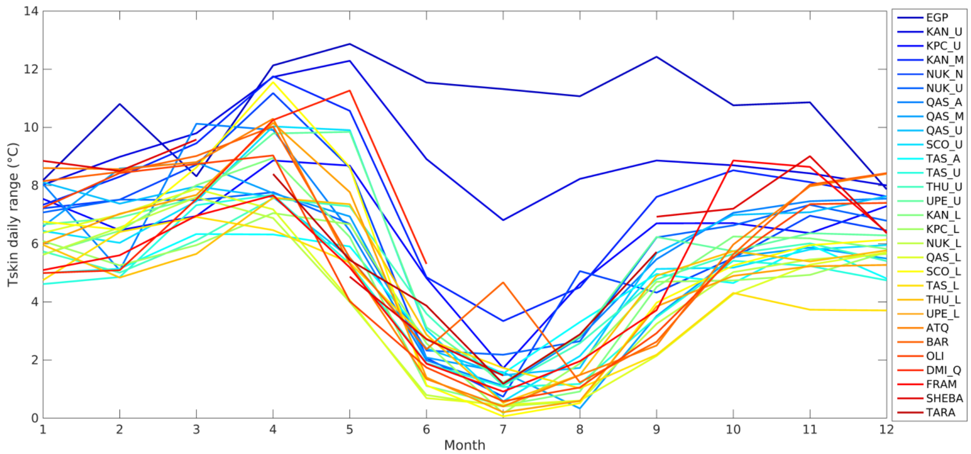
Tskin daily mean(°C)
Month
EGP
KAN_U
KPC_U
KAN_M
NUK_N
NUK_U
QAS_A
QAS_M
QAS_U
SCO_U
TAS_A
TAS_U
THU_U
UPE_U
KAN_L
KPC_L
NUK_L
QAS_L
SCO_L
TAS_L
THU_L
UPE_L
ATQ
BAR
OLI
DMI_Q
FRAM
SHEBA
TARA

(a)

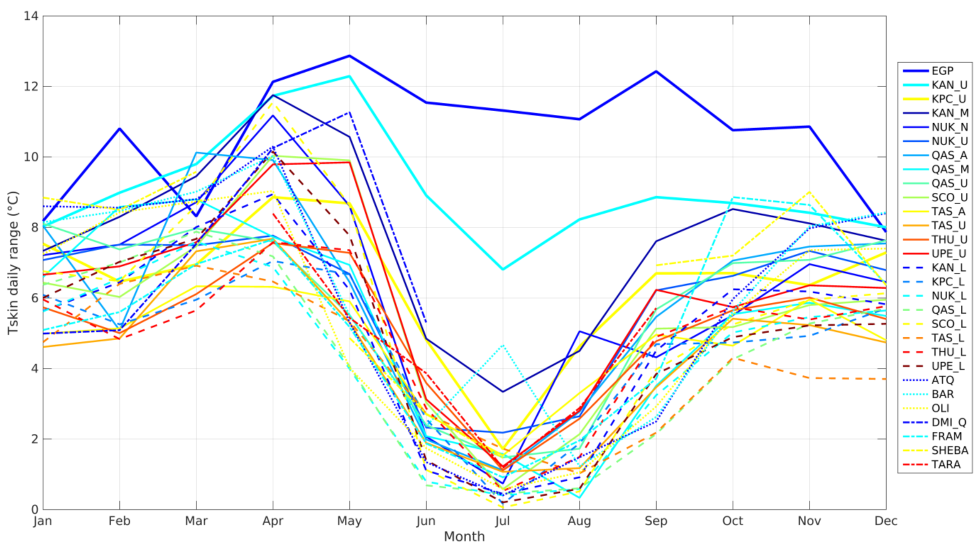


Tskin (°C)
Month
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
EGP
KAN_U
KPC_U
KAN_M
NUK_N
NUK_U
QAS_A
QAS_M
QAS_U
SCO_U
TAS_A
TAS_U
THU_U
UPE_U
KAN_L
KPC_L
NUK_L
QAS_L
SCO_L
TAS_L
THU_L
UPE_L
ATQ
BAR
OLI
DMI_Q
FRAM
SHEBA
TARA

