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Long-term trends in total cloud cover in the Arctic based on surface observations in 1985–2020

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Abstract. This paper provides an assessment of long-term trends in total cloud cover in the Arctic for the period 1985–2020 based on surface observations. Analysis shows that total cloud cover exhibits a substantial variation both between seasons and from year to year. Two areas of positive trends were found in the total cloud cover from October to April over the Arctic: one in the North Atlantic from 20° W up to 90° E and another from 150° E up to 150° W, which may be a result of atmospheric heat and moisture transport through the Atlantic and Pacific gates. Throughout the year, positive trends dominate over the Arctic Ocean and its seas (except for the Laptev Sea). Negative trends prevail over the continental parts of the Arctic.

Key words:
Arctic,
Arctic climate,
climate change,
cloud cover,
water vapour,
atmospheric heat transport,
atmospheric moisture transport

Introduction

The Arctic climate system is among the most sensitive to climate change (Solomon et al. 2007). The Arctic has been warming up at an unprecedented level since the 1980s, and this, the greatest regional warming on earth, has been accelerating since the end of 20th century – a phenomenon referred to as “Arctic amplification” (Serreze and Barry 2011; Wang et al. 2012), which is a result of several positive and negative feedbacks and other processes occurring over a range of timescales (ACIA 2005). Surface albedo feedback is cited as one of the most significant contributors to the warming of the Arctic; however, numerous studies admit the important effect of clouds on Arctic amplification (Przybylak 1999; Shupe and Intrieri 2004; Serreze and Barry 2011; Taylor et al. 2013). Also, recent studies have shown the importance of atmospheric heat and moisture transport on the Arctic warming (Graversen 2006; Graversen et al. 2008; Hwang and Frierson 2010; Alekseev 2019).

Nevertheless, our focus in this study is to investigate long-term trends in total cloud cover in the Arctic in 1985–2020 using observations from surface-based meteorological stations. Here we examine trends in total cloud cover to show how changes in moisture fluxes to the Arctic are expressed in changes in the total cloud cover and how these processes can be related to the Arctic amplification and Arctic climate change. We also present trends in the mean monthly air temperature in the Arctic and in the downward shortwave and longwave radiation at Ny-Ålesund station for the same period of time. It is important to note that the trends in total cloud cover presented in this paper are considered only as one of many factors of interannual changes in Arctic cloudiness and its influence on longwave radiation and temperature regime in the Arctic. The other radiatively important factors in the surface energy balance to mention are cloud temperature, base height, the amount and phase of condensed water, particle size and shape, optical depth, and ice/water contents (Curry and Ebert 1992; Shupe and Intrieri 2004).

To study long-term trends in total cloud cover, we have chosen a period from 1985 to 2020 that demonstrates amplified Arctic warming and sea-ice retreat as surface air temperature and sea-ice loss exhibit strong positive trends. Also, since the 1970s, near-surface air temperature has risen significantly over the Arctic seas – in winters after 1991 and in summers after 1996. Especially strong positive trends are observed from October to February, with peaks in December and January (Alekseev 2015).

We begin with a description of our data, analysis methods and processing methodology in "Data and methods". In "Results and discussion" we provide an assessment of the long-term trends in mean monthly air temperature, seasonal variability and trends in total cloud cover in the Arctic in 1985–2020. In the same section, we present long-term trends in downward fluxes of shortwave and longwave radiation at Ny-Ålesund station. "Conclusions" summarises the results and provides concluding remarks.

Data and Methods

The observational database for the Arctic is quite limited, with few long-term stations and a paucity of observations in general (ACIA 2005). One of the main sources of data on Arctic cloudiness is still in-situ observations. One of the advantages of using surface observations is that they offer long periods of record. Also, land stations are fixed at consistent locations and almost always give a report for their specified reporting times. However, surface observations – especially in the Arctic – are spatially and temporally limited because conditions in the Arctic are hard on instruments (Chernokulsky et al. 2017). For example, observations of cloud cover in the central Arctic are found only from drifting stations (Makshtas et al. 1999). Satellites, although they provide information with a wide spatial and temporal cover for remote and data-sparse areas like the Arctic, are limited by the poorly visible contrast between clouds and the highly reflective underlying surface (Chernokulsky and Mokhov 2012). Furthermore, there has been found to be a disagreement between different satellites observations – and between satellite and surface observations – in both the climatology and the trends (Eastman and Warren 2010; Chernokulsky and Mokhov 2012). Moreover, satellite data overestimate the mean monthly cloud cover in the winter and underestimate it in summer, as compared to visual observations (Makshtas et al. 1999). Reanalyses also have biases in assessments of Arctic clouds, especially in winter and over the ocean (Chernokulsky and Mokhov 2012).

