Reply to reviewer #1

We would like to thank the reviewer #1 for the constructive comments, which helped us to improve the manuscript. We have considered all the recommendations. Below, the reviewer's comments are in red. Our replies are given in black. Please note, that in the statements of the reviewer lines and figures refer to the original manuscript and may have changed in the revised version.

1 General comments

1) According to the title, the study addresses "anomalous atmospheric conditions", which could basically be anything. I recommend to have a more explicit title (for example "The influence of water vapor and temperature anomalies on clouds and their radiative effect at Ny-Ålesund").

- ✓ We changed the title to "The influence of water vapor anomalies on clouds and their radiative effect at Ny-Ålesund".

2) The text is very long and heavy to read. In order to help the reader to see the value and main results of the study the text needs substantial revision. I see that the manuscript would benefit from a notable cut in length (even cut of 1/3 of the length) to make its main content more clear.

- ✓ We implemented several modifications in order to shorten the manuscript a bit and make the content clearer. First, the introduction was shortened. Second, considering comments of the both reviewers, we decided to exclude temperature anomalies ("-T-IWV" and "+T+IWV") from the manuscript. Third, the summary was reorganized and shortened.
- ✓ Please note, that in order to address some of the reviewer's comments we had to include some additional discussions (e.g. sampling uncertainties, comparison of IWV from radiosondes and MWR). The additional figures were placed in the supplementary material, but the discussion was added to the manuscript.
- ✓ Overall, the shortening of the manuscript is about 15%. Since the journal does not have any restrictions on the length, we would still like to leave the remaining results in the manuscript.

3) The structure is not clear. Parts belonging to introduction are found in "Results" and "Conclusions". Some of the results are already presented in "Methods". Methods and data are presented in an order, which is not logical.

- ✓ We agree that there was a misleading structure. We reorganized the structure. Please see the corrections made in the answers to specific comments regarding these issues.

4) The atmospheric circulation behind the trajectories is described at an overly simplified

level. For example, the authors write several times about “air circulations in the Arctic region” as a source of dry anomalies. These circulations, and their dynamical setting, need to be more precisely described.

- ✓ Please note, that the main idea of this study is to show how the events of dry and moist conditions influence the cloud appearance and their radiative effect at Ny-Ålesund. The analysis of the back trajectories was made in order to check whether our definition of the anomalous conditions is consistent with literature, where a number of studies show that moist conditions at Ny-Ålesunds are caused by air masses coming from the North Atlantic, while dry conditions are typically caused by Air coming from the Arctic regions. In order to check the consistency, we checked primary directions of the air flow related to moist/dry conditions at Ny-Ålesund. Since, these directions agree with the literature we assume that the used definition of the anomalies is valid. We agree that in the initial version of the manuscript this was not explained well enough. We introduced a separate subsection (4.1) on this.

5) Ny-Ålesund is largely affected by the orography, but the orographical effects are not addressed in this study. Even if the impacts of orography are not the main focus here, they cannot be neglected. How representative are the results of this study for the Arctic?
Do they only represent relations seen at Ny-Ålesund, or do the results represent the Arctic conditions more generally? Orography has large impacts on the cloud formation, and therefore it should matter whether the flow meets mountains before it arrives to Ny-Ålesund.

- ✓ In the current manuscript we analyze relations between IWP and cloud properties in a vertical column at Ny- Ålesund. Of course, the atmosphere at Ny- Ålesund is influenced by a large number of factors including orographic effects, ocean, aerosols, and many others. These factors are explicitly mentioned in the introduction section. Please note, that the fact that we do not analyze these factors in this manuscript does not mean that they are neglected. These factors affect both IWV and cloud properties and thus the effects of these factors are in the measurements. The problem is that it is hard to identify individual effects by the different factors in the observations. Some first steps into this direction (identifying an influence of orography on clouds in Ny- Ålesund have been already made within the $(AC)^3$ project and are ongoing). The first results have been recently published or accepted by ACP (e.g. Schemann and Ebell 2020, and Gierens et al 2019).
- ✓ The following sentences were added to the section 4.3: “Since the anomaly type cannot fully explain this effect, it is probably also related to other factors such as differences in aerosol load, impact of local effects due to the surrounding orography, and an influence of the ocean. For instance, the seasonal change in the aerosol type affects the activation ability of CCN and IN efficiency in the Svalbard region which in turns influence the cloud

formation. In addition, the reduction in sea ice around the Svalbard archipelago and on the fjords may lead to more evaporation and therefore, affect cloud conditions. Since Ny-Ålesund is surrounded by mountains up to 800 m, the air flow is influenced by the local orography in the lowest 1 km altitudes (Maturilli and Kayser, 2017a) and thus might have an impact on cloud formation and change cloud properties."

- ✓ The results obtained within this work are relevant only for Ny-Ålesund and not mapped to the whole Arctic. Therefore, these results should not be considered as general Arctic conditions. Since Ny- Ålesund is located in the warmest part of the Arctic, the results are likely to be different with respect to other Arctic sites. This is one of the motivations why clouds are analyzed at Ny- Ålesund even though long-term cloud observations are available for example for Canadian Arctic and Greenland. This uniqueness of Ny-Ålesund is explicitly mentioned in the introduction. The comparison studies with other Arctic sites are planned in the future when more cloud measurements at Ny-Ålesund will be available.
- ✓ Please note, that directional dependence of clouds on wind direction at Ny- Ålesund has been recently analyzed by Gierens et al. 2019 (accepted by ACP).

6) Introduction covers many relevant topics, but is rather scattered. It would benefit from a clearer focus.

- ✓ The introduction has been restructured and shortened.

7) What are the accuracies (uncertainties) of the different instruments and data? Please give information.

- ✓ The detailed information on different instruments used in this study and their uncertainties has been provided in Nomokonova et al. 2019 that was published in the same special ACP issue. This study is properly referenced in the instrumentation section. The study gives a full overview of the instruments, retrievals, and their uncertainties. In the current manuscript we briefly described the instruments. If we include further information on the instruments the manuscript will become even more longer. In this case we would also publish the same information twice. This is why we would like to keep the section as it is.

8) In Section 4.5, I recommend to show a comparison of radiosonde IWV and Microwave radiometer IWV for the overlapping period to show how well they agree.

- ✓ Thank you for highlighting this aspect. We compared IWV derived from both instruments for the overlapping period. The results are shown in the figure below:

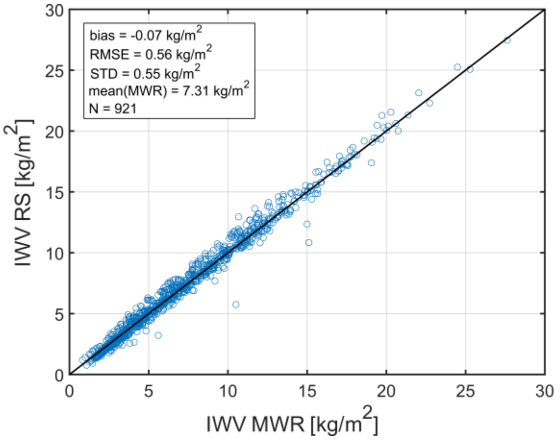


Figure 1. IWV comparison between MWR (mean value within 15 min after a radiosonde launch) and radiosonde (only around 11 UTC radiosondes included) for the period from 2011 to 2017. The data are from the AWIPEV station in Ny-Ålesund.

- ✓ This figure was added to the Supplement material (please see the attached file of the Supplement material, Figure S2). We also added a discussion on this comparison in the text of the manuscript: "Values of IWV retrieved from MWR were compared with ones derived from radiosondes for the period from 2011 to 2017 when both observations were available. IWV from MWR was averaged over 15 min interval after radiosonde launch. The results of the comparison are shown in the supplement material (Fig. S1) and are in a good agreement with the root mean squared difference of 0.56 kg m^{-2} and a bias is close to zero." Please see section 2.4.

9) In section 4.5, impacts of sea ice retreat around the archipelago of Svalbard are not considered at all. The changes in sea ice have, for sure, affected the moisture conditions in Ny-Ålesund and they should be addressed.

- ✓ We agree that the sea ice decline can affect the increased occurrence of moisture event and lead to the reduction of dry events. Thank you for highlighting this aspect. We added the discussion on this topic.
- ✓ Similar to the orographic effects (see comment 5 above), the influence of the sea ice extent (and any other effect) on water vapor and clouds is captured by measurements but it is hard to quantify this effect separately from other factors.
- ✓ We added the following discussion at the end of the Section 4.5: "In addition to the influence of air mass transport toward Svalbard region changes in sea-ice coverage around the archipelago of Svalbard might also impact the occurrence of moist and dry events. During summer and autumn the sea ice coverage is the lowest which can lead to enhanced evaporation and latent heat exchange between the ocean and the Arctic atmosphere. However, the largest sea ice loss rate over Svalbard has been observed in winter (Isaksen et al., 2016). Beside the changes of the sea ice coverage around the Svalbard archipelago a reduction of the local fjord ice cover has an impact on the local

climate (Isaksen et al., 2016, Dahlke et al., 2020) and therefore, might also lead to a change in occurrence of anomalous atmospheric conditions at Ny-Ålesund."

- ✓ The reference information of Isaksen et al., 2016, Dahlke et al., 2020 were added to the reference list.

10) "Summary and conclusions" should be half of its current length to emphasize the MAIN (and thus not all) results of the study. Please state the main findings here; clearly and relatively shortly. My recommendation is to summarize the results for each of the anomaly type (IWV+, IWV-: : :) instead of going through all the variables separately as in the results section. This would nicely summarize the impacts of the anomalies, which are the main focus of the study (as also indicated in the title).

- ✓ Thank you for highlighting to this aspect and recommendations. We made changes according to the recommendations.

- ✓ The Section 5 "Summary and conclusions" was reorganized in order to combine the results of this study into two groups related to anomaly types "+IWV" and "-IWV", respectively. The changes also covered some sentences which were rephrased and removed from the section.

2 Specific comments:

1) Lines 12-13: The analyses of past trends does not say anything about the future. Therefore, please use the past tense here. "have become", "have increased".

- ✓ Corrected

2) Line 12: add "ranging" before "from -12.8 …"

- ✓ Corrected

3) Lines 13-16: The two last sentences are not understandable

- ✓ These sentences have been removed

4) Lines 47: Clarify which differences are given here, because it is difficult to understand. What are these values?

- ✓ Due to the shortening of the introduction this part has been removed from the manuscript.

5) Line 62: "the specific synoptic regime" is a vague expression.

- ✓ We rephrased the following sentence: "A number of studies focus on observations at Ny-Ålesund located in the Svalbard region (Wendisch et al., 2019; Maturilli et al., 2013; Maturilli and Ebell, 2018; Yeo et al., 2018), an Arctic area where air masses transported from the lower latitudes bring more moisture in comparison to the rest of the Arctic (Dahlke and Maturilli 2017; Mewes and Jacobi, 2019).

6) Line 69: temperature at which level?

- ✓ Due to the shortening of the introduction this part has been removed from the manuscript.

7) Line 73: Add “in Ny-Ålesund”

- ✓ Added.

8) Lines 73-85: This part should be condensed and the text should have a more logical flow.

- ✓ We made this part shorter and added the connections between the sentences. The following sentences were rewritten: Dahlke and Maturilli (2017) showed an increasing air mass transport through the North Atlantic pathway and reducing flow from the north in the winter season in Ny-Ålesund. Yeo et al. (2018) investigated how the advection of warm and cold air masses affects cloudiness, longwave fluxes at the surface and near-surface temperature at Ny-Ålesund during winter. The authors analyzed a 10-day period in February with alternating warm and cold conditions related to distinct circulation patterns. During cold periods Yeo et al. (2018) observed a reduced cloudiness and downwelling longwave flux of 200–230 W m^2. In contrast, warm periods were associated with cloud occurrence close to 100 % and enhanced downwelling longwave flux of 300 W m^2. Since the author studied only a short period, an analysis of longer cloud observations is still needed.

9) Lines 101-103: This project information is unnecessary. It is enough to mention the project in the acknowledgements.

- ✓ $(AC)^3$ is a huge German initiative that we would like to emphasize and keep it here as well.

- ✓ We made this part shorter: “Within the Transregional Collaborative Research Center TRR 172 on Arctic Amplification ($(AC)^3$; Wendisch et al., 2017), the instrumentation at AWIPEV was complemented with a Doppler cloud radar in June 2016.”

1) Line 136: “were analyzed” instead of “will be analyzed”

- ✓ Corrected

2) Line 138: Add some reference to the model.

- ✓ We added the references to Mlawer et al., 1997 and Barker et al., 2003 after the RTTMG.

3) Line 151: Is this operational forecast or reanalysis data? Specify.

- ✓ The meteorological data used as input for FLEXTRA is not from reanalysis it is from initialized operational analyses of the NWP model of ECMWF with a temporal resolution of 6 hours (at 0, 6, 12, and 18 UTC) and a spatial resolution of 1.125 degree.
- ✓ We rephrased the following sentence: "The calculations of the trajectories are based on operational analysis data from NWP model of the European Centre for Medium range Weather Forecast (ECMWF) with the initialized analyses every 6 hours (at 0, 6, 12, and 18 UTC) …”.

4) Section 2.6 should be placed after other measurements (to be 2.4.) And then the methods should follow.

✓ Done

5) Section 3 could be much shorter. There is a lot of repetition and many things could be expressed in a shorter way.

✓ The Section 3 was shortened and split into two parts. We decided to leave only the first paragraph in the Section 3. The remaining paragraphs were moved to a new subsection 4.1 “Consistency check of the defined anomaly periods with existing studies”.

6) Section 2: Define months of winter, spring, summer and autumn somewhere.

✓ Please find the months in the section 4.1: “In winter (December, January and February) and spring (March, April and May), dry air typically comes from North of Russia over the North Pole region and northern Greenland. Mewes and Jacobi, (2019) have shown that a similar horizontal air mass transport happens when air from the North Pacific flows into the Arctic. In summer (June, July and August), dry anomalies are mostly associated with air coming from northern Canada and Greenland. In autumn (September, October and November), …”

7) Line 181: Add “horizontal” before “transport”

✓ Added

8) Line 182: “Coming from lower or higher latitudes” means basically from anywhere. This is too vague.

✓ We reformulated: A number of studies have shown that positive and negative anomalies in IWV often result from horizontal transport of air masses from mid- and Arctic latitudes, respectively.

9) Lines 186-188: The citation to Graversen (2006) is a bit unconnected here.

✓ The sentence was removed.

10) Lines 190-192: Again, description of circulation is vague.

✓ We rephrased the following sentences: “In winter (December, January and February) and spring (March, April and May), dry air typically comes from North of Russia over the North Pole region and northern Greenland. Mewes and Jacobi (2019) have shown that a similar horizontal air mass transport happens when air from the North Pacific flows into the Arctic.”

11) Lines 192-193: I cannot see that the MOST of dry anomalies in summer are coming with the air from Canada and Greenland in Fig. 2.

✓ We rephrased the following sentence: “In summer (June, July and August), dry anomalies are associated with air coming from the northern part of Canada and Greenland.”

12) Line 193: pathways for dry or moist air? Specify.

✓ Modified: “In autumn (September, October and November) during dry anomalies air masses come from the areas north of Greenland and Russia.”

13) Line 193: I do not see the two distinct pathways from south-east and west!

- ✓ Modified: “In autumn (September, October and November) during dry anomalies air masses come from the areas north of Greenland and Russia.”

14) Lines 195: Is this statistically significant. If not tested, use another word than “significant”. Give percentage value here.

- ✓ We replaced the word “significant” to “large”.

15) Results: The section 3 includes already results, so results section cannot start here.

- ✓ The Section 3 was shortened and split into two parts. We decided to leave only the first paragraph in the Section 3. The remaining paragraphs were moved to a new subsection 4.1 “Consistency check of the defined anomaly periods with existing studies”.

16) Lines 211-214: This is actually about methods, and could be omitted.

- ✓ The introduction to the section 4 was removed. One sentence was added to the subsection 4.2 “In this section we show how the anomalous conditions are related to cloud occurrence.”

17) Line 218: How much lower? Specify.

- ✓ The expression “is in general lower and …” was deleted to avoid misleading statement. In the same sentence the range of the values for different seasons is provided “..the FOC of clouds ranges from 26 % in spring to 70 % in summer”.

18) Lines 228-229: I disagree. These results are mentioned many times in this manuscript, without any deeper understanding. Please investigate this event so that you can say something what was so special in it.

- ✓ In order to make the manuscript shorter and due to the low number of cases for the temperature anomaly periods (comments by the reviewer 2) we decided to exclude them from the revised manuscript.
- ✓ However, to answer the questions from reviewers related to “-T-IWV” period, since this period was particularly interesting, we provided a detail analysis here in the replies. Please note, that this description will not be added to the manuscript. We investigated “-T-IWV” in more details and information on this event is provided below. During the 5-day “-T-IWV” period (from 26.09.2018 to 30.09.2018) we observed an increased cloud occurrence (>90%) and higher mean LWP (~120 g m-2) and IWP (~250 g m-2).
  The figure 2 below shows height-time cross sections of clouds for two first days of the “-T-IWV” period. On 26 Sept 2019 the liquid layer of mixed-phase clouds is located at the top of the cloud. In the afternoon the liquid layer is distributed within cloud boundaries. Measurements of the Doppler velocity from the cloud radar 94~GHz indicate the presence of up and down drafts (not shown).

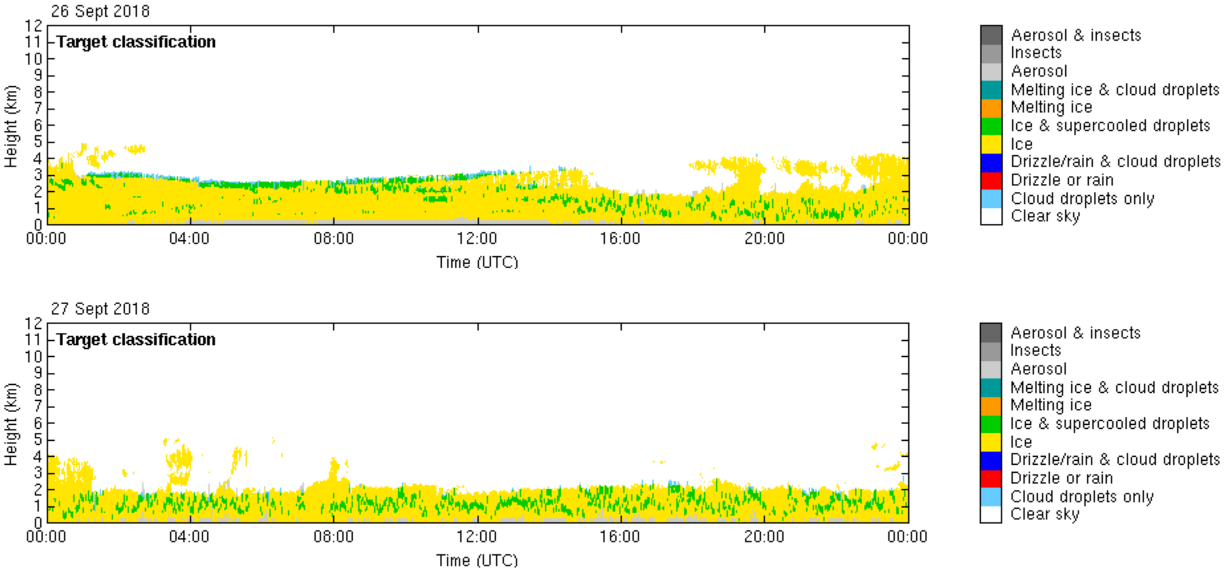


Figure 2. Cloudnet target classification on 26 and 27 September 2018. The quicklooks are taken from the official Cloudnet website (http://devcloudnet.fmi.fi/).

The analyses of radiosonde observations in figures 3-5 below show that on 25092018 (one day before “-T-IWV”) there was a temperature inversion, relative humidity with respect to water was ranging from 90-100 % and the wind was blowing from the north-west with higher wind speed in the lowest 1 km. The first day of “-T-IWV” (26092018) was associated with a fast decrease of temperature above 1 km. The wind speed above 1 km increase as well. These cold and windy conditions stayed for the next 5 days. The direction of wind from radiosondes is consistent with the backward trajectories for “-T-IWV” anomaly period (Fig.6). These cold conditions were associated with low pressure system above Barents sea and air masses coming from the northern Greenland which are shown on the screenshots from the online source of the automatic global ICON on the website https://www.ventusky.com/ (Fig.7). One day before the “-T-IWV” period the low-pressure system was only above the Spitzbergen and to the north relative to the archipelago. The screenshots with the air temperature at 850 hPa from the global ICON show that relatively cold air mases passed by the western part of Svalbard on 25092018 while the air masses coming to the Svalbard region on the next days led to the observed decrease in temperature at Ny-Ålesund. The analysis of potential and equivalent potential temperature for 5 days (fig. 9) reveals that during “-T-IWV” there were unstable conditions to vertical motions which were indicated by the decrease of equivalent potential temperature (solid lines) with a height up to 2 km. This led to a convection and therefore, mixing of cold air coming from the north-west reaching Ny-Ålesund with relatively warm and moist air parcels at the surface. This vertical mixing probably promoted enhanced cloud formation. Such complicated conditions are likely to be misinterpreted by the proposed classification scheme.