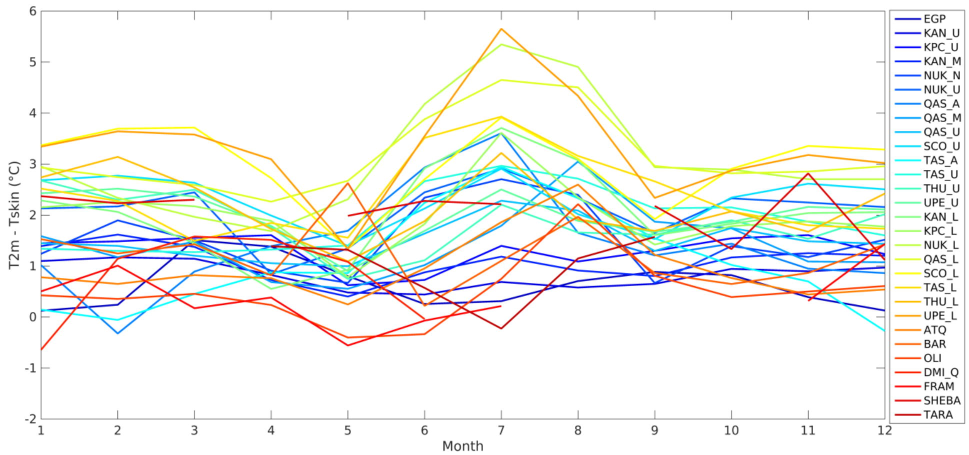
(a)


Tskin daily range (°C)
Month
EGP
KAN_U
KPC_U
KAN_M
NUK_N
NUK_U
QAS_A
QAS_M
QAS_U
SCO_U
TAS_A
TAS_U
THU_U
UPE_U
KAN_L
KPC_L
NUK_L
QAS_L
SCO_L
TAS_L
THU_L
UPE_L
ATQ
BAR
OLI
DMI_Q
FRAM
SHEBA
TARA

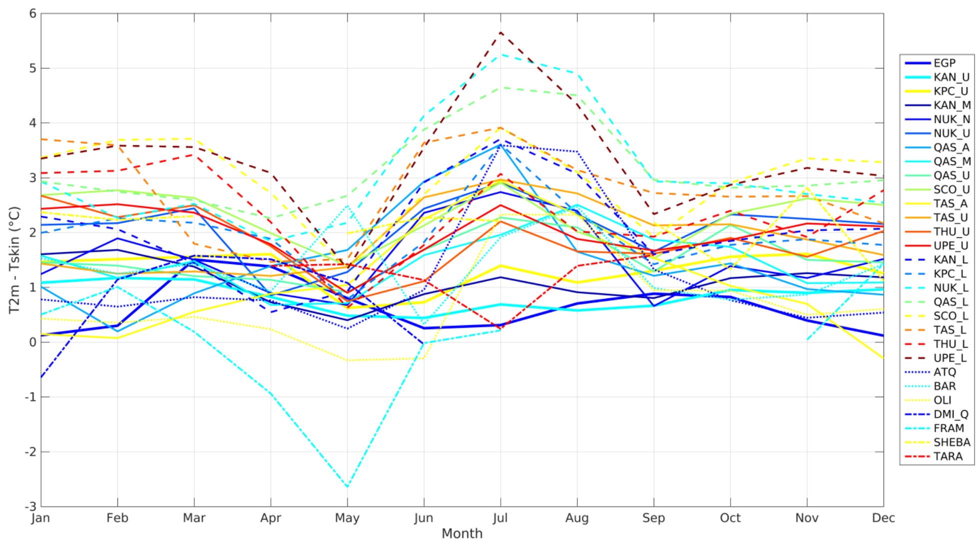
(b)


Tskin daily range (°C)
Month
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
EGP
KAN_U
KPC_U
KAN_M
NUK_N
NUK_U
QAS_A
QAS_M
QAS_U
SCO_U
TAS_A
TAS_U
THU_U
UPE_U
KAN_L
KPC_L
NUK_L
QAS_L
SCO_L
TAS_L
THU_L
UPE_L
ATQ
BAR
OLI
DMI_Q
FRAM
SHEBA
TARA

(b)



(c)



(c)

Figure 5: Monthly mean ~~of~~ Tskin (a) daily range in Tskin (b) and T2m-Tskin difference (c), for all sites. Each surface type has its own line style or line width. See Table 1 for station locations and types.

Table 2 Overall 2 m air temperature and skin temperature differences (T2m-Tskin, °C) for each surface type for different ~~under different circumstances in terms of~~ seasons and sky conditions. All months refer to the full time series as given in Table 1. The

square brackets are the ranges of the T2m-Tskin differences for the stations included in each surface type category. The DMI_Q site is excluded from the SICE averages.