The analysis presented here is based on routine visual surface cloud cover observations from 86 meteorological stations in the Arctic. The observations on mean monthly air temperature have been collected at 151 meteorological stations. The stations for trend analysis were selected if they had sufficient periods of record (from 1985 to 2020) and an adequate number of day and night observations. The data on total cloud cover and mean monthly air temperature were provided by the All-Russian Research Institute of Hydrometeorological Information (http://meteo.ru), the European Climate Assessment & Dataset (ECA&D) project of The Royal Netherlands Meteorological Institute (KNMI) (https://www.ecad.eu/) and the NOAA's National Centers for Environmental Information (NCEI) (https://www.ncei.noaa.gov/).

For trend analysis, we decided to consider total cloud cover, a conventional characteristic of cloudiness observable visually during standard meteorological observations and most frequently used in climate research for calculating radiative fluxes. The total cloud cover was determined as a fraction of the full sky to be covered with cloud of any type by an observer upon visual inspection of the sky above a meteorological station. It is important to note the differences in the reporting of information on total cloud cover. Usually, total cloud cover is given in tenths (sky cover ranging from 1 to 10) instead of octas (sky cover ranging from 1 to 8). To homogenise different observational measures, we converted all data from octas to tenths, since most stations used in our study report observations in tenths.

The data were processed to provide a consolidated dataset of individual observations of total cloud cover for the period 1985–2020. Those observations had passed through all processing procedures and quality controls beforehand, so they were ready to be used in further analysis. For further trend analysis, we created a time series of all overcast sky cases (corresponds to a total cloud cover range of 8–10 tenths). Cloud breaks and traces were counted as 9 and 0 tenths, respectively. The reasons for choosing this method of quantifying cloud amount are described in Section 3.2.

Trend analyses of total cloud cover, surface temperature, and radiation fluxes were performed using least-squares regression for individual stations during all months over the period 1985–2020. Each parameter was regressed with the year as the independent variable, and the trend value is the slope of the linear regression line along with a standard deviation of the slope. All trends reported in this study are statistically significant at the confidence level 90% or higher by Student's t-test and Mann–Kendall tests. The level α=0.05 was considered a sufficient threshold for the statistical significance of both tests.

The multilevel B-Spline Interpolation technique in the SAGA (System for Automated Geoscientific Analyses) program was used to interpolate the spatial variation of trends in overcast sky within the area. To show another example, Ansari et al. (2020) in their study used thin-plate spline interpolation technique for interpolating spatial variation in trends in total cloud cover. It is worth noting that such methods of averaging cloud data over large areas are designed to get spatial distribution of trends despite the sparseness of surface-based cloud observations over the Canadian Arctic, Greenland and other remote parts of the Arctic Ocean. Also, the stations used in this study are located in different topographic regions with correspondingly different cloud climatologies, which can also affect trends.

To analyse trends in the longwave radiation fluxes and their subsequent comparison with trends in total cloud cover, we used data on global and downward longwave radiation fluxes at Ny-Ålesund station for each month for the period 1992–2020 from the Baseline Surface Radiation Network – BSRN database of World Radiation Monitoring Center (https://bsrn.awi.de). The calculations were carried out with monthly average data and showed significant non-stationarity of the time series. Unfortunately, Ny-Ålesund is the only station in the Arctic that has data on longwave radiation fluxes (especially on downward longwave radiation fluxes) for a sufficient period of time to examine climate change trends (except for the Barrow station in Alaska, which has a record for 1992–2017), since other observation sites (for example, Tiksi or Alert stations) have records for a shorter period.

Results and Discussion

Trends in mean monthly air temperature in the Arctic in 1985-–2020

It is pointed out that cloud cover and surface temperature correlate with each other strongly. For example, Eastman and Warren (2010) showed an increasing trend in Arctic total cloud cover and a positive correlation between total cloud cover and surface air temperature in autumn, winter and spring. To analyse air temperature trends in the Arctic for the period 1985–2020, we mapped trend values in mean monthly air temperature obtained from linear regression equations on the study region for each station for each month of the year. Figure 1 shows the spatial distribution of the mean monthly air temperature trends in February, May, August and October over the Arctic.