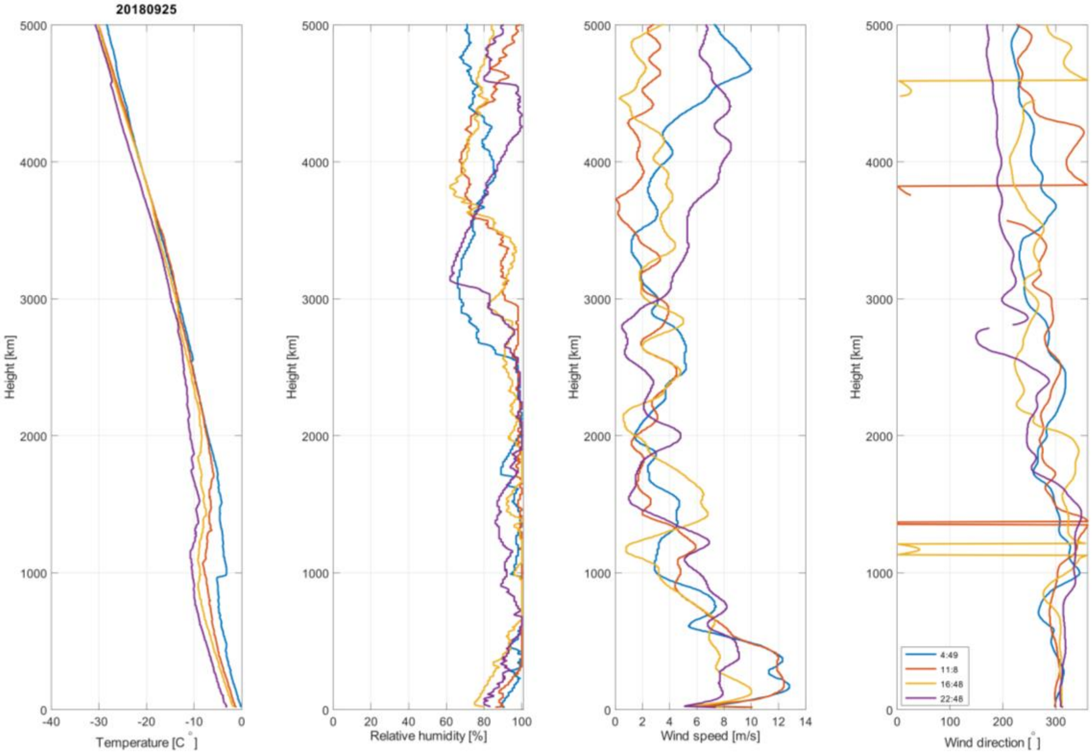


Figure 3. Temperature, relative humidity, wind speed, and wind direction profiles from radiosonde for 25092018 (one day before the “-T-IWV” period) launched at around 5, 12, 17 and 23 hours (UTC).

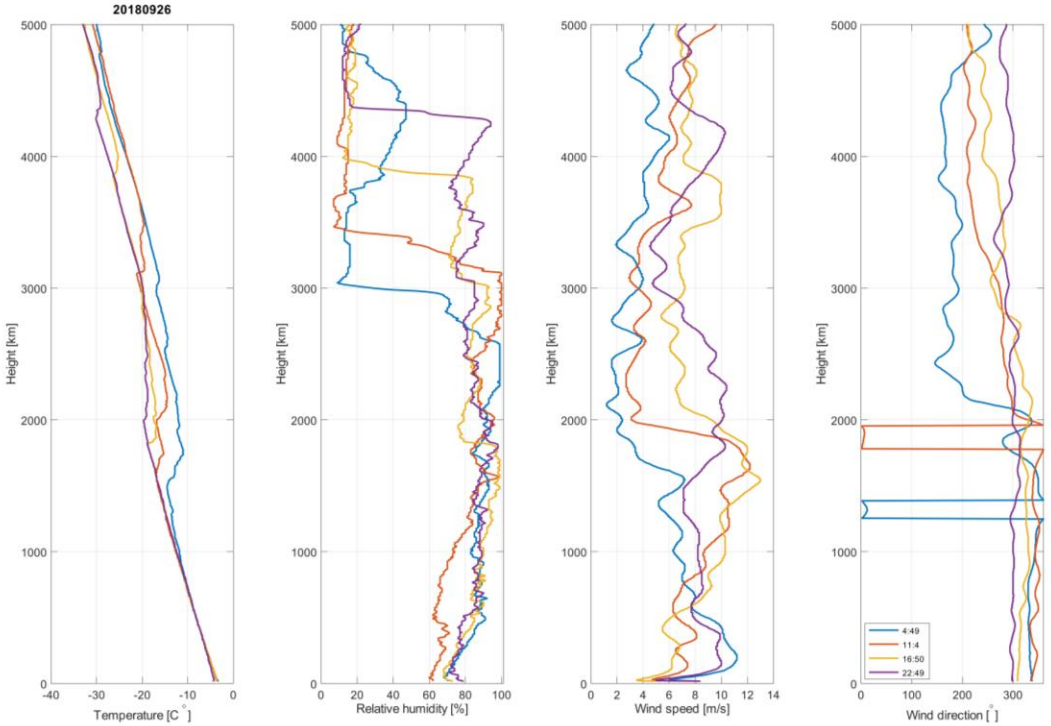


Figure 4. The same as Figure 3 but for 26092018 (first day of “-T-IWV” period).

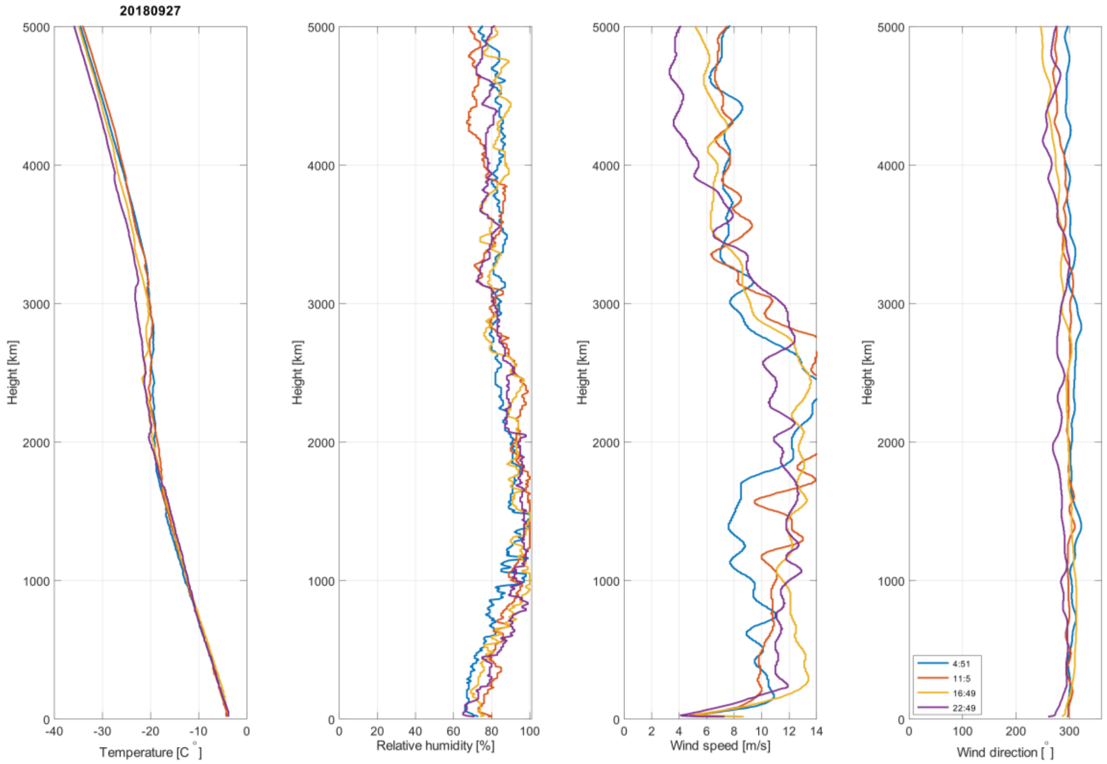


Figure 5. The same as Figure 3 but for 27092018 (second day of “-T-IWV” period).

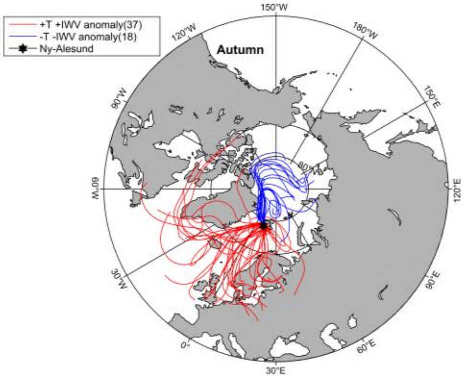
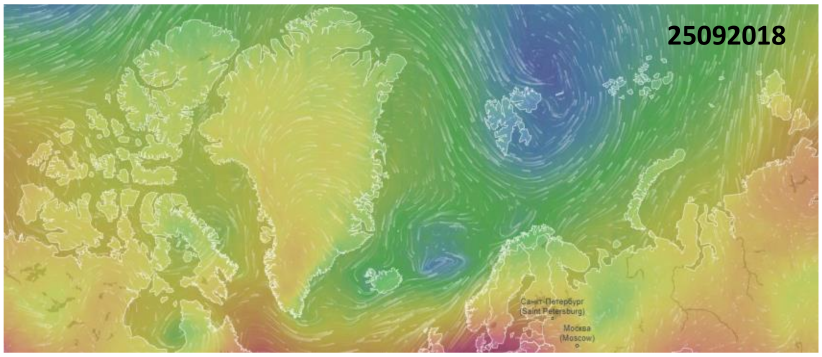


Figure 6. Backward trajectories for the “-T-IWV” period shown by blue lines.



Air pressure

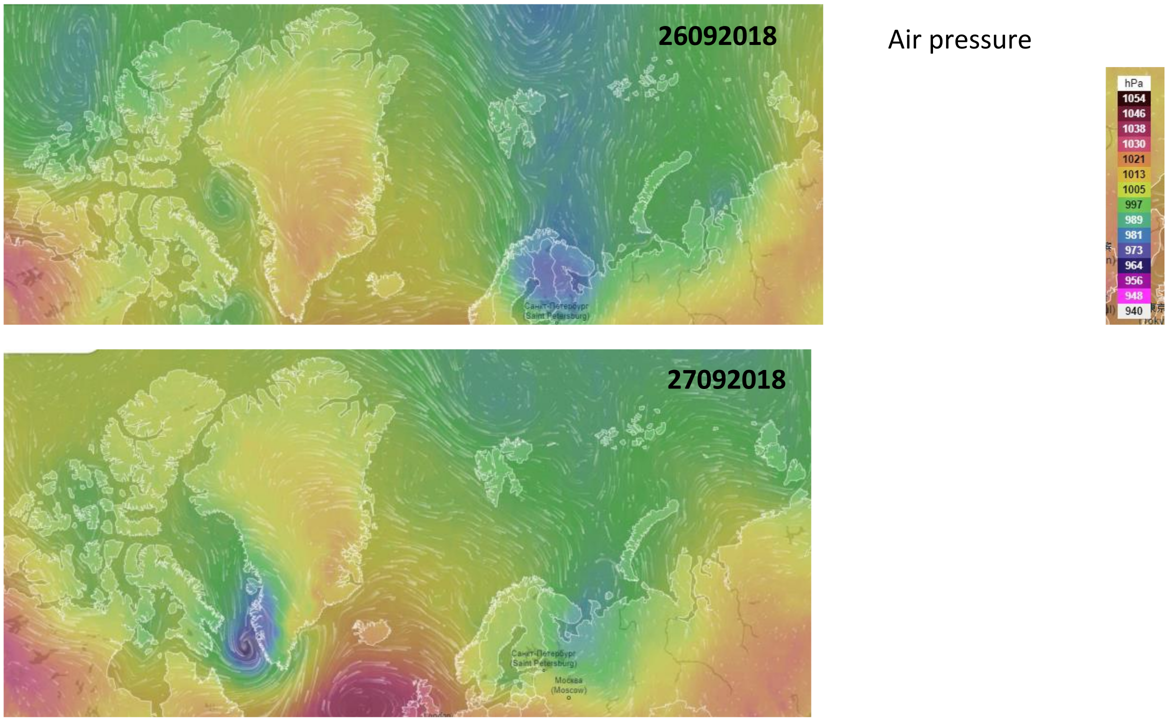
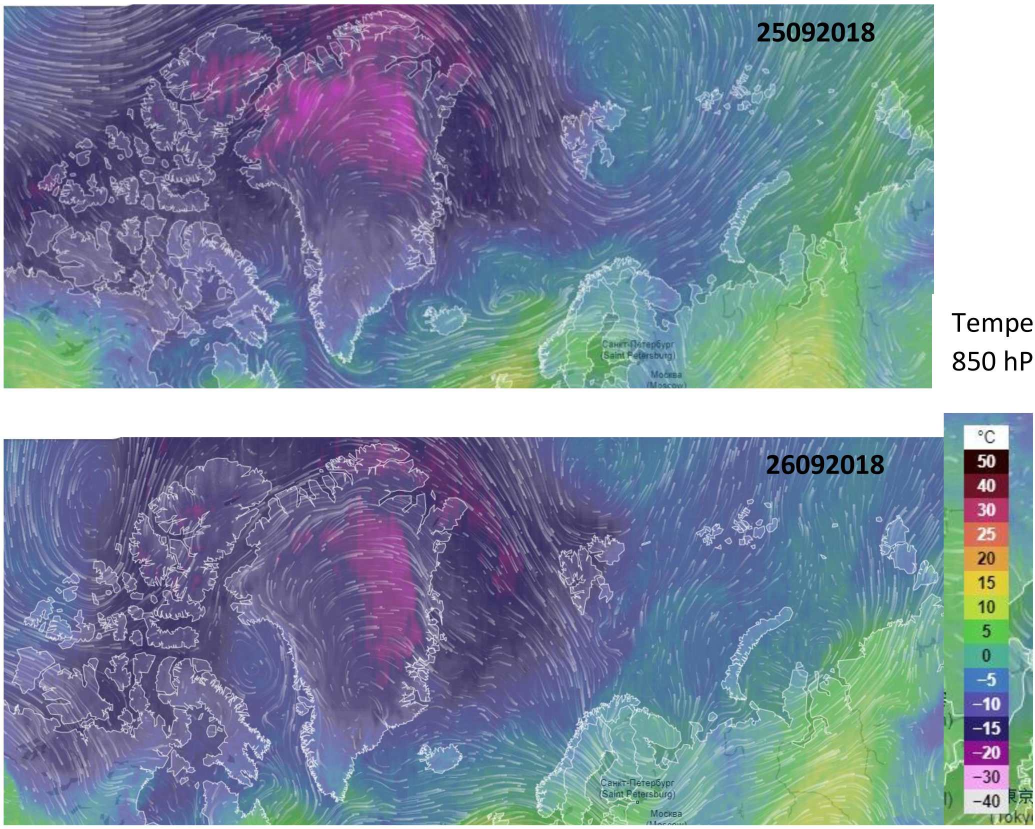


Figure 7. Screenshots of air pressure from the Global ICON model (The screenshots are taken from the available online source https://www.ventusky.com/?p=71;-27;2&l=temperature-850hpa&t=20180927/2100).



Temperature at 850 hPa, ~ 1500 m

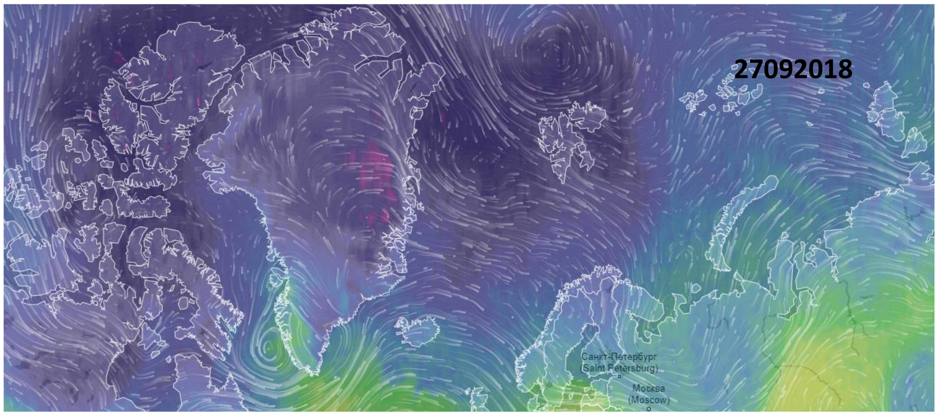


Figure 8. The same as Figure 7 but for temperature at 850 hPa.

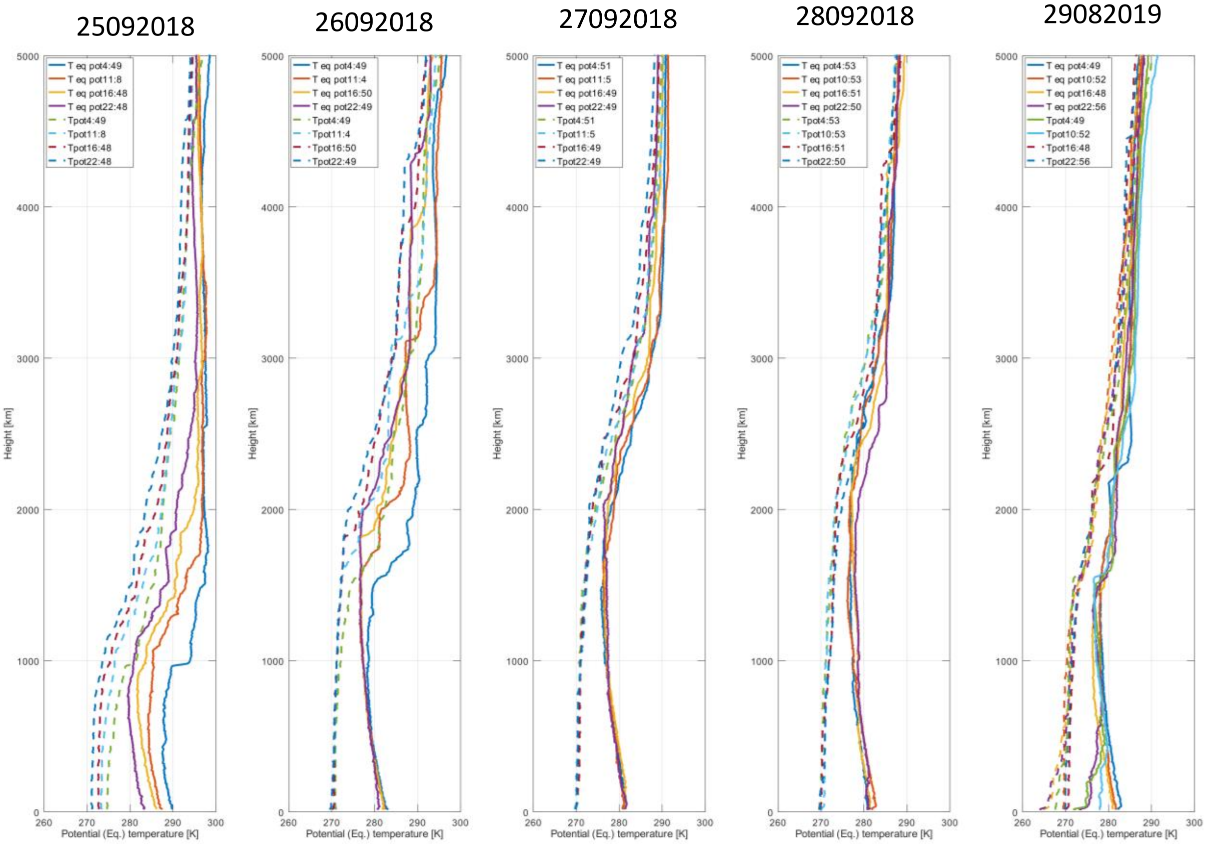


Figure 9. Potential (dashed lines) and equivalent potential temperatures (solid lines) obtained from radiosonde observations.

- ✓ We added the following sentence at the end of the Subsection 3.1 “Identification of periods…” in the revised version of the manuscript: “Since the number of cases for temperature anomalies ("+T +IWV" and "-T -IWV") is relatively low these types of anomalies were not considered for the further analysis.”.

- ✓ The categories “-T-IWV” and “+T+IWV” were removed from the table 1 and the expressions “(not shown)” were added to the following sentences: “Periods with "+T +IWV" anomaly take a major part (about 67%) of all moist anomalous cases (not shown). In contrast, occurrence of "-T -IWV" periods is only about 35% of all dry anomalies in all seasons except winter, when the occurrence is almost 90% (not shown).”

19) I cannot find any reference to Fig. 3 in the text.

- ✓ Please find the reference to Figure 3 in the second sentence of the subsection 4.2 of the revised manuscript.

20) Lines 237-241: This is introduction again. Omit or move.

- ✓ This part was removed and the section 3.3 was combined with the previous subsection. Now the combined subsection 3.2 has a title: “Cloud occurrence and phase”.

- ✓ The following sentence replaced the removed part: “Since the phase composition of clouds affects SW and LW radiative properties of clouds Ebell et al. (2020), we also analyzed the occurrence of different types of hydrometeors in the atmospheric column (Fig. 4).