		Jun-Aug	Dec-Feb	All months
ACC	Cloud	0.21 [0.13 – 0.34]	0.47 [0.16 – 0.66]	0.43 [0.35 – 0.49]
	Clear	0.79 [0.26 – 1.29]	1.99 [1.55 – 2.46]	1.05 [0.58 – 1.50]
	All	0.69 [0.43 – 1.07]	0.88 [0.16 – 1.41]	0.91 [0.65 – 1.29]
UAB	Cloud	1.77 [0.68 – 2.62]	0.67 [-0.79 – 1.52]	0.90 [0.16 – 1.45]
	Clear	2.49 [1.12 – 3.16]	2.71 [1.35 – 4.76]	2.36 [1.45 – 3.38]
	All	2.20 [0.98 – 2.77]	1.60 [0.07 – 2.65]	1.65 [1.05 – 2.26]
LAB	Cloud	2.81 [1.15 – 4.23]	1.38 [0.49 – 2.10]	1.63 [0.66 – 2.41]
	Clear	3.94 [3.01 – 5.22]	3.90 [2.82 – 4.81]	3.44 [2.46 – 4.42]
	All	3.51 [2.28 – 4.74]	2.73 [2.06 – 3.45]	2.65 [1.99 – 3.34]
SSC	Cloud	-0.08 [-0.59 – 0.26]	-0.05 [-0.17 – 0.04]	-0.08 [-0.27 – 0.06]
	Clear	1.57 [1.01 – 2.25]	2.32 [1.75 – 2.93]	1.80 [1.34 – 2.19]
	All	0.40 [-0.22 – 0.96]	0.84 [0.47 – 1.41]	0.65 [0.35 – 0.97]
SICE ÷ DMI_Q	Cloud	0.71 [-0.00 – 1.34]	0.35 [-0.33 – 1.04]	0.64 [-0.38 – 1.29]
	Clear	1.95 [0.40 – 3.73]	2.33 [1.09 – 3.56]	2.10 [0.43 – 3.86]
	All	1.09 [0.08 – 2.30]	1.51 [0.99 – 2.03]	1.25 [0.42 – 2.08]

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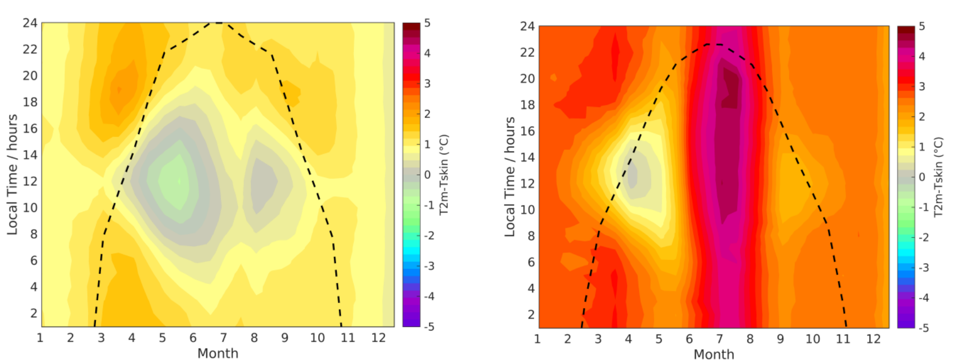

Figure 6: Mean difference between 2 m air temperatures (T2m) and skin temperatures (Tskin) ~~differences~~ for (a) ACC ~~(a)~~ and (b) LAB ~~(b)~~ sites as a function of time of year (with a bin size of 15 days) and local time of the day. The dotted lines indicate the maximum number of sunlight hours each month. ~~The dotted black lines indicate the total hours of sunlight.~~ All sites in each surface type category are weighted equal.

Formateret: Skrifttype: Ikke Fed

Formateret: Skrifttype: 9 pkt, Fed, Ikke Kursiv, Engelsk (Storbritannien)