21) Lines 244-245: What is meant by “only in summer” here? Is 8% little or much?

- ✓ We rephrased the following sentence: “In summer the increase in FOC of liquid containing profiles between moist and normal periods is less pronounced (8%).”

22) Line 275: The sentence starting “In contrast,: : :” is not clear.

- ✓ Rephrased: “In autumn during wet conditions the increase in mean IWP is about factor of 2 and during dry conditions the mean IWP does not decrease.”

23) Lines 277-289: A lot is written about aerosols here without a concrete connection to this study. Consider omitting or make the link to this study clearer.

- ✓ We removed the long discussion related to aerosols. We added the discussion on different factors and rephrased the following sentences in subsection 4.3.: “Since the anomaly type cannot fully explain this effect, it is probably also related to other factors such as differences in aerosol load, impact of local effects due to the surrounding orography, and an influence of the ocean. For instance, the seasonal change in the aerosol type affects the activation ability of CCN and IN efficiency in the Svalbard region which in turns influence the cloud formation. In addition, the reduction in sea ice around the Svalbard archipelago and on the fjords may lead to more evaporation and therefore, affect cloud conditions. Since Ny-Ålesund is surrounded by mountains up to 800 m, the air flow is influenced by the local orography in the lowest 1 km altitudes (Maturilli and Kayser et al.,2017a) and thus might have an impact on cloud formation and on cloud properties. Note, that within this study the influence of local effects and aerosols is not analyzed.”

24) Lines 286-289: Remove until “Figure 6 summarizes: : :” to remove repetition and

introduction-type text.

- ✓ This part was related to the motivation of the current subsection 4.4. And this part leads the reader to smoothly follow the topic of the current section and its connection to the previous sections.
- ✓ We made this part shorter. We left and rephrased the following sentence: “In the previous sections, we showed that water vapor anomalies affect cloudiness and the amount of liquid and ice in a column which will also influence the CRE at the surface at Ny-Ålesund.”

25) Line 291: Where and when? Is this a new result or based on a previous study which is mentioned.

- ✓ You are right. This information should be specified in order to avoid misunderstanding. We added a necessary information to the following sentence: “Values of LW CRE at Ny-Ålesund from June 2016 to October 2018 are in the range from 0 to 85 W m^{-2} and agree with the cloud occurrence and amount of liquid in a column (Ebell et al., 2020).”

26) Line 291: Add unit.

- ✓ The units were missing. We added the units.

27) Line 298: “increase in mean LW CRE” Which “mean”?

- ✓ In the previous version it was not clear what periods exhibit the changes in mean LW CRE. We rephrased the following sentence: “This increase in mean LW CRE due to moist anomalies in winter, spring, and autumn is associated…”.

28) Line 300: I do not see the lower LW CRE during moist anomalies in Fig. 6.

- ✓ Thank you for highlighting this mistake. This sentence was not correct. We rephrased the following sentence: “In contrast to other seasons, in summer the mean LW CRE during moist anomalies is not higher than under normal conditions.”

29) Lines 300-305: Effects of relative humidity remain unclear based on this. Explain why relative humidity can affect?

- ✓ The conditions with increased relative humidity are associated with concurrent increase in amount of atmospheric water vapor. Cox et al. (2015) showed that LW CRE depends on amount of IWV. The authors demonstrated that at the constant temperature and increased water vapor the LW CRE decreases (Fig. 4c, Cox et al., 2015). The LW CRE at the surface is lower for these cases because more absorption and emission from water vapor in the atmosphere between clouds and the surface leads to less emission from clouds transmitted through the atmosphere with increased amount of water vapor. Therefore, lower LW CRE was found for cases with increased humidity and temperature.

  We included an explanation and added the following sentences: “The authors analyzed data from radiative transfer simulations and observations obtained at Barrow, Summit and Eureka. They found that the increase in amount of atmospheric water vapor particularly between a cloud and the surface diminishes the impact of the infrared radiance emitted from the cloud due to more absorption and emission by water vapor itself. They showed that at constant temperature for higher relative humidity LW CRE is typically lower because of less emission by clouds passes to the surface through the atmosphere below the clouds.”

30) Lines 312-313: In addition, the summer cloud often radiate LW as a black-body, so an increase in LWP/IWP will not much affect their LW radiation in summer.

- ✓ Thank you for pointing to this aspect. We included the discussion on this aspect in the previous paragraph related to the moist anomaly period where we also discussed about the influence of water vapor in presence of optically thick clouds. The following sentences were added and rephrased in the manuscript in the previous paragraph: “In contrast to other seasons, in summer the mean LW CRE during moist anomalies is not higher than under normal conditions due to several factors. First, cloud occurrence does not change much between normal and moist conditions in summer. Second, in summer clouds often emit LW radiation as black bodies and therefore, an increase in LWP and/or IWP does not essentially affect their LW radiation. Moreover, a similar LW CRE in summer between moist and normal conditions may be caused by influence of water vapor in presence of optically thick clouds as was previously described by Cox et al. (2015).”

31) Lines 328-330: Do the author say that if LWP and IWP and frequency of occurrence of clouds do not vary, the cloud properties cannot vary? What about droplet size and aerosols affecting the SW CRE?

- ✓ SW CRE estimations used in the current manuscript were based on the RRTMG model (Ebell et al., 2020) output and therefore there is no interaction between aerosols and cloud properties included.

- ✓ In the RRTMG model, Ebell et al. (2020) use a constant climatological profile of aerosol properties. The variability of the aerosol load is currently not available and thus it is one of the sources of uncertainties of the modeled CRE. Since variability of the aerosols is not included into the used CRE, the changes in CRE which are discussed in this sentence are not associated to aerosol properties.

- ✓ At SW the extinction by cloud droplets is defined by the scattering. The scattering efficiency at SW is constant (about 2) since it is practically in the optical limit here. Extinction is determined by the optical depth which is directly proportional to LWP and proportional to $1/r_{eff}$, where r_{eff} is the effective radius of droplets. For a constant LWP, the projection area of cloud particles is inversely proportional to the effective radius of droplets. Thus, a change by a factor of 6 would require a 6-fold change or the effective radius of droplets. According to a number of studies focused on microphysical retrievals in the Arctic (e.g. Turner 2004, Shupe et al. 2005) cloud droplets in the Arctic are typically 5-8 micrometers in radius. Therefore, the variability in the cloud droplet sizes is not likely to be the major contributor to the factor of 6 variability in SW CRE.

32) Lines 344-347: Omit or shorten.

- ✓ Since some question related to the uncertainty sampling arose and were highlighted by the reviewer 2, we decided to keep this part as it is. Because it explains that the defined anomaly types were uniformly distributed and their occurrence were not associated with a dominant time period.

33) Line 408: Are the percentile threshold values taken here from the Microwave radiometer data or radiosounding data?

- ✓ Thank you for highlighting this point. The percentile threshold values are taken from the microwave radiometer data. We clarified this in the following sentence: "Therefore, we estimated the IWV value for each radiosonde profile and classified the profile using the thresholds defined in Sec. 1 based on MWR data."

34) Lines 422-426: remove from here, because this part belongs to " Summary and conclusions".

- ✓ Removed

35) Line 440: Was the correlation analyzed? If not, do not use the word "correlate".

- ✓ The word "correlated" was replaced by the word "associated".

36) Lines 442-443: Again, what is specifically meant by "air circulating in the Arctic"?

- ✓ Rephrased: "Dry periods in Ny–Ålesund are mainly related to air masses originating from latitudes north of the Arctic Circle, which is consistent with previous studies (Maturilli and Kayser, 2017a; Dahlke and Maturilli, 2017; Wu, 2017; Mewes and Jacobi, 2019)."

37) Line 445: Statistically significant?

- ✓ We replaced "significant" to "large".

38) Line 446: "counterclockwise air circulations" could be "cyclonic".

- ✓ We rephrased the following sentence: "In winter and spring dry conditions are associated with a low pressure system over the Barents sea causing northerly flow to the Svalbard region.".

39) Line 447: What is meant by "this type of circulation"?

- ✓ Rephrased: "In winter and spring dry conditions are associated with a low pressure system over the Barents sea causing northerly flow to the Svalbard region. This is in agreement with the results from Mewes and Jacobi (2019), who showed that in winter this northerly air mass transport to Svalbard region is related to the North Pacific pathway, which causes cold anomalies for the Svalbard region."

- ✓ Please note that this part was shifted in the revised version of the manuscript since we reorganized the Section "Summary and conclusions". Now it is placed in results for "-IWV" anomaly period.

40) Line 449: See my earlier comment about these directions. I could not see these results in the figure.

- ✓ In order to cut the length of the manuscript and since the anomaly periods "-T-IWV" and "+T+IWV" are a particular case of "-IWV" and "+IWV" periods, we decided to exclude the discussions related to “-T-IWV” and “+T+IWV” anomalies from the manuscript. We removed these sentences related to findings referred to “-T -IWV” anomaly type.

41) Lines 444-450: This part is far too long and the dynamical part is not well enough explained.

- ✓ We made this paragraph shorter by removing the part related to the “-T-IWV” anomaly type. Please see the answer to the previous comment.

42) Figure 8: From which level (height) the radiosonde IWV is taken?

- ✓ Calculations of IWV were based on the temperature, air pressure and humidity profiles from radiosondes. As radiosonde humidity sensor measurements are affected by low temperatures, their data reliability in the upper troposphere is limited particularly in the Arctic. Thus, we calculated IWV over a column from the surface up to 8 km height. In general, the largest contribution to the column atmospheric water vapor originates from the lowest altitudes up to 4 km (Nomokonova et al, 2019, Maturilli et al., 2016). Since the values of absolute humidity are quite low at altitudes higher than 8 km, we do not expect a substantial change in IWV values calculated for a column up to 8 km and up to higher altitudes of radiosonde profiles.

Reply to reviewer #2

We would like to thank the reviewer #2 for the constructive comments, which helped to improve the manuscript. We have considered all the recommendations. In the following reply we repeat the statements of the reviewer (in red) and the reply to each statement of the reviewer (in black). Note that in the statements of the reviewer the line and figure numbers refer to the original manuscript and may have changed in the revised version.

1 Specific comments:

The main concern I have is associated with the sampling uncertainty; I speak more about this below.

1) Why wasn’t the cloud radar included in the instrument list / description section? It is key for the CloudNet products, which are key for the rest of the paper.
    - ✓ You are right that the Doppler cloud radar is a key instrument for Cloudnet and we agree on it. However, all the necessary information on all the instruments including also a Doppler cloud radar was provided in the previous study Nomokonova et al., (2019) that we also referenced to in the current manuscript at the beginning of the Section 2 (Instrumentation and data products). In the current manuscript we paid more attention to describe the instruments and data products that have not been described and included in the previous study (Nomokonova et al., 2019). Therefore, we only briefly described instruments in

the current manuscript. If we include the detailed information on all the instrument it will make the manuscript too long and will lead to a repetition. And the first reviewer has asked us to shorten the existing manuscript. This is why we would like to keep the section as it is.

2) Why were NWP thermodynamic profiles used in the CloudNet classification, and not the profiles retrieved from the HATPRO?

✓ Please note that Cloudnet processing is a part of the ACTRIS European Research Infrastructure (www.actris.eu) focused on research of aerosols, clouds, and trace gases. Cloudnet either uses radiosonde and NWP data. NWP thermodynamic profiles are commonly used as input for Cloudnet by the community. In this study we use Cloudnet products as they are provided. We agree with the you that the microwave radiometer (MWR) HATPRO has certain advantages. One of the main advantages is continuous measurements with high temporal resolution. Nevertheless, this instrument cannot provide reliable observations during rain and conditions of condensation (fog) when the radome of the instrument is wet. Such cases are flagged and could not be used as input for Cloudnet. In addition, MWR do not provide the vertical resolution in temperature and humidity profiles needed for Cloudnet. In fact, the figures below show a comparison of temperature profiles retrieved from MWR HATPRO and NWP ICON model output for Ny-Ålesund with measured temperatures from radiosondes. MWR HATPRO shows a smaller bias in the lowest 1 km in comparison to NWP ICON model output. While the standard deviation of the temperature difference between MWR HATPRO and radiosondes is much higher in comparison to the ones between ICON model output and radiosondes for altitudes higher than 2 km. The standard deviation of the temperature difference between MWR HATPRO and radiosondes increases from around 1.5 °C at 1 km height to 5 °C at around 10 km.

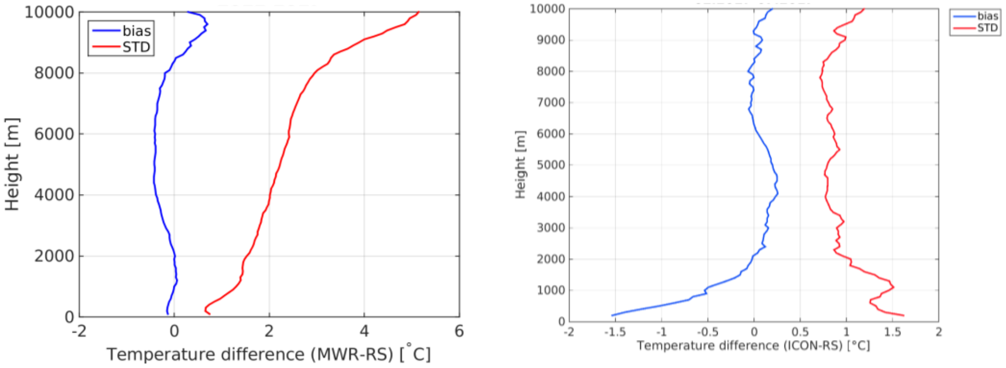


Figure 1. Temperature difference between MWR HATPRO and radiosondes (left) and NWP ICON model and radiosondes (right). Blue and red lines show the bias and the standard deviation, respectively.

All this information is provided in Nomokonova et al., (2019) and the link is provided in the current manuscript.

3) Line 138: the RRTMG should be referenced, as it is a critical component to this study

- ✓ We added the references to Mlawer et al., 1997 and Barker et al., 2003.

4) Are the uncertainties in the retrieved cloud properties (and in particular the phase classification) important to this study?

- ✓ The uncertainties of cloud properties and particular phase classification are, for sure, important for this study and they were discussed in detail in the previous study Nomokonova et al., (2019) published earlier in the same special issue. In Nomokonova et al., (2019) a detailed information on instruments, Cloudnet uncertainties and description of the method for cloud classification used in this study are provided. For classification Cloudnet algorithm identifies the 0 C° isotherm based on the wet-bulb temperature from the model data. Therefore, the model temperature uncertainty (Figure 1 here) may lead to a misclassification of liquid and ice. In addition, ceilometer signal can be attenuated in the first liquid layer and therefore, cloud particles above the first liquid layer might not be detected. These cases occur in multi-layer clouds and single-layer mixed-phase clouds. Since the calculations of some microphysical cloud properties are based on LWP retrieved by MWR HATPRO and therefore, might be also influenced by the accuracy LWP. IWC was calculated using method based on Z-T relationship (where T is a temperature and Z is radar reflectivity) described by Horgan et al., (2006). IWC has bias error and typical random error of 0.923 and 1.76 dB, respectively. The uncertainty of IWC retrieval estimated by Horgan et al, (2006) depends on temperature: -50 to +100% for T below -40 °C and ranging from -33 to 50% for temperatures above -20 °C (root mean squared errors are given with respect to the reference IWC). The uncertainty in the radar reflectivity also affects IWC retrieval. The total uncertainty of 2 dB correspond to uncertainty in IWC ranging from +40 to -30%. More information on uncertainties are provided in Nomokonova et al, (2019). All these uncertainties result in differences between the simulated and measured radiation fluxes estimated and discussed in Ebell et al. (2020), the latter is also provided in subsection 2.5 in the initial version of the manuscript. The resulting uncertainties in SW and LW CRE are similar to the ones found in other state-of-the art studies for other Arctic sites.

5) What vertical separation is required to identify multi-layer clouds?

- ✓ The method for cloud classification was provided in previous study Nomokonova et al., (2019) and in current manuscript the reference to this method is mentioned in current manuscript. A cloud layer is defined as a layer of at least three consecutive cloudy height bins (~20 m each). We considered cases as multilayer clouds if two or more cloud layers were separated by one or more clear sky height bins (~20 m resolution).

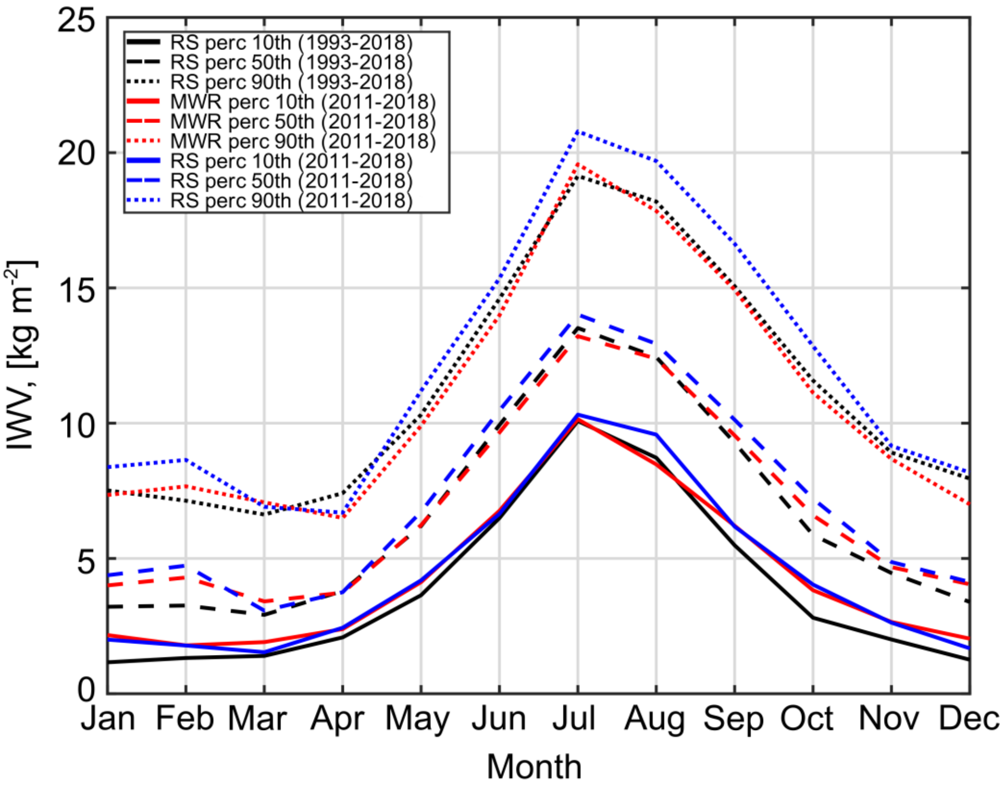
6) Are the backtrajectories allowed to touch the surface? Or if they touch the surface, do you call that the origin point for the trajectory?

- ✓ The backward trajectories used in this analysis were limited only by the travel time going back up to 6 days.
- ✓ The calculations of the backward trajectories are based on gridded meteorological fields of NWP model of ECMWF. The lowest model levels closest to the ground follow the topography (Stohl et al., 1998). All the files of calculated back trajectories have the orography height (Z_{oro}) which correspond to the height above ground. We have checked the minimum height above ground for all the backward trajectories shown in Figure 2 in the manuscript they have never touched the surface.
- ✓ The main purpose of the use of back trajectories in this study was to show the direction of air masses towards Ny-Ålesund rather than vertical displacement of the air mases which is particularly important, for instance, for aerosol studies. Therefore, we think that for a cluster analysis of backward trajectories that allows to discriminate distinct flows of two different anomaly types ("-IWV" and "+IWV") provided in this study with the emphases on the direction of air mases the information obtained from backward trajectories is still relevant.

7) Line 168: The HATPRO period is from 2011 to 2018. This isn't a very long period. Using the longer radiosonde record, how representative is the 2011-2018 period? It is clear that the mean values won't be the same (hence the trends over time), but is the range of variability (e.g., standard deviation of the IWV)) the same for the short period as the longer period? Ditto for the 2016-2018 period.

- ✓ We have checked the representativeness of the derived monthly values of IWV from MWR HATPRO and radiosondes for different periods. Figure 2 below shows the 10th, 50th, and 90th percentiles of monthly IWV values derived from different instruments. The monthly values of IWV derived from radiosondes for the periods from 1993-2018 and from 2011-2018 were compared with ones derived from MWR HATPRO. The results show a good agreement between IWV derived from radiosondes for both periods and from MWR HATPRO, the period from 2011-2018, which is used to identify the anomaly periods in the current manuscript. The monthly IWV for the longer period (1993-2018) is closer to the one from MWR HATPRO period with root-mean squared difference (RMSD) of the 10th and 90th percentiles of 0.6 and 0.5 kg/m^{-2}, respectively. Slightly higher monthly values of IWV from radiosondes were found for the same period as for MWR HATPRO (2011-2018) with RMSD of 0.4 and 1.2 kg/m^{-2} for 10th and 90th percentiles, respectively.

✓ The shorter period from 2016-2018 is shown on the right figure below. The results revealed that percentiles of IWV from radiosondes (2016-2018) and MWR HATPRO (2011-2018) consistent with RMSD of 0.5 and 1.1 kg/m^{-2} for 10th and 90th percentiles, respectively.



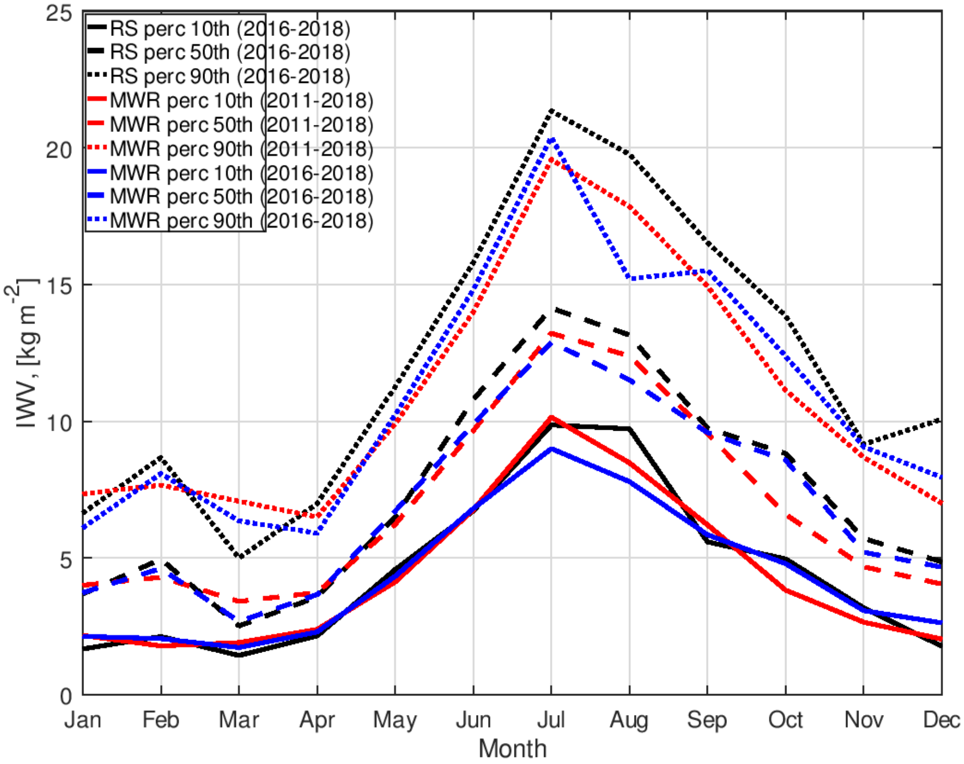


Figure 2. Monthly percentiles of IWV from MWR HATPRO and radiosondes at Ny-Ålesund for different periods. Black lines show 10th percentile (solid line), 50th percentile (dashed line), and 90th percentile (dotted line) of IWV calculated from radiosondes for the period from 1993 to 2018. Red lines are related to the correspondent percentiles of IWV retrieved from MWR HATPRO for the period from 2011 to 2018 (the same as shown in the current manuscript, Figure 1). Blue lines referred to correspondent percentiles of IWV derived from radiosondes for the period from 2011 to 2018.

✓ We added the upper figure to the supplement materials of the manuscript (please see the attached file of the Supplement material, Figure S3). We added the following sentence in the manuscript: “The representativeness and variability of IWV values obtained from MWR for the reference period from 2011 to 2018 was checked with respect to the long-term radiosonde record. The monthly values of IWV derived from radiosondes for the periods from 1993 to 2018 and from 2011 to 2018 were compared with ones derived from MWR HATPRO. The results are in a good agreement and summarized in Fig. S3 in supplement material. The monthly IWV for the longer period (1993-2018) is closer to the one from MWR HATPRO period with root-mean squared difference (RMSD) of the 10th and 90th percentiles around 0.6 and 0.5 kg m^{-2}, respectively. Slightly higher monthly values of IWV from radiosondes were found for the same period as for MWR HATPRO (2011-2018) with RMSD of 0.4 and 1.2 kg m^{-2} for 10th and 90th percentiles, respectively.”

8) I have a lot of questions regarding the sampling uncertainty, especially in the 2016-2018 dataset. The authors themselves hinted at this at line 225 when they say “Such a short period of time would probably not be representative: : :”. Table 1 shows that the number of cases in these “outlier” categories is small (less than 100, often less than 50). This is, by far, the biggest weakness of the paper. The authors must augment their discussion to talk about sampling uncertainties, which includes the two questions above regarding representativeness.

- ✓ We agree that the short period of temperature anomalies might be not representative particularly for the “-T-IWV” event in autumn because it was a unique case which lasted continuously only for 5-days. That is why we decided to exclude the categories of temperature anomaly periods from the manuscript. This also helps to keep the manuscript shorter as the first reviewer has requested. So far, the vertically resolved cloud observations are available at Ny-Ålesund for the period from 2016 -2018 and were analyzed in this study. According to the definitions of the anomalies, the anomalous periods represent 20% of all the cloud observations (10% dry and 10% moist).

- ✓ We added the following sentence at the end of the Subsection 3.1 “Identification of periods…” in the revised version of the manuscript: “Since the number of cases for temperature anomalies ("+T +IWV" and "-T -IWV") is relatively low these types of anomalies were not considered for the further analysis.”.

- ✓ The categories “-T-IWV” and “+T+IWV” were removed from the table 1 and the expressions “(not shown)”were added to the following sentences: “Periods with "+T +IWV" anomaly take a major part (about 67%) of all moist anomalous cases (not shown). In contrast, occurrence of "-T -IWV" periods is only about 35% of all dry anomalies in all seasons except winter, when the occurrence is almost 90% (not shown).”

- ✓ Please note that the numbers at the top of the figures 3 and 4 are the numbers of the 6-hourly periods. Within each 6 hourly period there are at least 70% of 30 s profiles. For instance, “-IWV” and “+IWV” events in autumn with 53 and 102 cases of 6-hourly periods include 34654 and 69605 cloud profiles, respectively. Thus, the number of analyzed cloud profiles for each anomaly type is enough to get statistics on cloud properties and their radiative effect and investigate their relation to changes in IWV. The vertically resolved cloud observations at Ny-Ålesund will continue within the (AC)^3 project and more data will be available in the future for further analysis.

- ✓ We also checked the representativeness of IWV thresholds used to identify the anomalous periods during the 2016-2018 period with the longer time period

(1993-2018). And the results of this comparison do not show essential difference. Please see the answer to the previous comment.

- ✓ The problems of the sampling uncertainty of anomaly periods were also discussed in the manuscript (Page 11, lines 344-362, original version of the manuscript). In the initial version of the manuscript we mentioned that the anomaly periods were uniformly distributed over a day. We added the figure with distributions of anomalous and normal cases among 6-hourly time periods in supplemental material (Fig. S2). The following expression “(Fig.~S2, supplement material)” was added to the text of the manuscript to link to this figure.

9) Line 227: you are talking about the “-T -IWV” cases, and stating that the LWC and IWC are larger than in normal conditions. This is indeed counterintuitive. Perhaps the authors could look at the column RH value (computed as IWV / saturated_IWV, where the temperature profile is retrieved from the HATPRO) to see if there are any differences in this value? It would seem that the column RH in the “-T -IWV” case must be larger than the normal conditions for the cloud water paths to be larger: : :

- ✓ In order to make the manuscript shorten and due to the low number of cases for the temperature anomaly periods anomalies (“-T-IWV” and “+T+IWV”) we decided to exclude them from the detailed analysis. However, to answer the questions from reviewers related to “-T-IWV” period since this period was particular interesting, we provided a detail analysis. Please see the answer above to the specific comment # 27) from reviewer 1.

10) Section around line 249, where the discussion focuses on ice clouds: I think that the authors should consider breaking the analysis into high ice clouds (e.g., cirrus) and “boundary layer” ice clouds. Generally speaking, I would not expect the former to have much of a dependence on IWV, whereas I can see how the BL ice clouds could depend on changes in IWV.

- ✓ Following the suggestion of the reviewer we performed an analysis of the altitudes of the ice-containing profiles. Ice-only profiles (blue color in Fig. 4) have the median cloud top height of ~3 km which corresponds to the median cloud top temperature of -31°C. It is well-known that clouds formed at temperatures warmer than -25°C are formed heterogeneously via liquid phase. Therefore, as expected, the mixed profiles have lower median cloud top height (~1.6 km) and are characterized by the median cloud top temperature of -6 °C in summer and -15 °C during other seasons.
- ✓ This analysis agrees well to the expectations of the reviewer, i.e. ice-only profiles (cirrus clouds) occurring at higher altitudes are less sensitive to changes in IWV. Mixed profiles (boundary layer clouds) appear at lower altitudes and depends more on changes in IWV.
- ✓ The following sentences have been added to the updated manuscript: “Profiles with both liquid and ice phases (green columns in Fig. 4) have the median cloud top height and temperature of 1.6 km and –15 °C (not shown), respectively. In the case of pure ice

profiles (blue columns in Fig. 4) the cloud top height and temperature are 3 km and –31 °C, respectively. Thus, ice-containing clouds occurring at higher altitudes are apparently less affected by IWV anomalies."

11) Line 266: To state that there is a 2x increase in LWP is not really clear enough. If the LWP is less than 10 g/m2, then a 2x increase is 20 g/m2 which is still close to the uncertainty in the HATPRO LWP retrievals. Would those retrievals have sensitivity to the atmospheric state, or in other words, is this 2x change in LWP an artifact of the retrieval?

- ✓ We agree with the reviewer that a comparison of numbers close to the uncertainties should be made carefully. In the line 266 of the initial manuscript the two fold increase in LWP was from 70 g/m^2 (the mean value indicated by the orange marker) during normal events to about 130 g/m^2 during -T-IWV conditions. Both numbers by far exceed the uncertainty of the retrieval.
- ✓ Sensitivity of the HATPRO LWP is around 1-2 gm^{-2}. The uncertainty of the 15 g/m^2 of the LWP retrieval is related to the long-term drifts which depend on atmospheric state (IWV and T) and TB stability. The figure 5 shows the values averaged over weeks and therefore, such a long averaging reduces the influence of this drifts and thus the uncertainty is lower.
- ✓ Please also note that all the results and conclusions made for -T-IWV and +T+IWV have been removed from the manuscript.

12) Line 269: again, where the ice clouds are located vertically may be important for this statement.

- ✓ In the comment 10 pure ice profiles and those containing both liquid and ice phase were compared in terms of cloud top height and temperature. There indeed the height could explain a lesser sensitivity of pure ice profiles to IWV anomalies. Here (line 269 of the initial manuscript) IWP changes are given for all ice-containing profiles (pure ice + liquid and ice in profile). Figure 4 shows that in summer a majority of the ice containing profiles have both liquid and ice in profile. In the comment 10 we wrote that these profiles are more sensitive to anomalies but these profiles have nearly the same cloud top height in different seasons. Therefore, the lower sensitivity of IWP to IWV anomalies in summer cannot be fully explained by the different altitudes of cloud tops.

13) Line 291: need to add units to the "0 to 85"

- ✓ Thank you for highlighting this point. We added the units.

14) Line 464: “excess and shortage” are odd words here. I think this phrase must be changed to be more clear

- ✓ We changed the structure of the Section 4 “Summary and conclusions” by splitting the main finding into “+IWV” and “-IWV” and this expression was rephrased.

15) Line 466: “reduction of LWP and IWP by an order of magnitude” seems to suggest both are decreased by a factor of 10, when I believe you only mean the IWP is changed by a factor of 10.

- ✓ Thank you for pointing to this aspect. This sentence was wrong.
- ✓ In order to shorten the section “Summary and conclusion” and present only the main results, this sentence and some others were excluded from this section.

16) Line 500: “patterns” is misspelled

- ✓ Corrected

17) Fig 6a: Is the autumn “-T -IWV” bar where it is due to that one 5-day period? I think the answer is yes, and this is a great example indicating that the sampling errors must be better discussed. And a note should be made in the caption here.

- ✓ We agree that this case “-T-IWV” was relatively short to draw conclusions. This event was unique, and we provided the detail analysis. Please see the answer to the comment # 27) from the reviewer #1. However, we decided to remove the temperature anomaly periods from the manuscript and not analyze them additionally.
- ✓ We removed anomaly periods referred to “-T-IWV” and “+T+IWV” from the manuscript since they are related to the short periods. Please see the answers above.

18) Fig 6c: it would be nice to have a horizontal line at CRE= 0.

- ✓ We added a horizontal line at CRE =0. Please see Figure 6c.

Additional changes

Note that the line numbers refer to the revised manuscript.

1) A year in the references Ebell et al., 2019 was changed from “2019” to “2020” throughout the manuscript. The information in the reference list was also changed.
2) **Figure 3 and Figure 4:** There were mistakes in numbers of anomaly cases mentioned at the top of the bars in Figures 3 and 4. The numbers of cases for dry (dry and cold) anomalies were mixed

up with ones for moist (moist and warm) cases. The figures 3 and 4 with the wrong numbers were replaced by new with correct numbers.

3) **Page 3 (updated manuscript):** We replaced "… in this study" to "… the following section".
4) **Page 3 (updated manuscript):** We replaced "… has been operating" to "… has been operated".
5) **Page 7 (updated manuscript):** We rephrased the sentence: "Clear-sky cases were not included in the statistics of LWP and IWP."
6) **Page 9 (updated manuscript**)**:** We added the following sentence "First, cloud occurrence does not change much between normal and moist conditions in summer.".
7) **Page 9 (updated manuscript**)**:** The following sentence was rephrased: "Moreover, the similar LW CRE in summer between moist and normal conditions may be caused by influence of water vapor in presence of optically thick clouds as was previously described by (Cox et al., 2015)."
8) **Page 9 (updated manuscript):** We added: "..., respectively." To the end of the sentence. "Thus, the strongest SW CRE can be found in summer. Under normal conditions in summer and spring the mean SW CRE is -115 and -19 W m^{-2}, respectively."
9) **Page 9 (updated manuscript):** We rephrased the sentence: "In summer the cloud properties during dry anomalies do not change as strongly with respect to normal conditions compared to other seasons, …".
10) **Subsection 3.2 and 3.3** were combined. Now the title for subsection 3.2 is "Cloud occurrence and phase". The numbers for the following subsections in Section 3 were shifted correspondingly.
11) **Page 10 (updated manuscript):** The expression "under dry conditions" was redundant and was removed (page 12, line 372 in original version of the manuscript).
12) **Page 10 (updated manuscript):** The following sentence was moved to the previous paragraph: "Since the effects of SZA are mitigated…".
13) **Page 10 (updated manuscript):** We added the reference to Table 2 and changed the numbers of mean normalized SW CRE in the text according the Table 2. The changes were made in following sentence: "Table 2 shows that under normal conditions …"
14) **Page 10 (updated manuscript):** the following sentences were rephrased: **"**If anomaly cases uniformly distributed over a season, we expect no difference in surface albedo between anomaly and normal conditions. Thus, similar relative changes in CRE_{SW} and $nCRE_{SW}$ and near-zero change in the surface albedo indicate similar SZA conditions for anomaly and normal cases. If anomaly cases distributed not uniformly over a season the diversion would show that anomaly cases were sparsely distributed over a season."
15) **Page 11 (updated manuscript):** We removed the following sentence: "Influences of water vapor anomalies have been previously discussed in details.".
16) **Page 12 (updated manuscript):** The following sentence "Figure 8 shows changes in anomaly occurrences." was rephrased by: "Figure 8 shows the frequency of occurrence of moist and dry anomalies for each season for the time period from 1993 to 2018."
17) **Page 12 (updated manuscript):** We removed the following sentence: "About a half of the profiles in autumn and winter of 1993 corresponded to dry anomalies.".
18) **Page 12 (updated manuscript):** Added the word "moisture" to the following sentence: "The main focus is on the impact of anomalous moisture conditions …".
19) We changed the title of the **Section 3** from "Identification of periods … " to "Definition of periods …"
20) In acknowledgments "Project-Number" was replaced by "Project-ID".

21) Some expressions and sentences were slightly changed throughout the manuscript.

The influence of ~~anomalous atmospheric conditions at Ny-Ålesund~~ water vapor anomalies on clouds and their radiative effect at Ny-Ålesund

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Abstract. ~~This study analyses~~ The occurrence of events with increased and decreased integrated water vapor (IWV) ~~and atmospheric temperature (T)~~ at the Arctic site Ny-Ålesund and their relation to cloud properties and the surface cloud radiative effect (CRE) is investigated. For this study, we used almost 2.5 years (from June 2016 to October 2018) of ground-based cloud observations processed with the Cloudnet algorithm, IWV ~~and T from~~ from a microwave radiometer (MWR), long-term radiosonde observations, and backward trajectories FLEXTRA. Moist and dry anomalies were found to be associated with North Atlantic flows and air ~~circulations in~~ transport within the Arctic region, respectively. The amount of water vapor is often correlated with cloud occurrence, presence of cloud liquid water, liquid and ice water path (LWP and IWP). In turn, changes in the cloud properties cause differences in surface CRE. During dry anomalies, in autumn, winter, and spring, the mean net surface CRE was lower by 2–37 W m^{-2} with respect to normal conditions, while in summer the cloud related surface cooling was reduced by 49 W m^{-2}. In contrast, under moist conditions in summer the mean net surface CRE becomes more negative by 25 W m^{-2}, while in other seasons the mean net surface CRE was increased by 5–37 W m^{-2}. Trends in occurrence of dry and moist anomalies were analyzed based on a 25-year-radiosonde database. Dry anomalies have become less frequent with rates for different seasons ranging from -12.8 to -4% per decade, while the occurrence of moist ~~event increases~~ events have increased at rates from 2.8 to 6.4% per decade. ~~Taking into account the relations between the anomaly types and cloud properties the trends might be related to an increase in cloud occurrence, LWP, and IWP. The change in cloud properties could, in turn, modulate the surface CRE and lead to stronger surface cooling and warming related to clouds in summer and other seasons, respectively.~~

1 Introduction

It is well known that during the past 3 decades the Arctic climate has been drastically changing. The change in the annual near-surface temperature over the Arctic region has been found to be a factor of 2 to 3 larger compared to the global average (IPCC, 2007; Solomon et al., 2007; Wendisch et al., 2017). In the period 1998-2012, the temperature increase in the Arctic was persistent in contrast to the "hiatus" in the global warming having been discussed in a number of studies (Wei et al., 2016; Huang et al., 2017).

This amplification of warming in the Arctic is caused by several feedback mechanisms. Among them are the reduced sea ice extent and high sea surface temperature (Serreze et al., 2011; Hegyi and Taylor, 2018), changes in atmospheric circulation (Maturilli and Kayser, 2017a; Overland et al., 2016; Overland and Wang, 2016; Wu, 2017) and energy transport (Graversen and Burtu, 2016; Hwang et al., 2011), surface albedo effect (Graversen et al., 2014), increased greenhouse effect of water vapor, and clouds (Yoshimori et al., 2017).

The analysis of contemporary climate models shows that on average the mean cloud feedback is one of the major mechanisms opposing the Arctic amplification from a top of atmosphere (TOA) perspective with relatively small contribution to the warming at the surface (Pithan and Mauritsen, 2014). Modeling of the cloud impact on the Arctic amplification is still uncertain (Pithan and Mauritsen, 2014; Hwang et al., 2011; Taylor et al., 2013) due to a large number of microphysical processes (Morrison et al., 2012) and complex relations between clouds and other feedback mechanisms of the Arctic climate (Graversen and Burtu, 2016; Hwang et al., 2011). As a result some models underestimate the amount of super-cooled liquid water (Sandvik et al., 2007; Nomokonova et al., 2019), which may lead to a bias in the surface temperature ranging from -7.8 to 0°C (Kay et al., 2016; Miller et al., 2017).

Properties of Arctic clouds are significantly affected by air masses transported from the mid-latitudes (Graversen and Burtu, 2016; Hwang et al., 2011). A number of studies have already related the air transport and atmospheric rivers to amount of water vapor, cloud properties, and the radiation budget (Hwang et al., 2011; Boisvert et al., 2016; Mortin et al., 2016; Sedlar and Tjernström, 2017; Hegyi and Taylor, 2018). Hegyi and Taylor (2018) reported that the episodes of poleward atmospheric water vapor transport are associated with periods of increased water vapor and cloud cover resulting in enhanced downwelling longwave surface fluxes and reduced surface cooling efficiency. ~~Raddatz et al. (2013) analyzed the impact of cloud coverage and increased water vapor on longwave downwelling radiation using ground-based observations installed at different sites in the Beaufort Sea–Amundsen Gulf region of the Canadian Arctic. The authors found that the cloud coverage and water vapor explain 84% of the variance of longwave downwelling radiation, while the remaining 16% are associated with cloud composition, cloud thickness and cloud-base height. Raddatz et al. (2013) estimated differences in longwave downwelling radiation between cases with typical and maximum values of water vapor. The authors associate the latter to moist intrusion events. The differences are 82 and 95 W m^{-2} in winter and 38 W m^{-2} and 45 W m^{-2} in summer for clear sky and cloudy conditions, respectively.~~ A limited number of studies show that air transportation patterns may influence phase partitioning and amount of liquid in Arctic clouds (Qiu et al., 2018; Tjernström et al., 2019).