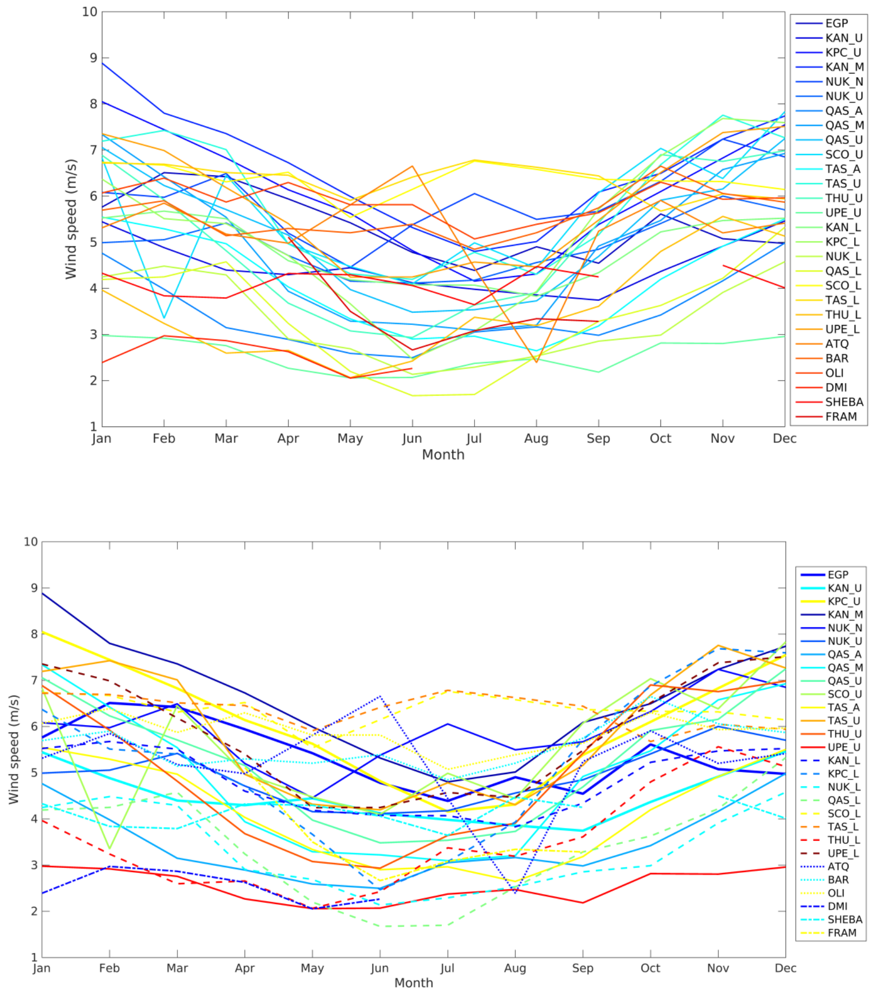

Figure 7: Monthly mean wind speed ($m\ s^{-1}$) ~~The average annual cycle in wind speed~~ **for all sites.** Each surface type has its own line style or line width. See Table 1 for station locations and types.

Formateret: Normal

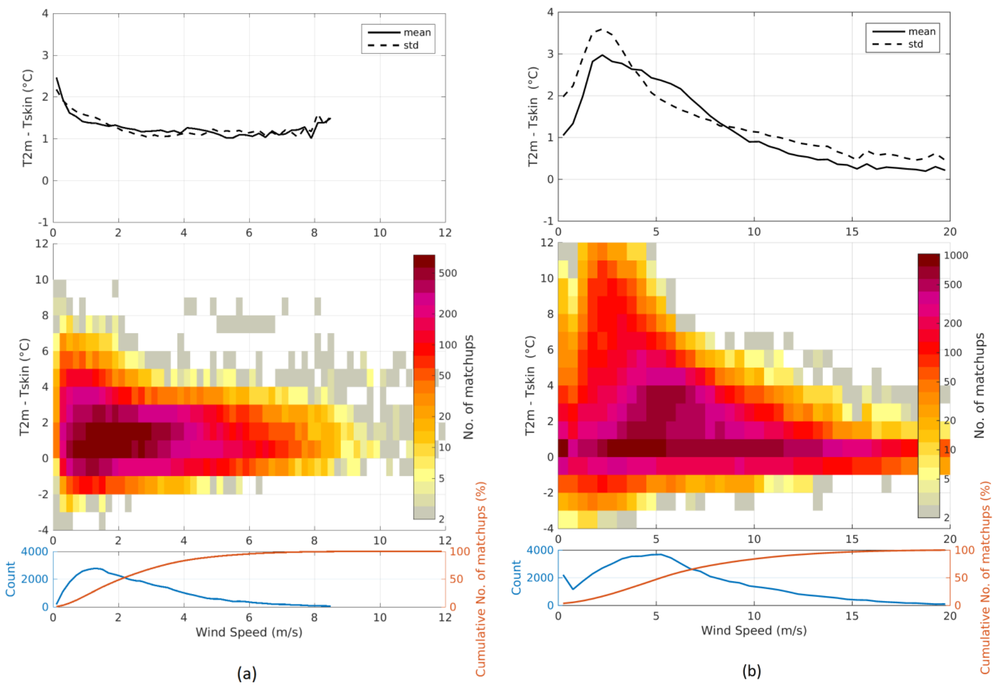

Figure 8: 2 m air temperature (T2m) and skin temperature (Tskin) difference as a function of binned wind speed for (a) DMI_Q (SICE site) and (b) THU_U (UAB site). The wind speed bin size is 0.5 m s^{-1}, the T2m-Tskin bin size is 1°C, and only bins with more than 50 members are included. The upper plots show the standard deviation (dashed lines) and mean difference (solid lines). The middle plots show the number of members in each bin, while the bottom plots show the number of members (blue lines) and the cumulative percentage of members (red lines) in each wind speed bin.