~~Many studies relate the advection of moist and warm air from the mid-latitudes with Arctic climate change (Woods and Caballero, 2016; C~~
~~, while only a few are focused on cold intrusions (Kanno et al., 2019). However, extreme cold events exhibit a stronger change in occurrence than extreme warm events (Sillmann et al., 2013; Collins et al., 2013). Kanno et al. (2019) reported that the occurrence of extremely cold air masses in the Arctic have been reduced by about 80% over the past 60 years. The authors mention that even though the main driver of this reduction is radiative forcing associated with green house gases, the relations of the extreme cold air masses with other components of the Arctic climate, such as humidity and cloudiness, have to be explored. Yamanouchi (2018) showed a case study with a contrast in cloud conditions and longwave radiation during a transition from cold to warm periods. The author concluded that the cold periods might be associated with low occurrence of clouds and~~

~~relatively thin clouds, while high cloudiness and thick clouds are typical for periods of warm and moist intrusions. Since the author investigated only on a short period, an analysis of longer cloud observations is still needed.~~

A number of studies focus on observations at Ny-Ålesund located in the Svalbard region (Wendisch et al., 2019; Maturilli et al., 2013; Maturilli and Ebell, 2018; Yeo et al., 2018), an Arctic area where ~~the specific synoptic regime brings more moisture~~ air masses transported from the lower latitudes bring more moisture in comparison to the rest of the Arctic (Dahlke and Maturilli, 2017; Mewes and Jacobi, 2019). The Svalbard region is also located in the area with the highest warming temperature trend in the Arctic (Susskind et al., 2019). Ny-Ålesund is located at the coastline of Svalbard and thus, its climate is significantly influenced by diabatic heating from the warm ocean (Serreze et al., 2011; Mewes and Jacobi, 2019) and by the surrounding orography (Maturilli and Kayser, 2017a).

~~Maturilli and Kayser (2017a) have shown highly pronounced warming and moistening of the tropospheric column in Ny-Ålesund. Analyzing a 22-year radiosonde dataset (1993-2014) the authors found that in winter time there has been a significant increase of atmospheric temperature (up to 3 K per decade) and mean integrated water vapor (+0.83±1.22 kg m^{-2} per decade). This tendency in winter is correlated with a strong increase in up- and downward longwave radiation of +11.6±10.9 W m^{-2} and 15.6±11.6 W m^{-2}, respectively (Maturilli et al., 2015). In contrast, during other seasons the trends in temperature and up- and downward longwave radiation are less pronounced.~~

Dahlke and Maturilli (2017) ~~reported that the observed trend in warming in the winter season is due to the~~ showed an increasing air mass transport through the North Atlantic pathway and reducing flow from the north in the winter season in Ny-Ålesund. Yeo et al. (2018) investigated how the advection of warm and cold air masses affects cloudiness, longwave fluxes at the surface and near-surface temperature at Ny-Ålesund during winter. The authors analyzed a 10-day period in February with alternating warm and cold conditions related to distinct circulation patterns. During cold periods Yeo et al. (2018) observed a reduced cloudiness and ~~down-welling~~ downwelling longwave flux of ~~200-230~~200–230 W m^{-2}. In contrast, warm periods were associated with cloud occurrence close to 100 % and enhanced ~~down-welling~~ downwelling longwave flux of 300 W m^{-2}. Since the author studied only a short period, an analysis of longer cloud observations is still needed.

~~Most of the studies on the Arctic climate are focused on winter. Nevertheless, Mortin et al. (2016) and Hegyi and Taylor (2018) pointed out the importance of the representation of the atmospheric variability during the transition periods. Significant anomalies in temperature,water vapor, and cloud properties initiate the surface melt in spring, while in autumn these factors affect ice freeze-up. Maturilli et al. (2015) showed that at Ny-Ålesund the trend in the net radiation budget is highest in summer. Even though this trend does not directly translate into the surface temperature increase, the additional radiation income may affect some other feedback mechanisms in the Arctic.~~

In this study, the main scientific question is how ~~the large scale circulation and advection~~ periods of increased and decreased integrated water vapor (IWV) influence cloud appearance at Ny-Ålesund and how this influence affects the cloud radiative effect. ~~We put our focus on periods of increased and decreased amount of integrated water vapor (IWV) and temperature, since these periods can be related to the changes in large scale circulation and synoptic situation.~~ Even though only IWV ~~and temperature are~~ is considered in this study, cloud formation and development also depends on a number of other factors such as aerosol load and chemical composition (Baustian et al., 2012; Murray et al., 2012; Wex et al., 2019), dynamics (Korolev and Field, 2008; Schmidt et al., 2014), influence of surface layer (Morrison et al., 2012) and local orographic effects (Houze, 2012) and other processes. ~~Analysis~~ The analysis of these factors is out of the scope of this study. We used ground-based cloud observations at Ny-Ålesund. Instrumentation and data products used in this study are presented in section 2. The definition of warm/cold and moist/dry anomalous periods is described in section 3. In section 4 the occurrence of different types of clouds, cloud properties and their radiative effect are analyzed and related to the anomalous periods of IWV and atmospheric temperature. Finally, the discussion of the results and the summary are given in section 5.

2 Instrumentation and data products

This study is based on thermodynamic and cloud measurements from a set of passive and active remote sensors continuously running at the AWIPEV observatory, operated by the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI) and the French Polar Institute Paul Emile Victor (PEV). Within the Transregional Collaborative Research Center ~~(TR~~ TRR 172 ~~) project “Arctic Amplification : Climate Relevant Atmospheric and Surface Processes, and Feedback Mechanisms (AC)^3” (Wendisch et al., 2017),~~ on Arctic Amplification ((AC)^3; Wendisch et al., 2017), the instrumentation at AWIPEV ~~observatory~~ was complemented with a Doppler cloud radar ~~since~~ in June 2016. The analyzed period ranges from June 2016 to October 2018, when continuous cloud radar observations were available at AWIPEV observatory. In addition to ground-base observations, we also used a number of observation and modeling products characterizing clouds, air transportation, and radiation budget. Most of instrumentation and products are the same as in Nomokonova et al. (2019) and, therefore, only briefly described in ~~this study~~the following section.

2.1 Microwave radiometer observations

The humidity and temperature profiler (HATPRO; Rose et al., 2005) has been ~~operating~~ operated at the AWIPEV station since 2011. HATPRO is a fourteen-channel microwave radiometer that measures brightness temperatures (TB) at K-band (22.24-31.40 GHz) and at V-band (51.26-58 GHz) frequencies with a temporal resolution of 1-2 s. The TBs measured at K-band are used for retrievals of the integrated water vapor (IWV), liquid water path (LWP) and humidity profiling. The V-band channels are located along the oxygen absorption complex at 60 GHz and are used for vertical temperature profiling. For this study we used temperature profiles, IWV, and LWP retrieved as described in Löhnert and Crewell (2003). The retrievals were recently adapted for an operation at Ny-Ålesund (Nomokonova et al., 2019). HATPRO measures continuously but cannot provide reliable information during rain conditions when the radome of the instrument is wet. In these cases, data are flagged and excluded from the analysis.

2.2 Ceilometer

Since 2011 a Vaisala ceilometer CL51 has been operated at the AWIPEV observatory (Maturilli and Ebell, 2018). The ceilometer emits pulses at 905 nm wavelength and measures atmospheric backscatter with a temporal resolution of about 10 s and a vertical resolution of 10 m. The maximum profiling range is 15 km.

The ceilometer is sensitive to the surface area of the scatterers and is thus strongly affected by high concentrations of particles like cloud droplets and aerosols (Hogan et al., 2006). On the one hand, it is thus well suited to detect liquid layers and cloud base heights. On the other hand, the near-infrared signal is significantly attenuated by liquid layers. Therefore, the ceilometer often cannot detect cloud particles above the lowest liquid layer when optical depth exceed a value of around 3. Therefore, for this study we used a cloud base height which is the lowest altitude of cloud boundary detected by ceilometer.

2.3 Cloudnet products

The Cloudnet algorithm suite (Illingworth et al., 2007) running at Ny-Ålesund combines observations from a Doppler cloud radar, Vaisala ceilometer CL51 (Maturilli and Ebell, 2018), HATPRO, and thermodynamic profiles from a NWP model.

In this study we used the target categorization, which is a standard product of Cloudnet. This product has a temporal and vertical resolution of 30 s and 20 m, respectively. The Cloudnet categorization was used for the cloud classification as described in Nomokonova et al. (2019). In addition, based on the target categorization for cloud regions with ice particles we calculated the ice water content (IWC) based on radar reflectivity factor Z and environment temperature according to Hogan et al. (2006). More detailed description of the used Cloudnet products and their uncertainties is given in Nomokonova et al. (2019).

2.4 Radiosonde observations

Radiosondes at the AWIPEV station have been launched at least once per day since 1993 (Maturilli and Kayser, 2017a). The radiosonde data since June 2006 have been routinely processed by GRUAN version 2 data processing algorithm (Sommer et al., 2012; Matu . More details on the radiosonde dataset can be found in Maturilli and Kayser (2016, 2017b). In the present study the radiosonde data for the period from 1993 to 2018 were used to analyze the long-term changes in IWV. Values of IWV retrieved from MWR were compared with ones derived from radiosondes for the period from 2011 to 2017 when both observations were available. IWV from MWR was averaged over 15 min interval after radiosonde launch. The results of the comparison are shown in the supplement material (Fig. S1) and are in a good agreement with the root mean squared difference of 0.56 kg m^{-2}.

2.5 Surface cloud radiative effect

The surface cloud radiative effect (denoted as CRE throughout the study), which ~~will be~~ were analyzed for the different humidity conditions, was derived from the broadband radiative transfer calculations by ~~?~~ Ebell et al. (2020) with the rapid radiative transfer model RRTMG (Mlawer et al., 1997; Barker et al., 2003) for the analyzed period at Ny-Ålesund. The model provides vertically resolved shortwave (SW) and longwave (LW) up- and downward fluxes and heating rates. In this study CRE is calculated as follows:

$$\text{CRE} = (F_{\downarrow} - F_{\uparrow}) - (F_{\downarrow clr} - F_{\uparrow clr}), \tag{1}$$

where $F_{\downarrow}$ and $F_{\uparrow}$ are down- and upwelling all-sky fluxes at the surface, respectively. $F_{\downarrow clr}$ and $F_{\uparrow clr}$ are surface down- and upwelling fluxes, which would be if the sky were cloud free. LW, SW, and net fluxes from the model are used in Eq. 1 for the calculation of LW, SW, and net CRE, respectively. ~~?~~ Ebell et al. (2020) estimated the uncertainties in CRE using 10-min averaged fluxes observed by the baseline surface radiation network (BSRN). The uncertainties in CRE depend on averaging time. For time periods ranging from days to month, which are analyzed in this study, the uncertainties are estimated to be smaller than 6.4, 2.0, and 6.7 W m^{-2} for SW, LW, and net CRE, respectively.

2.6 Backtrajectories FLEXTRA

In order to analyze which patterns in air transportation are related to episodes of warm/cold and moist/dry conditions at Ny-Ålesund, we used the output of the 3-dimensional FLEXTRA trajectory model version 3.0 (Stohl et al., 1995; Stohl and Seibert, 1998; Stohl, 1998). The calculations of the trajectories are based on ~~data~~ operational analysis data from NWP model of the European Centre for Medium range Weather Forecast (~~EMCWF~~ECMWF) with the initialized analyses every 6 hours ~~and~~ (at 0, 6, 12, and 18 UTC) and horizontal resolution of 1.125°. The temporal resolution of the back trajectories is 3 hours. We used FLEXTRA files (see https://projects.nilu.no//ccc/trajectories/evdc/ for detailed information) generated for the Zeppelin station (78.9°N 11.88°E), the arrival height of 1500 m, and going 6 days back. Since Ny-Ålesund is surrounded by up to 1000-m high mountains, the arrival height of 1500 m altitude was chosen in order to avoid orographic effects in the large scale air transport.

2.7 ~~Radiosonde observations~~

~~Radiosondes at the AWIPEV station have been launched at least once per day since 1993 (Maturilli and Kayser, 2017a). The radiosonde data since June 2006 have been routinely processed by GRUAN version 2 data processing algorithm (Sommer et al., 2012; Matu~~ ~~. More details on the radiosonde dataset can be found in Maturilli and Kayser (2016, 2017b). In the present study the radiosonde data for the period from 1993 to 2018 were used to analyze the long-term changes in occurrence of moist and dry conditions, respectively.~~

3 ~~Identification~~ Definition of periods with increased/decreased moisture and temperature

In this study we analyze 6-hour periods with distinct values of temperature and IWV. ~~Throughout the study periods with decreased and increased values are denoted by "-" and "+" signs prior to a variable symbol, respectively (e.g. "+T" corresponds to periods with increased temperature), while typical values are indicated just by a variable symbol (e.g. "T").~~

In order to decide whether a period is associated with a particularly high (low) value of water vapor and temperature, we use a dataset of 6-hourly mean values of IWV and temperature at 1450 m from HATPRO for the period from 2011 to 2018 (this period is used as reference throughout the study). The 1450 m HATPRO range bin was chosen to account for the large scale transport rather than local effects which are related to the orography around Ny-Ålesund (Maturilli and Kayser, 2017a). This altitude is also the closest to the arrival height of the FLEXTRA back trajectories. Since the atmospheric conditions vary throughout a year, we calculated the 10th and 90th percentiles of the temperature and IWV for each month using the reference dataset (Fig. 1). The percentiles of IWV and 1450 m temperature are used as thresholds for the event classification. If a 6h-period has a mean IWV value below the 10th or above the 90th percentile it is considered as dry ("-IWV") or moist ("+IWV"), respectively. Otherwise it is assumed that the value of water vapor of this period is normal ("IWV"). Similarly, the 1450 m temperature periods "-T" and "+T" ~~correspond to a period with an average 1450 m temperature below the 10th or above the 90th percentile, respectively~~were defined. As many studies consider water vapor as a driver of changes in radiative properties of the Arctic atmosphere, we use IWV as an indicator of anomalous periods. ~~Typical periods corresponding to the~~ A normal period is denoted as "IWV" ~~class are further denoted as normal. An~~ and an anomalous period is one with "-IWV" (dry anomaly) or "+IWV" (moist anomaly), regardless which temperature class the period has. ~~In addition we also analyze periods when the water vapor anomalies are supported by temperature anomalies, i.e. classes "-T -IWV" and "+T +IWV".~~

~~Since the anomalies in temperature and IWV are often driven by certain weather patterns which are related to the~~

4 Results and discussion

4.1 Consistency check of the defined anomaly periods with existing studies

A number of studies have shown that positive and negative anomalies in IWV often result from horizontal transport of air masses ~~coming from lower or higher latitudes(Maturilli and Kayser, 2017a; Dahlke and Maturilli, 2017; Mewes and Jacobi, 2019; Wu, 201~~
~~, we analyzedback trajectories for all dry and moist anomalies~~from mid- and Arctic latitudes, respectively (Maturilli and Kayser, 2017a; Dal
. Therefore, in order to evaluate the definition of anomalous conditions at Ny-Ålesund given in Sec. 3, paths of air masses were analyzed. We identified all 6-hourly periods with an anomaly class within the analyzed period and found FLEXTRA back trajectory files with corresponding reaching time. Figure 2 shows 6-day-trajectories with the end point in Ny-Ålesund for "-IWV" and "+IWV" anomalies in different seasons. 6-day trajectories are sufficient to capture the air transportation to the Arctic. ~~Graversen (2006) found a correlation between intensity of the atmospheric northward energy transport across 60°N and the Arctic warming/cooling with the time lag of about 5 days.~~ As expected, the occurrence of moist anomalies ("+IWV", red lines in Fig. 2) is associated with the air transport from the south, while the dry anomalies ("-IWV", blue lines in Fig. 2) related to the air coming from the north. There is a slight difference between the seasons. In winter ~~and spring,~~ (December, January and February) and spring (March, April and May), dry air typically ~~circulates counterclockwise,~~ comes from North of Russia over the North Pole region and northern Greenland. Mewes and Jacobi (2019) have shown that ~~this kind of circulation~~ a similar horizontal air mass transport happens when air from the North Pacific flows into the Arctic. In summer ~~,~~ (June, July and August), dry anomalies are ~~mostly~~ associated with air coming from ~~northern~~ the northern part of Canada and Greenland. In autumn ~~, there are two distinct pathways, from south-east and west, although the "-T -IWV" anomalies are related to air coming predominantly from the west (not shown)~~(September, October and November) during dry anomalies air masses come from the areas north of Greenland and Russia. Wet anomalies are mostly driven by the air advected from the North Atlantic. In autumn and summer, a ~~significant~~ large part of moist events originates ~~in~~ from the Scandinavian region and Barents sea. The transport pathways for "-T -IWV" and "+T +IWV" events (not shown) are in general similar to those of "-IWV" and "+IWV", respectively, which is in agreement with the results found by Mewes and Jacobi (2019), who showed that the air transport from the North Atlantic sector is typically associated with ~~the~~ a positive temperature anomaly, while the transport from Siberia and the North Pacific is connected to a negative temperature anomaly in the Arctic.

Table 1 summarizes the occurrence of different types of periods for the analyzed period from June 2016 to October 2018. The occurrence of moist anomalies in winter and summer for the analyzed period is nearly the same as for the reference period, when, according to our definition, the occurrence of moist and dry anomalies was 10%. In spring and autumn the occurrence is 8 and 14.2%, respectively. The increase in occurrence of moist anomalies during the polar-night season of 2016-2017 was recently reported by (Hegyi and Taylor, 2018). The authors analyzed the whole Arctic region and related the increase to more frequent moisture intrusions from the Atlantic and Pacific regions. Our results show that the occurrence of dry anomalies is about 8% for winter and autumn. In spring and summer, dry anomalies were observed about 13% of time. Periods with "+T +IWV" anomaly take a major part (about 67%) of all moist anomalous cases (not shown). In contrast, occurrence of "-T -IWV" periods is only about 35% of all dry anomalies in all seasons except winter, when the occurrence is almost 90% (not shown). Thus, the dry anomalies are not regularly accompanied by a negative anomaly in temperature, while the opposite is valid for moist anomalies. Since the number of cases for temperature anomalies ("+T +IWV" and "-T -IWV") is relatively low these types of anomalies were not considered for the further analysis.

4.2 Cloud occurrence and phase

5 ~~Results and discussion~~

In this section we show how the anomalous conditions are related to cloud ~~macro- and microphysical parameters such as occurrence, type, phase partitioning, and liquid and ice water path (IWP) and cloud radiative properties. For the characterization of clouds we apply the cloud detection and classification method based on Cloudnet that was previously described in Nomokonova et al. (20~~ ~~. Note, that the method is applied on Cloudnet profiles with no liquid precipitation.~~

4.1 ~~Cloud occurrence~~

occurrence. Figure 3 shows the frequency of occurrence (FOC) of different cloud types during anomalous and normal conditions. Clouds are present in 70–80% of cases with normal values of IWV. Among them about a half are multi-layer clouds.

In dry anomalous events, the FOC of clouds ~~is in general lower and~~ ranges from 26% in spring to 70% in summer. The decrease in FOC of clouds is mostly caused by less frequent multi-layer clouds (MC), whose occurrence in "-IWV" conditions drops by a factor of 2 to 4. ~~During spring and autumn clouds are about a factor of two more frequent during "-T -IWV" events than in "-IWV" cases. The enhanced FOC of clouds may be due to a higher probability of cloud particle formation at lower temperatures for a given amount of water vapor. Nevertheless, during winter and summer there is less difference in cloud occurrence between "-IWV" and "-T -IWV" events.~~

~~Unexpectedly high occurrence of clouds (∼92%) was found during "-T -IWV" episodes in autumn. We found that all "-T -IWV" events in autumn occurred from 26 to 30 September 2018. Such a short time period would probably not be representative for autumn "-T -IWV" cases if a longer dataset were analyzed. According to the FLEXTRA back trajectories for this time period, air was primarily transported from the northern Greenland area. As it will be shown below, the "-T -IWV" episodes in~~

~~autumn were also characterized by LWP and IWP values exceeding those under normal conditions. A deeper understanding of this phenomenon requires further investigations, which are out of the scope of this study.~~

Higher availability of water vapor ("+IWV") leads to an increase in FOC of clouds up to 90–99%. The increase is mostly caused by changes in MC, while the FOC of single-layer clouds (SC) is not much affected. ~~As it was mentioned in Sec. 3, moist anomalies are often accompanied by positive temperature anomalies. Therefore, differences in cloud occurrence between "+IWV" and "+T +IWV" events are small. Our findings are in agreement with the study by Gallagher et al. (2018) for Greenland. They showed that during atmospheric circulations associated with increased (decreased) moisture, the number of clear sky scenes reduces (increases).~~

4.1 ~~Cloud phase~~

~~Cloud ice and liquid have distinct microphysical properties. For instance, the size of ice particles is in general larger than for liquid droplets while the latter have a higher number concentration (Korolev et al., 2003). Ice particles can have a large variety of shapes (Bailey and Hallett, 2009). In addition, liquid water and ice have different dielectric properties (Ray, 1972). Thus, the~~

Since the phase composition of clouds affects SW and LW radiative properties of clouds ~~(?). Therefore~~(Ebell et al., 2020), we also analyzed the occurrence of different types of hydrometeors in the atmospheric column (Fig. 4).