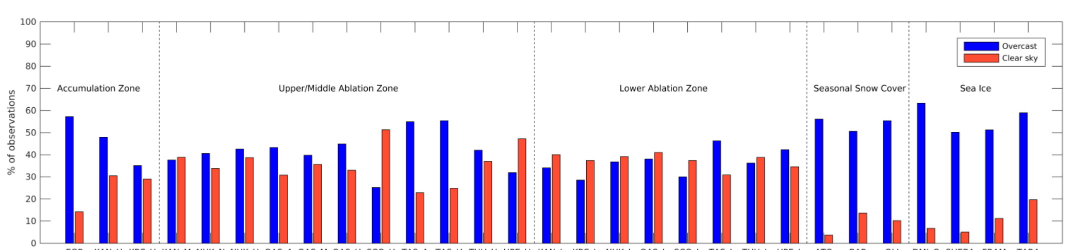

Figure 9: Frequency of clear-sky and overcast observations in percent of all observations for each site.

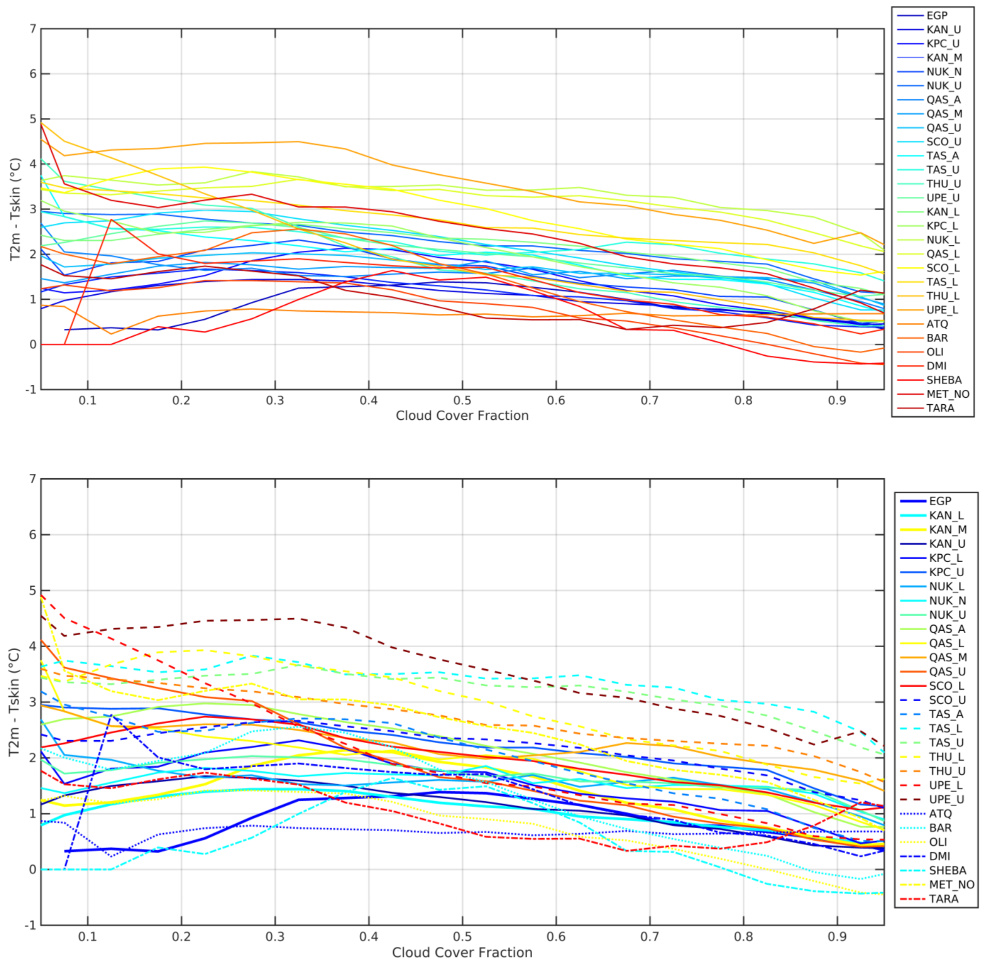

Figure 10: 2 m air temperature and skin temperature differences for all sites as a function of binned cloud cover fraction (CCF). The CCF bin size is 0.05, the T2m-Tskin bin size is 1°C, and only bins with more than 50 members are considered. Each surface type has its own line style or line width.

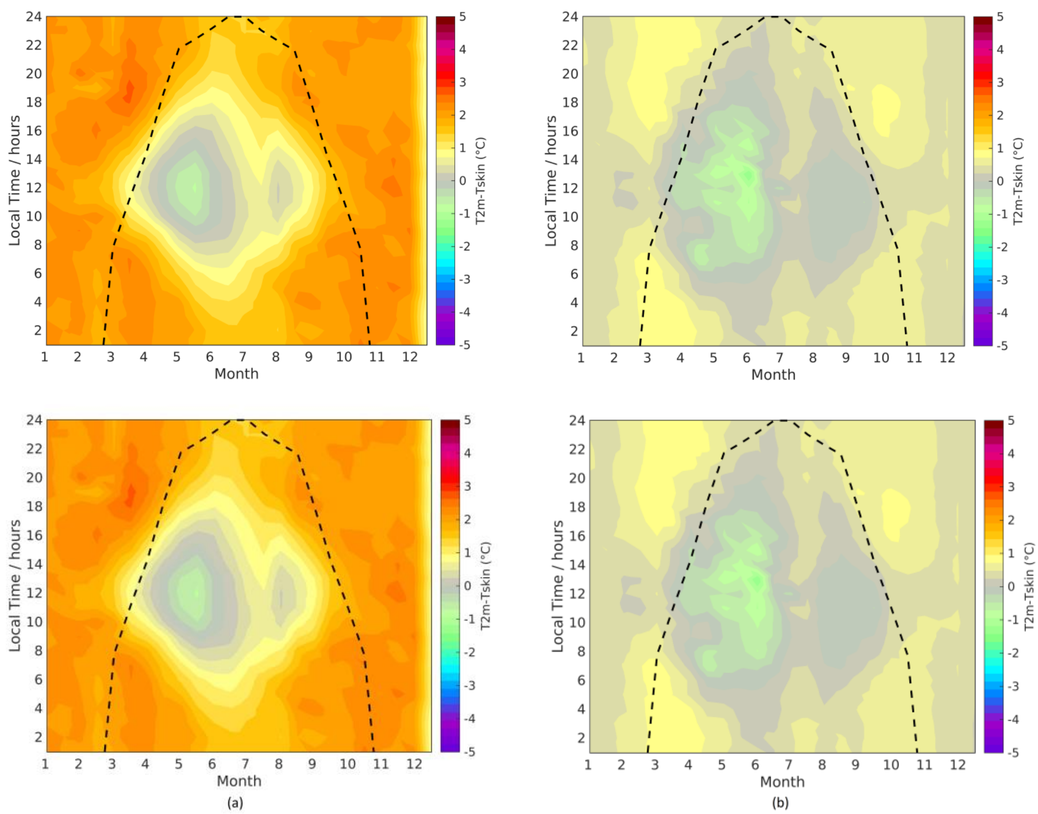

Figure 11: Mean difference between 2 m air temperatures (T2m) and skin temperatures (Tskin) for ~~Similar to Fig. 7a but with 2 m air temperature and skin temperature differences for~~ ACC sites in cases of (a) clear-sky ~~(a),~~ and (b) overcast conditions ~~(b)~~. The dotted ~~black~~ lines indicate the maximum number ~~total hours of~~ of sunlight hours each month. All sites in each surface type category are weighted equal.

~~**Table 2 Overall 2 m air temperature and skin temperature differences (T2m-Tskin, °C) for each surface type under different circumstances in terms of season and sky conditions. The square brackets are the ranges of the T2m-Tskin differences for the stations included in each surface type category.**~~

		~~Jun-Aug~~	~~Dec-Feb~~	~~All months~~
	~~Cloud~~	~~0.21 [0.13 – 0.34]~~	~~0.47 [0.16 – 0.66]~~	~~0.43 [0.35 – 0.49]~~
~~ACC~~	~~Clear~~	~~0.79 [0.26 – 1.29]~~	~~1.99 [1.55 – 2.46]~~	~~1.05 [0.58 – 1.50]~~
	~~All~~	~~0.69 [0.43 – 1.07]~~	~~0.88 [0.16 – 1.41]~~	~~0.91 [0.65 – 1.29]~~