In general, profiles with liquid phase (sum of green and orange columns in Fig. 4) occur more often during moist periods and less often during dry periods. The FOC of liquid containing profiles during "+IWV" and "-IWV" was characterized by the change of more than +30 and -30% relative to normal conditions. ~~Only in~~ In summer the increase in FOC of liquid containing profiles between moist and normal periods is less pronounced (8%). The increase in FOC of clouds in "+IWV" events was mostly related to higher occurrence of MC. ~~FOC of liquid containing clouds during "+IWV +T" and "-IWV -T" anomalies do not differ much from the corresponding water vapor anomalies in all seasons except autumn, when all events corresponded to the single continuous 5-day episode with air masses transported from northern Greenland mentioned in Sec. 4.2.~~

Ice containing profiles (sum of blue and green columns in Fig. 4) occur more often under "+IWV" ~~and "+IWV +T"~~ conditions and less during "-IWV"~~and "-IWV -T"~~. The change in ice containing profiles is mostly defined by the change in profiles with both liquid and ice (green columns in Fig. 4), since FOC of pure ice phase (blue columns in Fig. 4) varies only slightly with change in IWV. Profiles with both liquid and ice phases (green columns in Fig. 4) have the median cloud top height and temperature of 1.6 km and -–15 °C (not shown), respectively. In the case of pure ice profiles (blue columns in Fig. 4) the cloud top height and temperature are 3 km and –31 °C, respectively. Thus, ice-containing clouds occurring at higher altitudes are apparently less affected by IWV anomalies. Gallagher et al. (2018), who investigated the influence of atmospheric circulations on cloud composition in Greenland, similarly showed that moist ~~/dry~~(dry) conditions lead to increase ~~/decrease~~(decrease) in occurrence of mixed-phase clouds, which are the dominant type of liquid containing clouds in the Arctic (Shupe et al., 2006). Gallagher et al. (2018) also noted that ice clouds are not constrained by circulation types to the same degree as mixed-phase clouds.

4.1 Liquid and ice water path

Moist and dry anomalies influence not only the cloud occurrence and composition but also water content. We therefore link LWP and IWP to the different types of anomalies (Fig. 5). Note, that LWP and IWP were only calculated for liquid-containing and ice-containing profiles, respectively. Clear-sky cases were not ~~added for calculations of~~ included in the statistics of LWP and IWP.

Following the changes in occurrence of liquid- and ice-containing clouds, LWP and IWP increase under moist conditions and decrease under dry conditions. "+IWV" anomalies cause an increase in mean LWP by a factor of 1.5–2.0 relative to normal conditions and also increase the variability in LWP. During dry anomalies, LWP is significantly ~~lowered~~ lower and does not exceed 12 and 94 g m^{-2} in winter/spring and summer/autumn periods, respectively. Gallagher et al. (2018) recently showed that atmospheric circulation types associated with enhanced water vapor in Greenland often lead to increased LWP. The authors also showed that the opposite is valid for dry conditions, when decreased values of LWP are more likely. ~~Note, that the unexpected two-fold LWP increase during the "-T -IWV" periods in autumn correspond to the 5-day episode with air mass transported from northern Greenland mentioned in Sec. 4.2.~~

Moist anomalies correspond to an increase in mean IWP by a factor 3 relative to normal conditions in winter and spring, and by a factor of 2 in summer and autumn. In winter and spring, dry conditions decrease mean IWP ~~values~~ by an order of magnitude, which may be related to a strong reduction in occurrence of ice containing clouds and less efficient ice particle growth during "-IWV" events. In contrast, during summer and autumn, mean IWP is reduced by a factor of 1.3.

Thus, the results reveal a strong impact of the anomalous periods on LWP and IWP and, in particular in winter and spring. Even though mean IWP values during normal conditions are nearly the same in winter and autumn, relative changes in IWP caused by dry and moist anomalies differ drastically among the two seasons. In winter, wet and dry conditions lead to a 3-fold increase and 10-fold decrease, respectively. In ~~contrast,~~ autumn during wet conditions the increase in ~~autumn is a~~ mean IWP is about factor of 2 and ~~there is almost no~~ during dry conditions the mean IWP does not decrease. Since the anomaly type cannot fully explain this effect, it is probably also related to other factors ~~. One of such factors could be aerosols. Weinbruch et al. (2012); Lange et al. (2018); Jung et al. (2018); Wex et al. (2019) have shown that concentration and chemical composition of cloud condensation (CCN) and ice nuclei (IN) also have a seasonal variability in the Arctic region. Dall´Osto et al. (2018) and Lange et al. (2018) found that accumulated aerosol mode is dominant in winter season, while in summer ultrafine aerosol population becomes more abundant. Jung et al. (2018) showed that~~ such as differences in aerosol load, impact of local effects due to the surrounding orography, and an influence of the ocean. For instance, the seasonal change in the aerosol type affects the activation ability of CCN and IN efficiency in the Svalbard region ~~and found the highest activation efficiency in winter and lowest in summer, with intermediate values in spring and autumn. Wex et al. (2019) investigated the annual cycle of IN particles in different Arctic regions. The authors found that IN concentration is often an order of magnitude higher in summer and autumn than in winter and spring~~which in turns influence the cloud formation. In addition, the reduction in sea ice around the Svalbard archipelago and on the fjords may lead to more evaporation and therefore, affect cloud conditions. Since Ny-Ålesund is surrounded by mountains up to 800 m, the air flow is influenced by the local orography in the lowest 1 km altitudes (Maturilli and Kayser, 2017a) and thus might have an impact on cloud formation and on cloud properties. Note, that within this study ~~aerosols are~~ the influence of local effects and aerosols is not analyzed.

4.2 Surface cloud radiative effect

In the previous sections, we showed ~~the changes of cloudiness and~~ that water vapor anomalies affect cloudiness and the amount of liquid and ice in a column ~~under various atmospheric states. Liquid-containing and pure ice clouds have a different impact on the radiation budget at~~ which will also influence the CRE at the surface at Ny-Ålesund~~(?) and occurrence of these types of clouds varies for dry and moist conditions. Therefore, we also estimated the surface CRE under different atmospheric conditions.~~. Figure 6 summarizes the surface SW, LW, and net CRE for different anomaly periods.

Values of LW CRE at Ny-Ålesund from June 2016 to October 2018 are in the range from 0 to 85~~and correlate~~ W m^{-2} and agree with the cloud occurrence and amount of liquid in a column ~~(?)~~(Ebell et al., 2020). The large variability of LW CRE distributions (Fig. 6a) is explained by their bimodality (Shupe and Intrieri, 2004): clear sky cases and profiles with ice only are characterized by no or low LW CRE, while for liquid containing clouds LW CRE is typically high with values from 50 to 85 W m^{-2} ~~(?)~~(Ebell et al., 2020). The upper limit of LW CRE corresponds to clouds with LWP $>$ 50 g m^{-2} and/or IWP $>$ 150 g m^{-2} ~~(Miller et al., 2015; ?)~~(Miller et al., 2015; Ebell et al., 2020).

During moist anomalies the mean LW CRE increased to 60–70 W m^{-2} in winter, spring, and autumn. Thus, the mean LW CRE, enhanced under moist anomalies in winter, spring, and autumn, can exceed the typical mean LW CRE in summer (Fig. 6b, white box). This increase in mean LW CRE due to moist anomalies in winter, spring, and autumn is associated with high cloud occurrence, which mostly exceeds 90% under moist conditions. In addition "+IWV" cases are typically characterized by high mean LWP and IWP exceeding 90 and 200 g m^{-2}, respectively. In contrast to other seasons, in summer the mean LW CRE during moist anomalies ~~becomes lower~~ is not higher than under normal conditions ~~. This effect~~ due to several factors. First, cloud occurrence does not change much between normal and moist conditions in summer. Second, in summer clouds often emit LW radiation as black bodies and therefore, an increase in LWP and/or IWP does not essentially affect their LW radiation. Moreover, a similar LW CRE in summer between moist and normal conditions may be caused by influence of water vapor in presence of optically thick clouds as was previously described by Cox et al. (2015). The authors ~~found that~~ analyzed data from radiative transfer simulations and observations obtained at Barrow, Summit and Eureka. They found that the increase in amount of atmospheric water vapor particularly between a cloud and the surface diminishes the impact of the infrared radiance emitted from the cloud due to more absorption and emission by water vapor itself. They showed that at constant temperature for higher relative humidity LW CRE is typically lower ~~. ?~~ because of less emission by clouds passes to the surface through the atmosphere below the clouds. Ebell et al. (2020) identified a similar effect at Ny-Ålesund, where the decrease in LW CRE at the surface for higher IWV corresponds to clouds with LWP exceeding 300 g m^{-2}. In general, relative humidity at Ny-Ålesund is high in summer (Maturilli and Kayser, 2017a; Nomokonova et al., 2019). Moreover, in "+IWV" cases we would expect even higher values of relative humidity~~, since on average there are no positive temperature anomalies relative to normal conditions~~.

Dry anomalies correspond to a reduction of the mean LW CRE to 5–11 W m^{-2} in winter and spring and to 29–32 W m^{-2} in summer and autumn. Hence, the dependence of the mean LW CRE on IWV is more pronounced in winter and spring than in autumn and especially in summer. Such a behavior though is not directly related to changes in IWV itself but rather to coupling of the changes in IWV to cloud properties. As it was previously shown, dry anomalies are associated with reduced cloud occurrence, amount of liquid-containing clouds, LWP, and IWP, while increased values of these parameters are related to moist periods. In summer the cloud properties ~~do not show as strong change~~ during dry anomalies do not change as strongly with respect to normal conditions ~~as in~~ compared to other seasons, which may reflect into the smaller corresponding change in LW CRE.

Besides the influence of cloud occurrence and microphysical properties, the LW CRE also depends on altitude at which clouds occur. Shupe and Intrieri (2004); Dong et al. (2010) showed that the LW CRE increases with decreasing cloud base height (CBH). Shupe and Intrieri (2004) show that Arctic clouds with bases below ~~and above~~(above) 3 km have median LW CRE around 45 ~~and~~ (20) W m^{-2}~~, respectively~~. Figure 7 shows CBH measured by the ceilometer for the analyzed period. Note, that due to the instrument limitations (see section 2.2), which are related to the attenuation of the ceilometer signal in optically thick clouds, only the lowest CBH was taken into account. Throughout a year, CBH is mostly below 2 km. During moist and dry anomalies CBH either does not change or slightly decreases, which may cause an increase in LW CRE. ~~Although~~However, Yeo et al. (2018), who analyzed the dependence of LW fluxes measured at Ny-Ålesund on CBH, showed that the mean LW CRE of clouds within the lowest 2 km does not differ by more than 10 W m^{-2}. Only dry anomalies in spring and moist anomalies in summer are related to higher CBH. Taking into account low cloud occurrence during dry conditions in spring the increase in CBH should not change LW CRE much. In summer the increase in CBH during moist conditions could be another factor (in addition to the effect of water vapor described above) preventing an increase in LW CRE.

The SW CRE is only significant when the sun is above the horizon. Thus, the strongest SW CRE can be found in summer. Under normal conditions in summer and spring the mean SW CRE is -115 and -19 W m^{-2}, respectively. An absolute change in $\mathrm{CRE}_{\mathrm{SW}}$ can in general be caused by three main factors: cloud properties, solar zenith angle (SZA), and surface albedo (α). ~~The~~ Since FOC of clouds, LWP, and IWP vary only slightly, the 6-fold difference in the mean SW CRE in spring and summer ~~might be~~ is rather associated with the changes ~~only~~ in surface albedo and SZA ~~, since FOC of clouds, LWP, and IWP vary onlyslightly~~only.

A number of studies have already shown that the surface albedo ~~under clear sky and cloudy conditions~~ can alter the SW CRE at the surface ~~(Shupe and Intrieri, 2004; Miller et al., 2015; Miller et al., 2017; ?). ?~~ (Shupe and Intrieri, 2004; Miller et al., 2015; Miller et . Ebell et al. (2020) found that at Ny-Ålesund the surface albedo ~~(ratio between upward and downward SW fluxes at the surface retrieved by the RRTMG)~~ exceeds 0.8 when the surface is covered by snow and is below 0.15 in bare tundra. For the analyzed period, the change in the mean surface albedo between normal conditions and anomalies does not exceed ±0.05 in spring and ±0.1 in summer and autumn. Shupe and Intrieri (2004) showed that SW CRE is nearly proportional to $1-\alpha$. The changes in SW CRE between normal and anomalous conditions caused by the variability in the surface albedo ~~do not~~ should thus exceed 30% in spring and 15% in summer and autumn.

In addition to the surface albedo, the SW CRE at the surface depends on SZA (Minnett, 1999; Miller et al., 2018). ~~?~~ Ebell et al. (2020) showed that in Ny-Ålesund the lowest SZA, which corresponds to the highest position of the sun, is in summer with the minimum of 55° in June. In spring values of SZA are larger. Shupe and Intrieri (2004) have found that for

SZA higher than 70° the shortwave cooling effect of clouds decreases due to a rapid decrease of solar insolation. When the sun is high in the sky, the shading effect of the clouds becomes stronger (Shupe and Intrieri, 2004).

There are two ways SZA can influence differences in SW CRE between anomalous and normal cases: (1) an anomaly can have a dominant daytime of occurrence, while normal conditions are uniformly distributed over a day, and (2) an anomaly can concentrate in a certain part of a season. In order to check for changes in SW CRE between anomalous and normal cases caused by diurnal cycles of SZA we checked whether anomalies have a dominant time of occurrence. We found that for the analyzed period normal and anomalous cases were nearly uniformly distributed among 6-hourly periods (Fig. S2, supplement material) and therefore time of a day is neglected in the following analysis. In order to mitigate the remaining effects of SZA due to the sparse distribution of anomalies over seasons we adopt the approach of Sengupta et al. (2003) and calculate the normalized SW CRE at the surface:

$$\mathrm{nCRE}_{\mathrm{SW}} = \frac{\mathrm{CRE}_{\mathrm{SW}}}{F_{\downarrow\mathrm{clr,SW}} - F_{\uparrow\mathrm{clr,SW}}}, \qquad (2)$$

where $\mathrm{CRE}_{\mathrm{SW}}$ is the surface SW CRE, and $F_{\downarrow\mathrm{clr,SW}}$ and $F_{\uparrow\mathrm{clr,SW}}$ are down- and upwelling SW fluxes at the surface that would be if the sky were cloud free. Since the effects of SZA are mitigated in $\mathrm{nCRE}_{\mathrm{SW}}$, the variability in mean $\mathrm{nCRE}_{\mathrm{SW}}$ for different anomalies is mainly determined by the cloud properties and the surface albedo.

~~Under~~ Table 2 shows that under normal conditions the mean $\mathrm{nCRE}_{\mathrm{SW}}$ is ~~-0.2 and -0.45~~ –0.31 and –0.59 in spring and summer, respectively. Dry conditions increase the mean $\mathrm{nCRE}_{\mathrm{SW}}$ to ~~nearly 0 and -0.2~~ –0.4 and –0.1 in spring and summer, respectively. In moist events the mean $\mathrm{nCRE}_{\mathrm{SW}}$ decreases below –0~~.4. Since the effects of SZA are mitigated in $\mathrm{nCRE}_{\mathrm{SW}}$, the variability in mean $\mathrm{nCRE}_{\mathrm{SW}}$ for different anomalies is mostly defined by cloud properties and the surface albedo.~~ .6.

The relative change in $\mathrm{CRE}_{\mathrm{SW}}$ is ~~unsusceptible~~ insusceptible to differences in SZA but only when anomaly cases are uniformly distributed over a season. ~~For anomaly cases~~ If anomaly cases are uniformly distributed over a season~~we also~~ , we expect no difference in surface albedo between anomaly and normal conditions. Thus, similar relative changes in $\mathrm{CRE}_{\mathrm{SW}}$ and $\mathrm{nCRE}_{\mathrm{SW}}$ and near-zero change in the surface albedo indicate similar SZA ~~and surface albedo~~ conditions for anomaly and normal cases~~, while the diversion~~. In contrast, if anomaly cases are distributed not uniformly over a season the diversion of changes in $\mathrm{CRE}_{\mathrm{SW}}$ and $\mathrm{nCRE}_{\mathrm{SW}}$ would show that anomaly cases were sparsely distributed over a season.

In Table 2 we summarize changes in $\mathrm{CRE}_{\mathrm{SW}}$, $\mathrm{nCRE}_{\mathrm{SW}}$, and the surface albedo related to dry and moist anomalies. The results show that dry cases are related to positive absolute changes in SW CRE, thus pointing to less efficient SW surface cooling by clouds relative to normal conditions. The largest difference of 67.2 W m^{-2} is in summer, when the cloud can produce the strongest SW shading ~~(Shupe and Intrieri, 2004; ?)~~(Shupe and Intrieri, 2004; Ebell et al., 2020). In spring and summer $\mathrm{CRE}_{\mathrm{SW}}$, $\mathrm{nCRE}_{\mathrm{SW}}$ change by nearly the same factor and the absolute change in the surface albedo does not exceed 0.05. Similar relative changes in $\mathrm{CRE}_{\mathrm{SW}}$, $\mathrm{nCRE}_{\mathrm{SW}}$ and near-zero absolute change in the surface albedo indicate that the difference in the mean SW CRE is mainly caused by changes in cloud properties and not by SZA. In autumn $\mathrm{CRE}_{\mathrm{SW}}$ changed by –94% while $\mathrm{nCRE}_{\mathrm{SW}}$ changed by –60%. The difference in the relative changes indicates that it is caused by differences in SZA because dry autumn cases were not uniformly distributed over the season. The absolute change in the surface albedo was 0.45. Thus, the difference in SW CRE between dry and normal cases ~~under dry conditions~~ in autumn were caused by all three factors, i.e. cloud properties, SZA, and the surface albedo. The direction of the changes in CRE_{SW} is consistent with Shupe and Intrieri (2004), who showed that an increase in the surface albedo corresponds to a reduction in the cloud induced surface SW cooling.

During moist anomalies SW CRE is more negative than for normal conditions. In summer the relative changes in CRE_{SW} and nCRE_{SW} are ~~close~~ similar and the surface albedo is not altered by more than 0.06. Therefore, we conclude that the change in the mean SW CRE of –25.6 W m^{-2} is mainly caused by cloud properties. In spring and autumn during moist conditions the absolute change in the surface albedo is also relatively low. Nevertheless, the relative changes in CRE_{SW} and nCRE_{SW} differ. This indicates that the absolute change in the mean SW CRE is likely caused not only by cloud properties but also by SZA.

Gallagher et al. (2018) showed an effect of moist and dry anomalies on CRE. The authors analyzed the Summit site in Greenland, where typical IWV values are in the order of 1–3 kg m^{-2} (Pettersen et al., 2018) ~~, which is drier than at the~~ and thus smaller than at Ny-Ålesund ~~station~~ (see Fig. 1). Gallagher et al. (2018) used data from 2011 to 2015. The authors found that the southern transport pattern, associated with increase in IWV by 0.69 kg m^{-2}, leads to a change in LW and SW CRE of +13 and –3 W m^{-2}, respectively, relative to corresponding typical values. Since Gallagher et al. (2018) did not analyze seasons separately, in order to compare the results, we also averaged our results over the whole analyzed period. For Ny-Ålesund we found mean differences between "+IWV" and "IWV" for LW and SW CRE of +21.2 and -10.2 W m^{-2}, respectively. In contrast, a northern circulation pattern in Greenland leads to a decrease in IWV by 0.34 kg m^{-2} and changes LW and SW CRE by -6.1 and 0.1 W m^{-2} (Gallagher et al., 2018), respectively. Our results for Ny-Ålesund are -21.5 and 21.6 W m^{-2}, respectively. Note, that the absolute values may differ because of more humid environment in Svalbard or differences in cloud properties. Nevertheless, the sign of the LW CRE change is the same. SW CRE values are difficult to compare due to ~~and possible~~ differences in SZA and surface albedo. For instance, the change in SW CRE at the Summit station could be closer to 0 due to the high albedo in Greenland throughout a year, while at Ny-Ålesund the surface albedo is less than 0.15 in summer ~~(?)~~(Ebell et al., 2020).

Figure 6c depicts ~~a relation of~~ the net CRE ~~to~~ for the anomaly types. As was reported by Curry et al. (1996), due to the absence of sunlight in the Arctic region during the polar night the LW CRE is dominant and the Arctic clouds warm the surface. Therefore, the mean net CRE in autumn and winter is mostly defined by LW CRE. ~~Influences of water vapor anomalies have been previously discussed in details.~~

In summer and spring, both LW and SW contribute to the mean net CRE resulting in -71.5 and 24.7 W m^{-2} under normal conditions, respectively. Dry conditions correspond to less positive LW and less negative SW CRE, which lead to the mean net CRE of -19 and 4.3 W m^{-2} in summer and spring, respectively. During moist periods LW CRE increases relative to normal conditions in spring and does not change much in summer, while SW CRE becomes more negative in both seasons. Thus, the mean net CRE under moist conditions in spring changes to 31.5 W m^{-2} and to –101 W m^{-2} in summer.