	~~Cloud~~	~~1.77 [0.68 – 2.62]~~	~~0.67 [-0.79 – 1.52]~~	~~0.90 [0.16 – 1.45]~~
~~UAB~~	~~Clear~~	~~2.49 [1.12 – 3.16]~~	~~2.71 [1.35 – 4.76]~~	~~2.36 [1.45 – 3.38]~~
	~~All~~	~~2.20 [0.98 – 2.77]~~	~~1.60 [0.07 – 2.65]~~	~~1.65 [1.05 – 2.26]~~
	~~Cloud~~	~~2.81 [1.15 – 4.23]~~	~~1.38 [0.49 – 2.10]~~	~~1.63 [0.66 – 2.41]~~
~~LAB~~	~~Clear~~	~~3.94 [3.01 – 5.22]~~	~~3.90 [2.82 – 4.81]~~	~~3.44 [2.46 – 4.42]~~
	~~All~~	~~3.51 [2.28 – 4.74]~~	~~2.73 [2.06 – 3.45]~~	~~2.65 [1.99 – 3.34]~~
	~~Cloud~~	~~-0.08 [-0.59 – 0.26]~~	~~-0.05 [-0.17 – 0.04]~~	~~-0.08 [-0.27 – 0.06]~~
~~SSC~~	~~Clear~~	~~1.57 [1.01 – 2.25]~~	~~2.32 [1.75 – 2.93]~~	~~1.80 [1.34 – 2.19]~~
	~~All~~	~~0.40 [-0.22 – 0.96]~~	~~0.84 [0.47 – 1.41]~~	~~0.65 [0.35 – 0.97]~~
	~~Cloud~~	~~0.71 [-0.00 – 1.34]~~	~~0.35 [-0.33 – 1.04]~~	~~0.64 [-0.38 – 1.29]~~
~~SICE + DMI_Q~~	~~Clear~~	~~1.95 [0.40 – 3.73]~~	~~2.33 [1.09 – 3.56]~~	~~2.10 [0.43 – 3.86]~~
	~~All~~	~~1.09 [0.08 – 2.30]~~	~~1.51 [0.99 – 2.03]~~	~~1.25 [0.42 – 2.08]~~

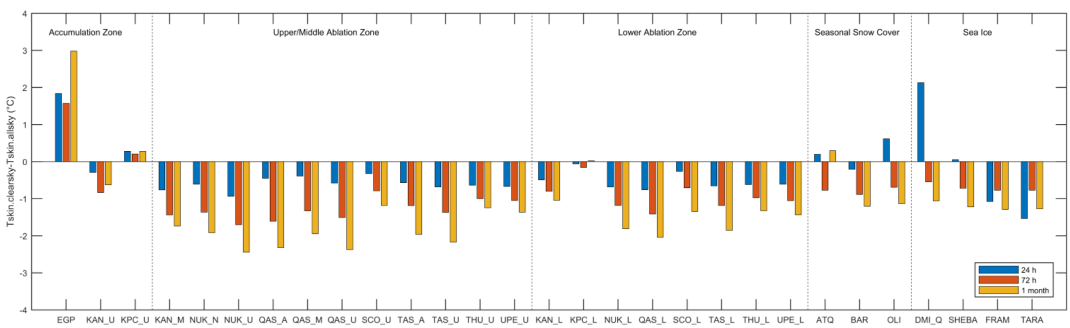

Figure 12: Observed clear-sky biases (Tskin_clearsky-Tskin_allsky) averaged for different time intervals, for all sites (°C).

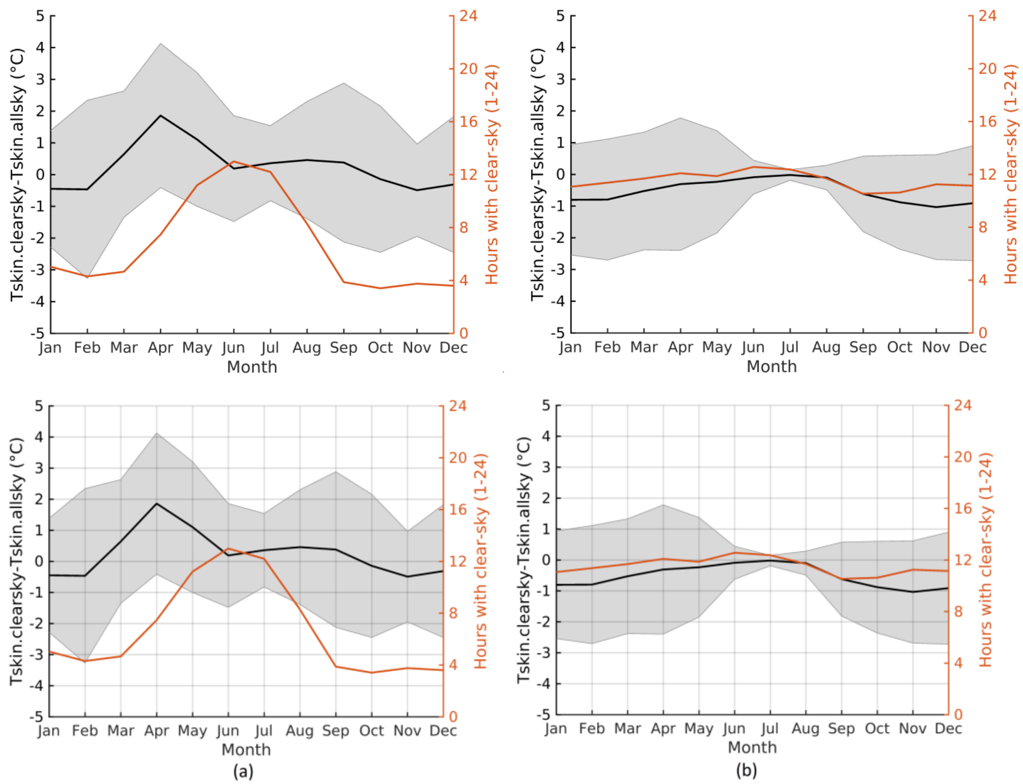

Figure 13: Monthly mean d~~D~~ifferences between 24 h averaged clear-sky and all-sky skin temperatures for (a) ACC stations ~~(a)~~ and (b) ~~and~~ LAB stations ~~(b) for each month~~. The orange~~red~~ lines show the 24 h average number of hours with clear-sky (CCF≤~~>~~0.3)~~7~~ per day for each month. The grey bands show the monthly average of the daily standard deviations. All sites in each surface type category are weighted equal.

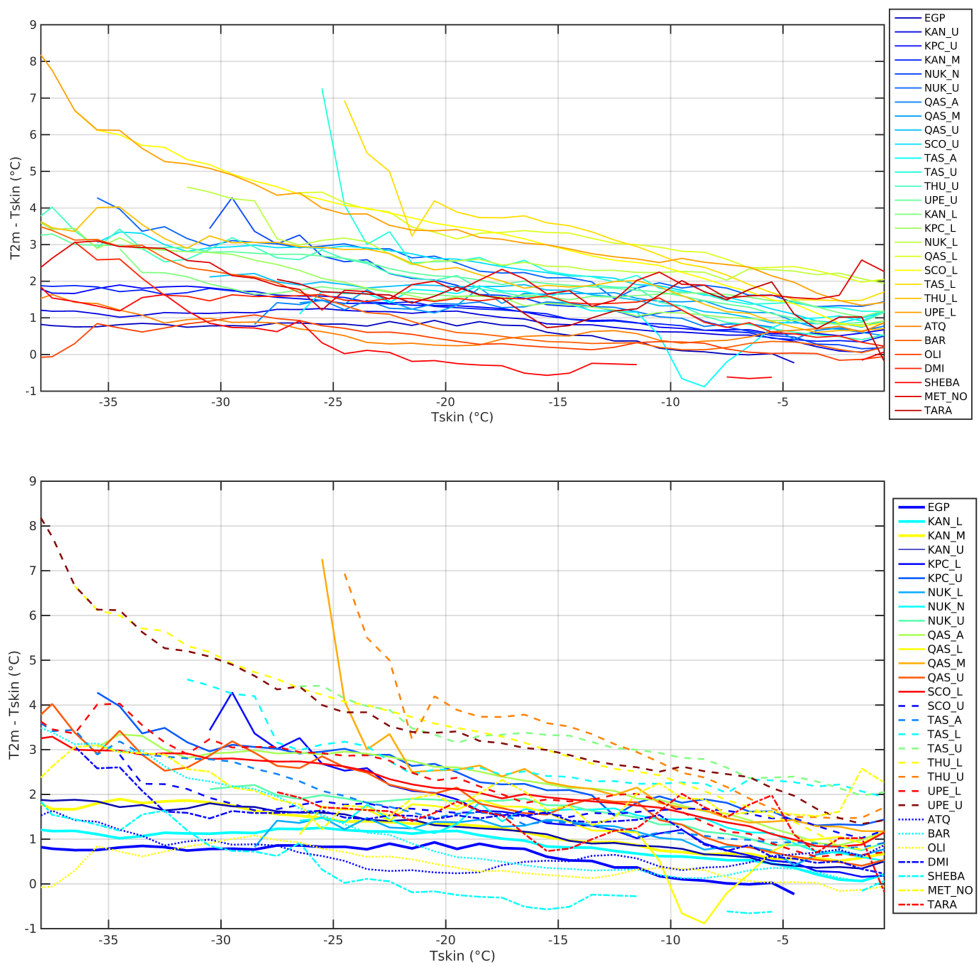

Figure 14: Mean 2 m air temperature and skin temperature differences (T2m-Tskin) for all sites as a function of binned skin temperature (Tskin). The Tskin bin size is 1°C, the T2m-Tskin bin size is 1°C, and only bins with more than 50 members are considered. Each surface type has its own line style or line width.