4.3 Trends in anomaly occurrence

Since IWV anomalies show a strong impact on cloud properties and their radiative effect, the next question is how the occurrence of dry and moist conditions at Ny-Ålesund has changed in the last decades. The MWR observations at Ny-Ålesund are only available since 2011, and, therefore, cannot be used for such a long-term analysis. Instead, the radiosonde observations were used for the estimation of the occurrence of "-IWV" and "+IWV" events for the time frame from 1993 to 2018. Note, that 6-hour averaged values of IWV from MWR used for the previous analysis cannot be obtained from radiosondes. Therefore, we ~~estimate~~ estimated the IWV value for each radiosonde profile and ~~classify~~ classified the profile using the thresholds defined in Sec. 1 ~~. Even though, results obtained from a radiometer would probably have been slightly different, the radiosondes still show a tendency in the IWV anomalies.~~ based on MWR data. The representativeness and variability of IWV values obtained from MWR for the reference period from 2011 to 2018 was checked with respect to the long-term radiosonde record. The monthly values of IWV derived from radiosondes for the periods from 1993 to 2018 and from 2011 to 2018 were compared with ones derived from MWR HATPRO. The results are in a good agreement and summarized in Fig. S3 in the supplement material. The monthly IWV for the longer period (1993-2018) is closer to the one from MWR HATPRO period with root-mean squared difference (RMSD) of the 10th and 90th percentiles of 0.6 and 0.5 kg m^{-2}, respectively. Slightly higher monthly values of IWV from radiosondes were found for the same period as for MWR HATPRO (2011-2018) with RMSD of 0.4 and 1.2 kg m^{-2} for 10th and 90th percentiles, respectively.

Figure 8 shows ~~changes in anomaly occurrences.~~ the frequency of occurrence of moist and dry anomalies for each season for the time period from 1993 to 2018. According to a two-sided t-test, dry and moist anomalies in all seasons show significant trends with the 95% confidence level except for moist anomalies in spring. Dry anomalies have significant negative trends in all seasons, which are especially pronounced in autumn and winter with values of -10.7 and -12.9% decade^{-1}, respectively. ~~About a half of the profiles in autumn and winter of 1993 corresponded to dry anomalies.~~ These trends might be associated with changes in atmospheric circulation found by Dahlke and Maturilli (2017) for the Svalbard region. The frequency of occurrence of of dry events in spring and summer also exhibit negative trends but ~~the decrease of their occurrence is at lower~~ at less strong rates of –6.8 and –4% decade^{-1}, respectively. The ~~highest rate of~~ largest positive trends for "+IWV" cases ~~were~~ was found for winter and autumn with ~~slopes~~ values of 5.6 and 6.4% decade^{-1}, respectively. Our results are in line with Mewes and Jacobi (2019), who showed that in winter the occurrence of North Atlantic and North Pacific pathways has increased and decreased, respectively. The North Atlantic and North Pacific air transports are associated with increased and decreased surface temperature and IWV in the Svalbard region (Dahlke and Maturilli, 2017).

~~Taking into account the link between anomaly types, cloud properties, and CRE (Figs. 3–6), we conclude that during the last 25 years the changes in~~

In addition to the influence of air mass transport toward Svalbard region, changes in sea-ice coverage around the archipelago of Svalbard might also impact the occurrence of moist and dry events. During summer and autumn the sea ice coverage is the lowest which can lead to enhanced evaporation and latent heat exchange between the ocean and the Arctic atmosphere. However, the ~~occurrence of dry and moist anomalies at~~ largest sea ice loss rate over Svalbard has been observed in winter (Isaksen et al., 2016). Beside the changes of the sea ice coverage around the Svalbard archipelago a reduction of the local fjord ice cover has an impact on the local climate (Isaksen et al., 2016; Dahlke et al., 2020) and therefore, might also lead to a change in occurrence of anomalous atmospheric conditions at Ny-Å~~lesund may have lead to an increase in cloud occurrence, LWP, and IWP in all seasons. In turn, this could have enhanced the cloud related surface warming in autumn, winter , and~~

~~spring but produce stronger cooling in summer. If the trends of anomaly occurrence continue in the future, we expect that CRE will become more positive in autumn, winter, and spring and more negative in summer~~lesund.

5 Summary and conclusion

This study is devoted to the analysis of anomalous ~~,~~ atmospheric conditions in terms of IWV ~~and temperature at 1450 m altitude, atmospheric conditions at~~ at Ny-Ålesund. The main focus is on the impact of anomalous moisture conditions on cloud properties and their CRE. Within this work, anomalies are defined as a deviation of 6-hour averaged IWV and/or temperature below and above 10th- and 90th percentile of the corresponding parameter over the reference period from 2011 to 2018. Different anomaly types were related to air flows using back-trajectories FLEXTRA and cloud observations from Cloudnet. The output of the rapid radiative transfer model recently applied by ~~?~~ Ebell et al. (2020) to the Ny-Ålesund observations was used to associate the anomaly types to a variation in CRE.

~~A number of studies on anomalous conditions in the Arctic concentrate only on moist intrusions and/or cover only the winter season (Woods and Caballero, 2016; Graversen and Burtu, 2016; Johansson et al., 2017; Hegyi and Taylor, 2018). In this study we focus not only on warm and moist events, but also on dry and cold anomalies, which have recently been shown to have an impact on the Arctic climate (Sillmann et al., 2013; Collins et al., 2013; Kanno et al., 2019). The study also covers all seasons since, for example, surface melt and ice freeze-up in transition periods strongly depend on anomalies in temperature and water vapor (Mortin et al., 2016; Hegyi and Taylor, 2018). The~~ The main findings of this work are listed below:

~~(1) The periods of positive and negative anomalies in temperature and water vapor are correlated with large-scale air transport. Most of the moist events are associated with air flow~~

Moist events often occur when air masses come from the North Atlantic ~~, while dry periods are mainly caused by air circulating in the Arctic region. This finding~~ which is in agreement with previous studies (Maturilli and Kayser, 2017a; Dahlke and Maturilli, 2017; Wu, 2017; Mewes and Jacobi, 2019). An analysis of seasonal variability of transport pathways shows that in autumn and summer~~a significant~~, a large part of moist events originates from the Scandinavian region and Barents sea. ~~In winter and spring dry conditions were associated with counterclockwise air circulations over the North Pole region. This is in agreement with the results from Mewes and Jacobi (2019), who showed that in winter this type of circulation is related to the North Pacific pathway, which causes cold anomalies for the Svalbard region. In autumn, two distinct pathways, leading to dry conditions at Ny-Ålesund, have been found: from South-East and West. The latter brought the 5-day "-T -IWV" episode observed from 26 to 30 September 2018 with unexpectedly high (typically the FOC of cloud is low during dry anomalies) occurrence of clouds.~~

~~(2)~~ 67% of moist anomalies at Ny–Ålesund are accompanied by a strong temperature increase~~, while only 43% of dry cases correspond to cold anomalies~~.

~~(3) Anomalies in IWV correlate with FOC of clouds. In general, dry anomalies are related~~

Moist anomalies are associated with more cloud related surface SW cooling which is increased by 25 W m^{-2} compared to normal conditions in spring and summer. In winter, spring and autumn the mean LW CRE raises from 35–41 W m^{-2} under normal conditions to ~~cloud occurrence ranging from 26% in spring to 70% in summer, which is on average more than 30% lower than during normal conditions . We found, that dry conditions also show FOC of multi-layer clouds decreased by a factor of 2 to 4. Although, for autumn and spring FOC of clouds was 2 times higher for "-T -IWV" eventsthan for "-IWV" cases, which is probably due to higher likelihood of cloud particle formation at lower temperatures for a given amount of water vapor. During the moist periods, the FOC of clouds increases~~ 64-71 W m^{-2} during moist events. The changes in LW and SW CRE are related to a high cloud occurrence of up to 90–99%. ~~This increase is mainly caused by more frequent multi-layer clouds while FOC of single-layer clouds is almost not affected. In contrast to dry anomalies, the occurrence of clouds between~~ In addition, in comparison to normal conditions "+IWV" ~~and~~ cases are characterized by an increase in LWP and IWP with a factor of 2–3 and mean values of 90 and 200 g m^{-2}, respectively. In summer, mean LW CRE did not change during "+~~T +~~IWV" ~~events does not show a large difference because most of the time moist anomalies were accompanied by the periods with the positive temperature anomaly.~~ periods relative to normal conditions. Moist anomalies in this season are related only to a slight increase in cloudiness. In addition, a large part of clouds in summer are relatively opaque clouds and, therefore, an increase in LWP does not affect LW CRE.

~~(4) "-IWV" events are characterized~~ Moist conditions increase the mean net CRE at the surface in autumn, winter, and spring by ~~30~~5–37 W m^{-2} with respect to normal conditions. This change is mostly defined by cloud radiative properties in LW, which are related to enhanced cloudiness, LWP, and IWP. In summer the net CRE is dominated by the SW CRE and, therefore, moist conditions show stronger cloud related surface cooling.

Long-term radiosonde observations show that moist anomalies become more frequent. The trend varies for different seasons from 2.8 to 6.4%~~relative decrease in FOC of profiles containing both ice and liquid with respect to normal conditions. This type of profiles becomes 30% more frequent under moist conditions relative to normal conditions. Profiles with only ice or only liquid are affected by water vapor anomalies to a lesser degree.~~ decade^{-1} being the largest in winter.

~~(5) Excess and shortage in water vapor has been found to be correlated with mean LWP and IWP. During winter and spring, "+IWV" events are related to a factor of 2–3 increase in LWP and IWP relative to normal conditions, while dry anomalies lead to a reduction of LWP andIWP by an order of magnitude. For example, during normal conditions the mean IWP in autumn is nearly the same as in winter. Nevertheless, the relative change in mean IWP during dry and moist events in spring does not exceed a factor of 2. Thus, the difference between winter/spring and summer/autumn cannot be explained only by water vapor anomalies and should be related to other feedback processes (e. g. difference in aerosol load, orographic effect, dynamics and etc.). During dry anomalies in summer mean LWPdecrease by a factor of 2, while mean IWPdoes not change much. In autumn mean LWP and IWP increase by 30% during dry anomalies. Under moist anomalies mean LWP and IWP increase by a factor of 1.5 and 2.3, respectively. In autumn LWP and IWP increase by a factor of 2 during moist conditions~~Dry periods in Ny–Ålesund are mainly related to air masses originating from latitudes north of the Arctic Circle, which is consistent with previous studies (Maturilli and Kayser, 2017a; Dahlke and Maturilli, 2017; Wu, 2017; Mewes and Jacobi, 2019). In winter and spring dry conditions are associated with a low pressure system over the Barents sea causing northerly flow to the Svalbard region. This is in agreement with the results from Mewes and Jacobi (2019), who showed that in winter this northerly air mass transport to Svalbard region is related to the North Pacific pathway, which causes cold anomalies for the Svalbard region. Our results show that 43% of dry anomalies at Ny–Ålesund are accompanied by cold anomalies.

~~(6) Dry (moist) anomalies are associated with less (more)~~ Dry anomalies are linked to less cloud related surface SW cooling. In spring and summer during dry anomaly periods, the mean SW CRE ~~was higher. Relative to the normal conditionsthe changes~~ is less pronounced. Compared to normal conditions, changes in SW CRE were 19 and 67 W m^{-2} in spring and summer, respectively. The ~~higher values are~~ weaker SW cooling effect by clouds is associated with lower cloudiness and LWP in dry cases. ~~The difference between~~ Under dry anomalies, cloud occurrence ranges from 26% in spring to 70% in summer, which is on average about 30% lower than during normal conditions. The decrease is mostly caused by the reduction of multi-layer clouds (by a factor of 2 to 4) and particular liquid-containing clouds. However, the difference between mean SW CRE in summer and spring is not only related to changes in clouds but is also caused by the variability of SZA and the surface albedo. ~~During moist periods in spring and summer the cloud related cooling is enhanced by 25 W m^{-2} compared to normal conditions.~~

~~(7) The mean LW CRE~~ The LW warming effect by clouds at the surface is reduced during dry anomalies with respect to normal cases by 25–35 W m^{-2} in winter and spring, and by 11–19 W m^{-2} in summer and autumn~~. In contrast, moist periods are related to an increase of the mean LW CRE in comparison to normal conditions. The increase was observed in all seasons except summer. For instance, in winter, spring and autumn the mean LW CRE raises from 35–41 W m^{-2} under normal conditions to 64-71 W m^{-2} during moist events. Thus, in winter the mean LW CRE during moist periods was even higher than the typical value in summer (51 W m^{-2}). In summer mean LW CRE did not change during "+IWV" periods and decreased by 6 W m^{-2} during "+T +IWV" periods relative to normal conditions. The effect of reduction in LW CRE during warm and moist conditions in summer is consistent with findings by Cox et al. (2015) and **?**.~~

~~(8) Moist conditions increase the mean net CRE at the surface in autumn, winter, and spring by 5–37 W m^{-2} with respect to normal conditions. This change is mostly defined by cloud radiative properties in LW, which are related to enhanced cloudiness, LWP, and IWP.~~ , respectively. Dry conditions reduce the mean net CRE by 2–37 W m^{-2} in autumn, winter, and spring. ~~In summer the net CRE is dominated by the SW CRE and, therefore, moist conditions show stronger cloud related surface cooling.~~ During dry conditions in summer, there is an increase in the mean net CRE by 49 m^{-2}.

~~(9)~~ Long-term radiosonde observations show ~~significant trends in the IWV anomaly occurrence . Moist anomalies are getting more frequent with a slope varying for different seasons from 2.8 to 6.4% decade^{-1}, while occurrence~~ that the occurrence of dry anomalies declines at rates from -12.9 to -4% decade^{-1} ~~. Similar results were found for Greenland in study by Mattingly et al. (2016), which shows that most pronounced increasing moist and decreasing dry IWV patterns were in winter. Since moist and dry anomalies are associated with the North Atlantic and the North Pacific, respectively, our results are consistent with findings of Mewes and Jacobi (2019). The authors showed an increase and decrease in occurrence of the North-Atlantic and North-Pacific air transports in winter, respectively. Dahlke and Maturilli (2017) also showed an increase in occurrence of air masses coming from North Atlantic in winter season. Matthes et al. (2015) reported that cold spell events are becoming less frequent in winter and summer for the whole Arctic region.~~

~~(10) Since the anomalies are related to a certain patters in cloud propertiesand CRE,~~ with the ~~trends in the anomaly occurrence over the past~~ largest trend in winter.

Taking into account the link between anomaly types, cloud properties, and CRE (Figs. 3–6), we conclude that during the last 25 ~~years may have lead to increased~~ years the changes in the occurrence of dry and moist anomalies at Ny-Ålesund may have led to an increase in cloud occurrence, LWP, ~~IWP and , therefore, to higher~~ and IWP in all seasons. In turn, this could have enhanced the cloud related surface warming ~~. In addition, if the~~ in autumn, winter, and spring and the cloud related surface cooling in summer. If the trends of anomaly ~~occurrences persist~~ occurrence continue in the future, ~~CRE might be~~ we expect that CRE will become more positive in autumn, winter, and spring and more negative in summer.

These results show some aspects on how atmospheric conditions, which often are driven by large-scale air transportation~~may influence atmospheric conditions and , consequently, CRE~~ , may influence cloud properties and their radiative effect at Ny-Ålesund. This information is essential for better understanding of ~~relations between these three components of the~~ the feedback mechanism in the Arctic climate. As we indicated in this study, the significant trends in the occurrence of anomalous conditions are expected to lead to changes in cloud properties and their radiative effect. Nevertheless, qualitative estimates of these changes are challenging since a long-term Cloudnet dataset at Ny-Ålesund is ~~not currently available. Within the AC^3 (ArctiC Amplification: Climate Relevant Atmospheric and SurfaCe Processes, and Feedback Mechanisms) project~~ currently not available. Therefore, the cloud measurements are planned to be continued within the (AC)^3 project .

Data availability. The radiosonde data were taken from the information system PANGAEA: https://doi.org/.10.1594/PANGAEA.845373 (Maturilli and Kayser, 2016), https://doi.org/10.1594/PANGAEA.875196 (Maturilli and Kayser, 2017b), https://doi.org/10.1594/PANGAEA.879767 (Maturilli, 2017a), https://doi.org/10.1594/PANGAEA.879820 (Maturilli, 2017b), https://doi.org/10.1594/PANGAEA.879822 (Maturilli, 2017c), and https://doi.org/10.1594/PANGAEA.879823 (Maturilli, 2017d). The Cloudnet data are available at the Cloudnet website (http://devcloudnet.fmi.fi/). The FLEXTRA data are available at the nilu website (https://projects.nilu.no//ccc/trajectories/evdc/). The HATPRO MWR data is available in the website of the information system PANGAEA: https://doi.pangaea.de/10.1594/PANGAEA.902140 (Nomokonova et al., 2019a), https://doi.pangaea.de/10.1594/PANGAEA.902142 (Nomokonova et al., 2019b), https://doi.pangaea.de/10.1594/PANGAEA.902143 (Nomokonova et al., 2019c), https://doi.pangaea.de/10.1594/PANGAEA.902096 (Nomokonova et al., 2019d), https://doi.pangaea.de/10.1594/PANGAEA.902098 (Nomokonova et al., 2019e), https://doi.pangaea.de/10.1594/PANGAEA.902099 (Nomokonova et al., 2019f), https://doi.pangaea.de/10.1594/PANGAEA.9 (Nomokonova et al., 2019g), https://doi.pangaea.de/10.1594/PANGAEA.902146 (Nomokonova et al., 2019h), https://doi.pangaea.de/10.1594/PANGAEA. (Nomokonova et al., 2019i).

Author contributions. TN applied the statistical algorithm, performed the analysis, prepared and wrote the manuscript. KE, UL, MM contributed with research supervision, discussions of the results and manuscript review. KE applied the RRTMG for Ny-Ålesund to derive vertically resolved SW and LW fluxes. MM provided long-term radiosonde dataset. CR provided instrumentation data for this study.

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

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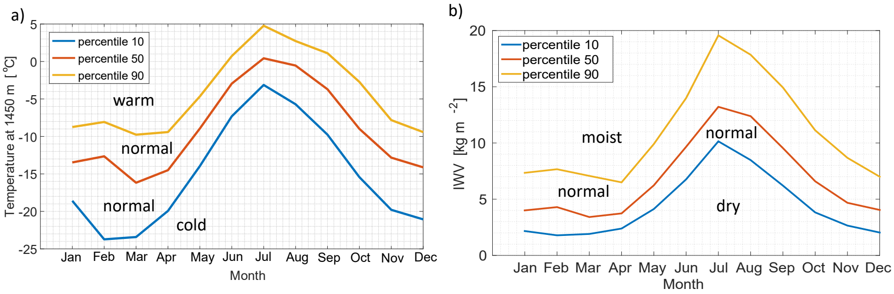

Figure 1. Monthly percentiles of 6-hourly (a) mean temperature at 1450 m and (b) IWV from microwave radiometer at Ny-Ålesund from 2011 to 2018 used as criteria for determination of periods of decreased (below 10th percentile, blue line) and increased (above 90th percentile, yellow line) T and IWV. Red line corresponds to the 50th percentile.

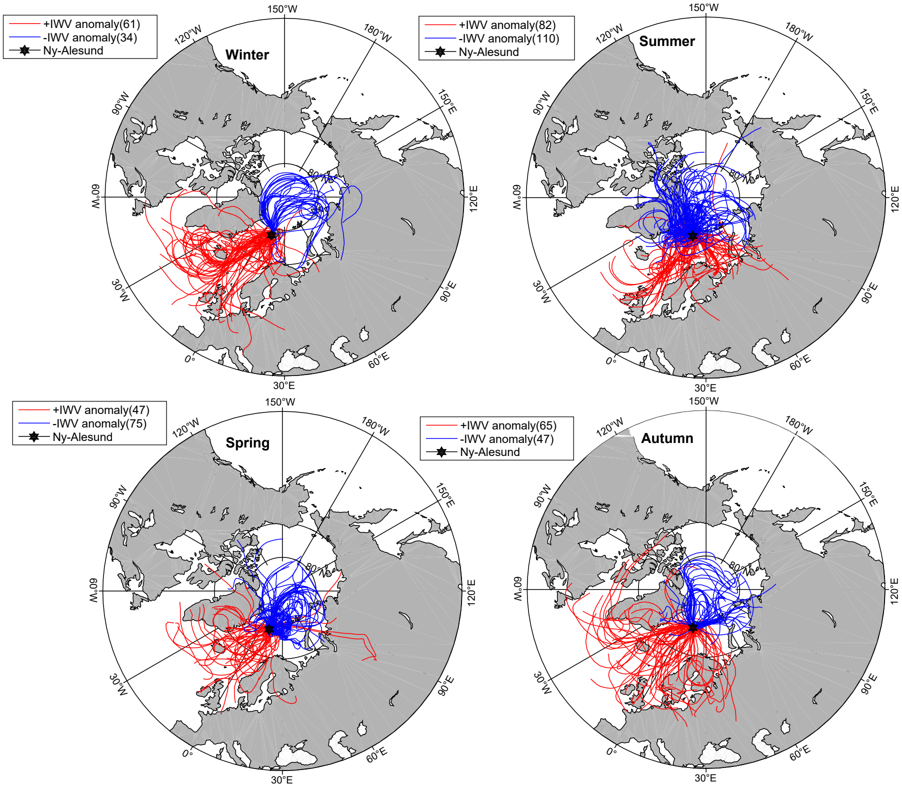

Figure 2. Backward trajectories (6 days) for the periods of +IWV and -IWV anomalies arriving at Ny-Ålesund at 1500 m from June 2016 to October 2018. The black star shows the location of Ny-Ålesund. Numbers in brackets show the number of back trajectories available for the corresponding anomaly class. Note that the numbers might be different from those provided in Table 1 due to the lower availability of the back trajectories pathways.

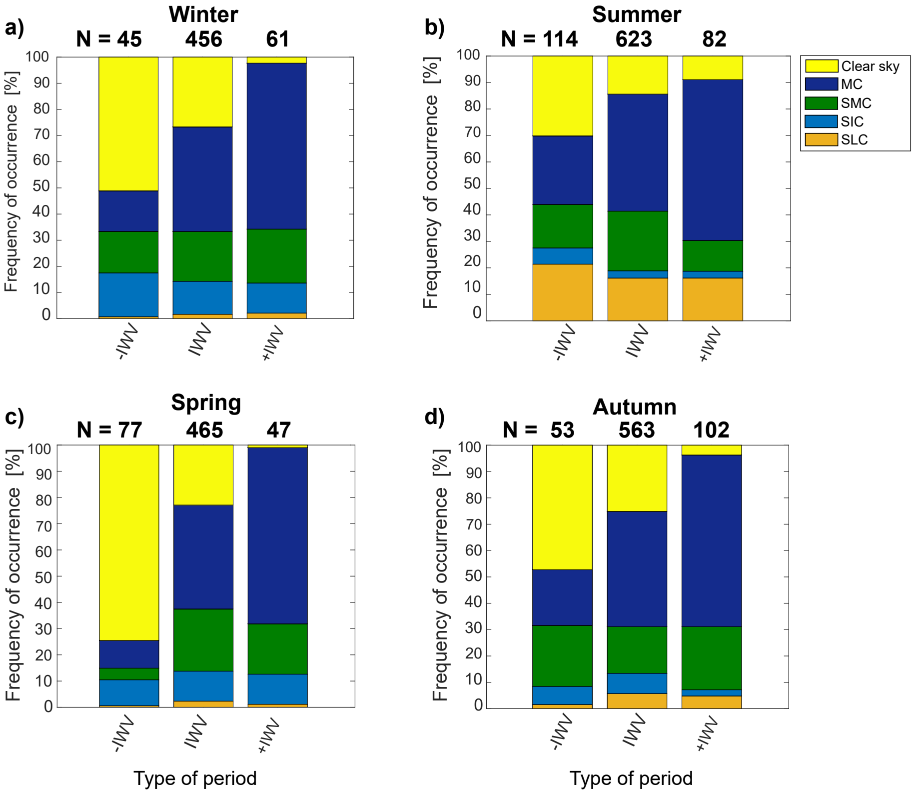

Figure 3. Frequency of occurrence of different cloud types for different anomaly periods for winter(a), summer(b), spring(c), and autumn (d). The frequency is normalized to the total number of cases of each anomaly type period. Numbers at the top of bars for each anomaly type show the number of periods included in the corresponding anomaly type based on 6-hourly mean IWV and 1450 m temperature. MC denotes multi-layer clouds, SMC, SIC and SLC stand for single-layer mixed-phase, ice, and liquid clouds, respectively.

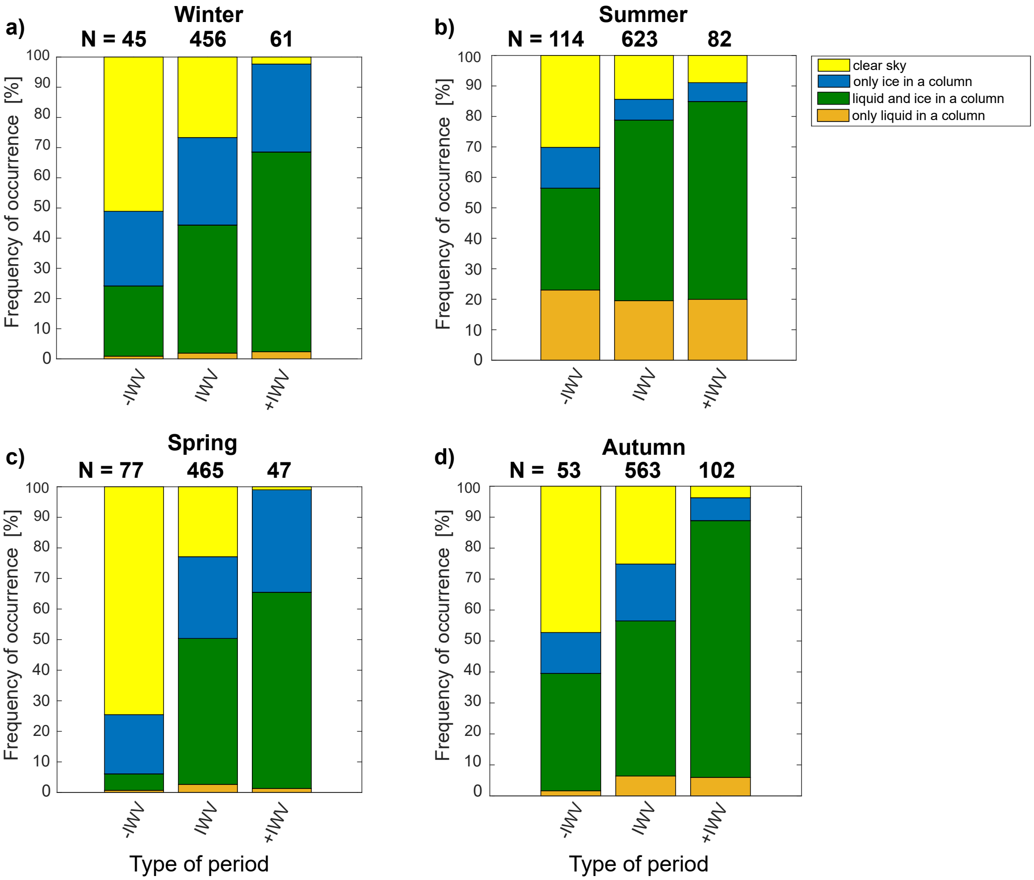

Figure 4. Frequency of occurrence of different types of hydrometeors during different anomaly periods for winter(a), summer(b), spring(c), and autumn (d). Numbers at the top of bars for each anomaly type show the number of periods included in the corresponding anomaly type based on 6-hourly mean IWV and 1450 m temperature.

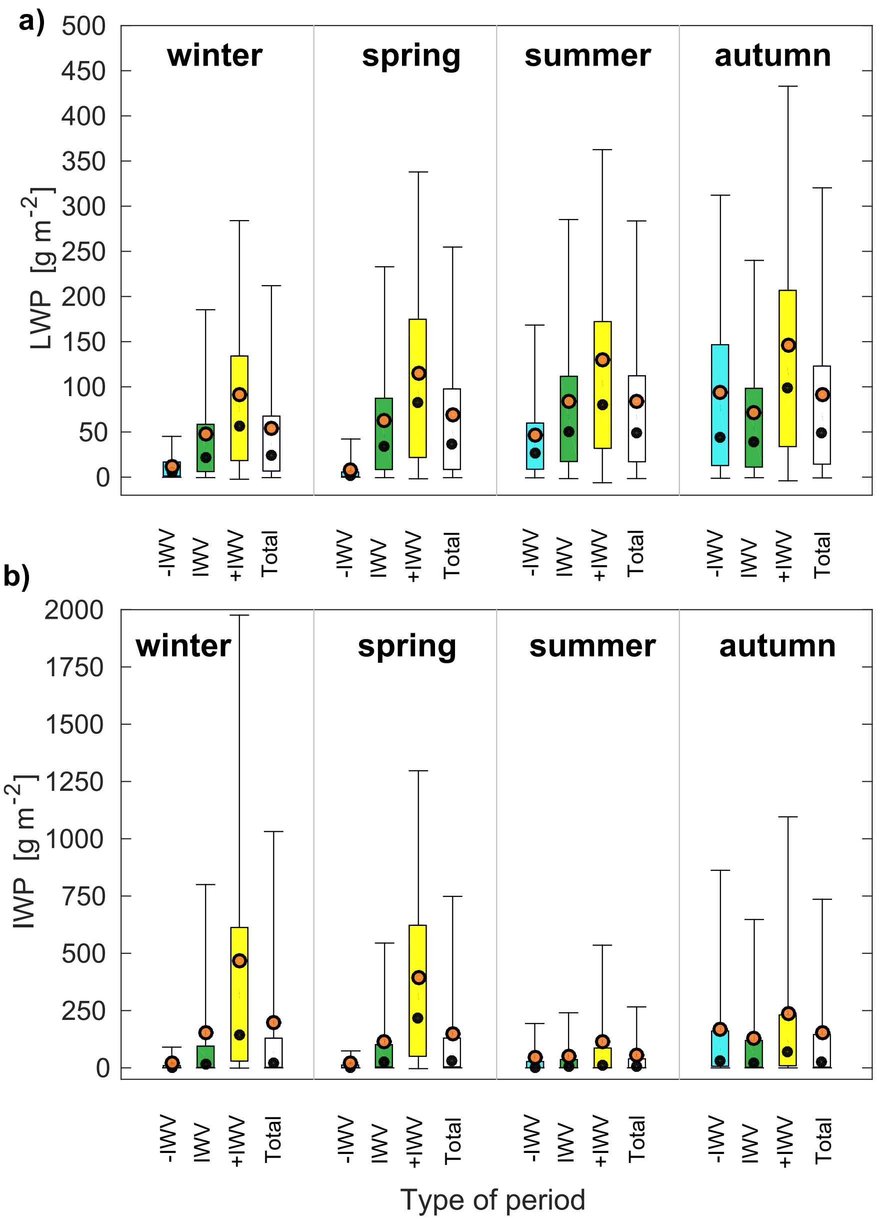

Figure 5. LWP (a) and IWP (b) for different anomaly periods and different seasons. Boxes indicate the 25th and 75th percentiles. Upper and lower whiskers show the 95th and 5th percentiles. The white boxes include all cases within a season. Mean (median) values are shown by the orange in black (black) circle marker.

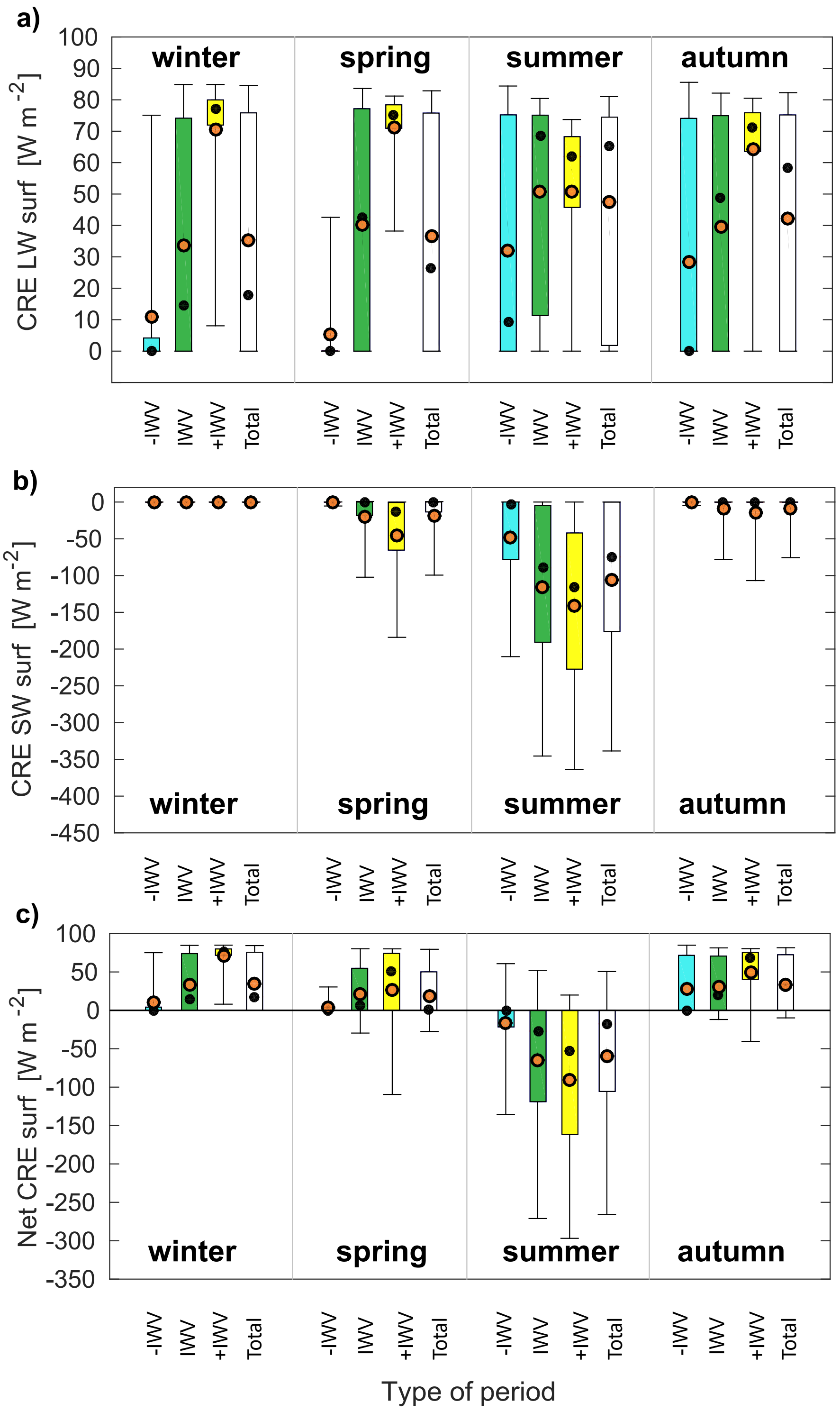

Figure 6. SW (a), LW (b), and net cloud radiative effect (c) at the surface for different anomaly periods and different seasons. Boxes indicate the 25th and 75th percentiles. Upper and lower whiskers show the 95th and 5th percentiles. The white boxes include all cases within a season. Mean (median) values are shown by the orange in black (black) circle marker.

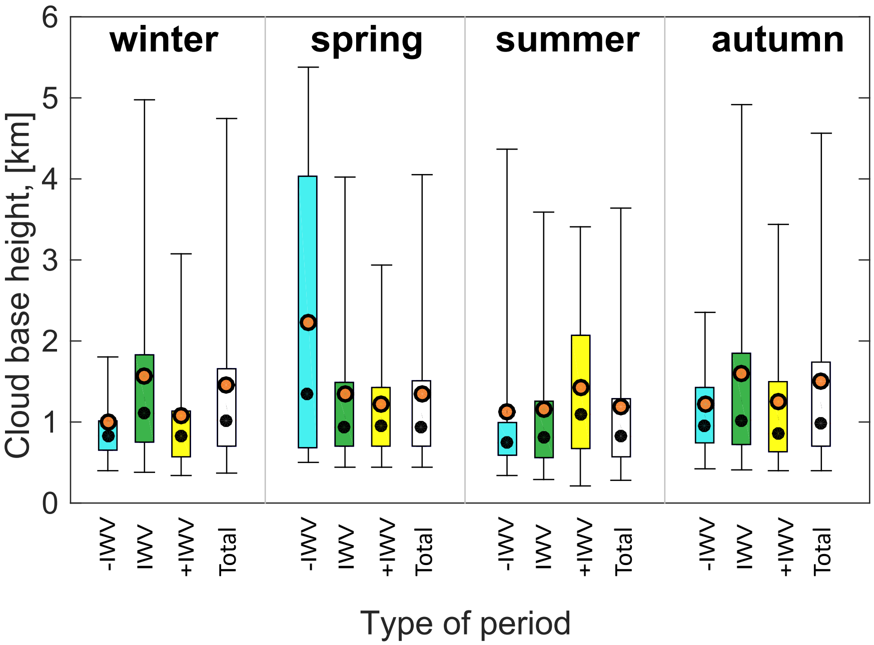

Figure 7. Cloud base height of liquid-containing clouds for different anomaly periods and different seasons. Boxes indicate the 25th and 75th percentiles. Upper and lower whiskers show the 95th and 5th percentiles. The white boxes include all cases within a season. Mean (median) values are shown by the orange in black (black) circle marker.

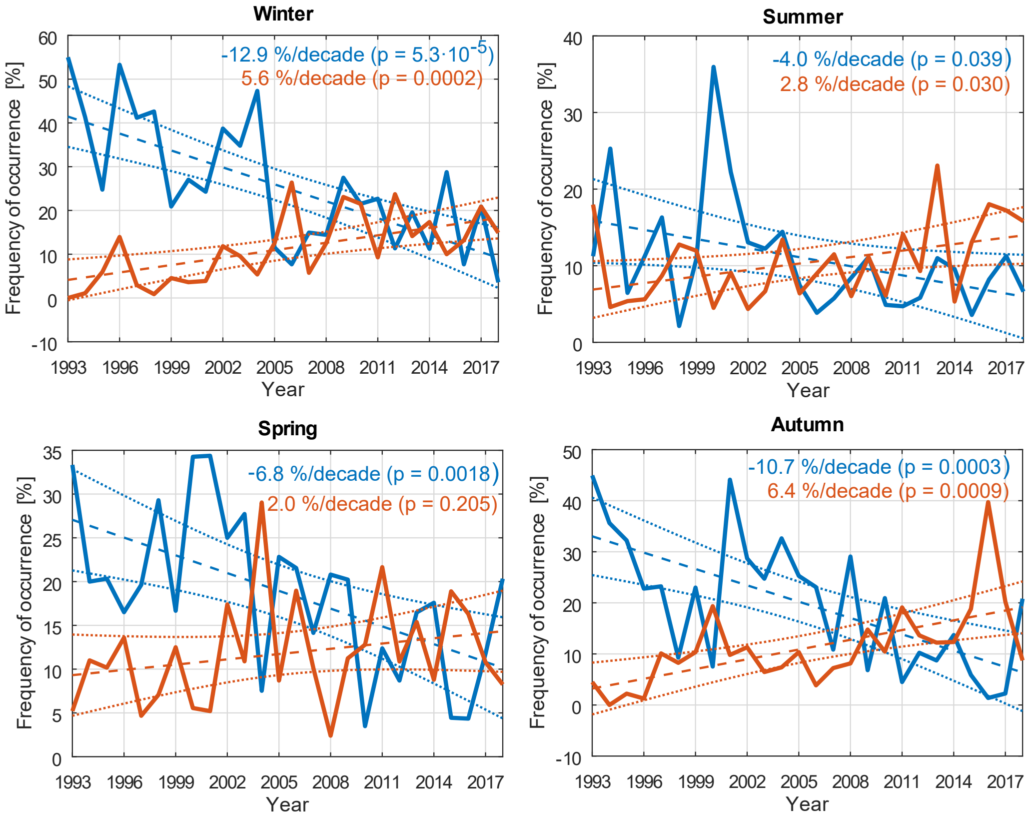

Figure 8. Frequency of occurrence of moist ("+IWV", red line) and dry ("-IWV", blue line) events using radiosonde data from 1993-2018 for different seasons (winter (a), summer (b), spring (c), autumn (d)). The red and blue lines correspond to the frequency of occurrence of dry and moist events, respectively. The dashed lines show the linear trend. Dotted lines show the 95th confident intervals for the trends derived by the bootstrapping resampling method. The significance (p value) of the two-sided t-test at 95% level is shown in brackets.

Table 1. Number of 6-hourly long periods with increased ("+IWV") and decreased ("-IWV") IWV for the whole period of cloud observations from 2016 to 2018 and for different seasons. "IWV" corresponds to periods with normal IWV values, regardless which T class the period has. The % values are with respect to all 6-hourly long periods included in the study. See text for more details.

Type of period	Winter, n cases (%)	Spring, n cases (%)	Summer, n cases (%)	Autumn, n cases (%)	all seasons, n cases (%)
+IWV	61 (10.9)	47 (8.0)	82 (10.0)	102 (14.2)	292 (10.9)
IWV	456 (81.1)	465 (78.9)	623 (76.1)	563 (76)	2107 (78.4)
-IWV	45 (8.0)	77 (13.1)	114 (13.9)	53 (7.4)	289 (10.7)

Table 2. Absolute and relative changes in $\mathrm{CRE_{SW}}$, $\mathrm{nCRE_{SW}}$, and surface albedo (α) related to dry and moist anomalies. The absolute changes are calculated as a difference between anomalous and normal cases. The relative changes are shown in brackets and are given in percent with respect to normal conditions. Mean values of $\mathrm{CRE_{SW}}$ (in $\mathrm{W\ m^{-2}}$), $\mathrm{nCRE_{SW}}$, and α during normal condition are shown in the rightmost column "Normal conditions.

Parameter	"–IWV"			"+IWV"			Normal conditions		
	$\Delta\mathrm{CRE_{SW}}$	$\Delta\mathrm{nCRE_{SW}}$	$\Delta\alpha$	$\Delta\mathrm{CRE_{SW}}$	$\Delta\mathrm{nCRE_{SW}}$	$\Delta\alpha$	$\mathrm{CRE_{SW}}$	$\mathrm{nCRE_{SW}}$	α
Spring	+18.8(–95)	+0.2(–98)	+0.05(+7)	–25.2(+128)	–0.3(+156)	–0.06(–7)	-19.73	-0.31	0.81
Summer	+67.2(–58)	+0.2(–51)	+0.03(+26)	–25.6(+22)	–0.1(+19)	+0.06(+50)	-115.71	-0.59	0.13
Autumn	+8.8(–94)	+0.2(–60)	+0.45(+173)	–4.9(+52)	–0.4(+115)	–0.08(–30)	-9.39	-0.31	0.26