Overall for the Arctic, as shown in Figure 1, the mean monthly air temperature increased dramatically in 1985–2020 at a decadal rate of +0.92 °C in winter. The strongest heating occurred around the Barents and Kara seas. During the three warm seasons (spring, summer, autumn), the mean monthly air temperature also increased at decadal rates of +0.69 °C, +0.41 °C and +0.85 °C, respectively. A few instances of cooling trends are observed in northern eastern Russia in winter, as well as in northern central Russia in March and June.

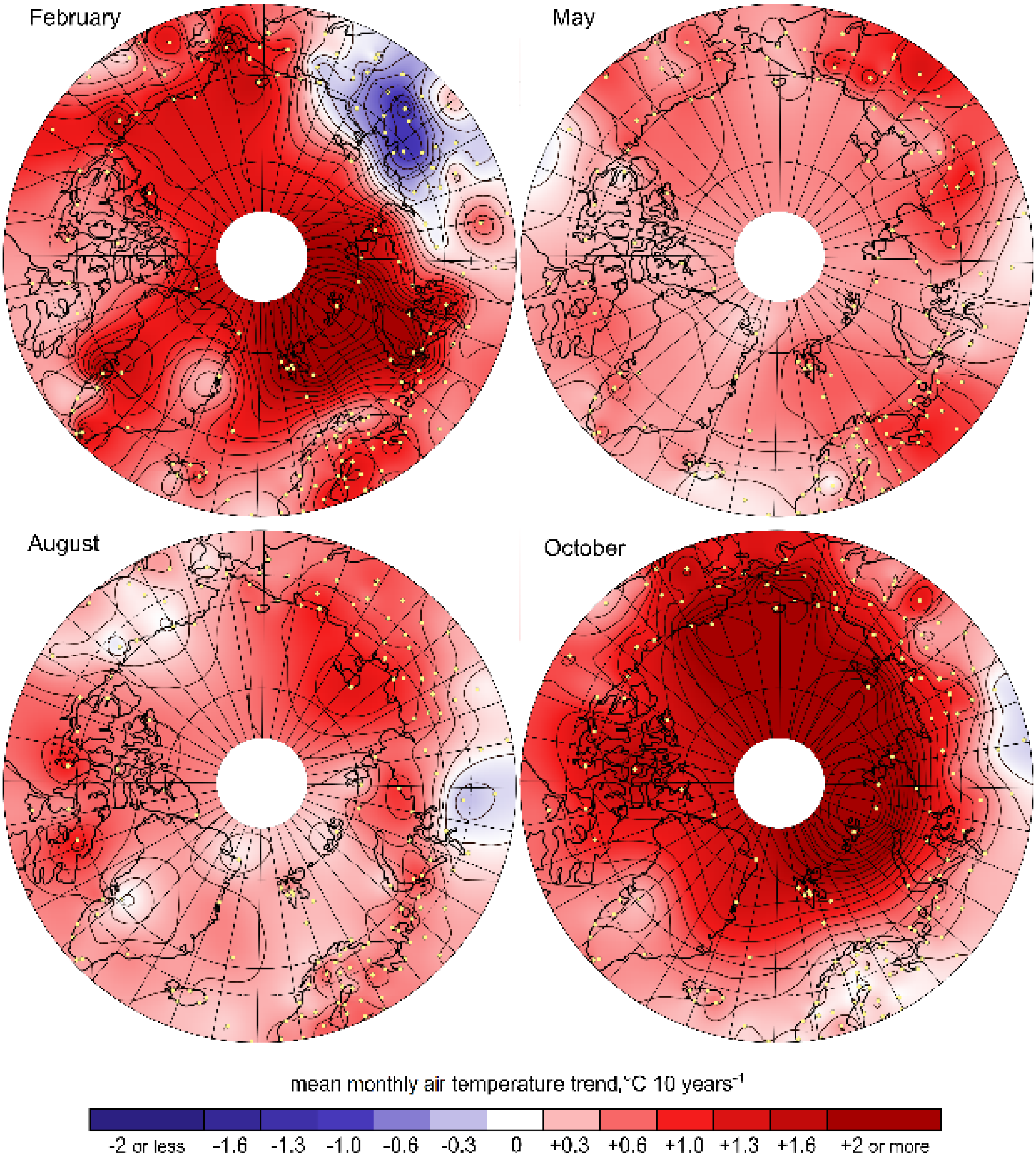

Fig. 1. Mean monthly air temperature trend maps for the Arctic in February, May, August and October over the period 1985–2020. Contours and colours represent trend values in degrees per 10 years. Dashed circles show the Arctic circle; black circles show latitude lines at 70° N and 80° N. Small yellow dots indicate stations

Seasonal variability of total cloud cover in the Arctic in 1985–2020

We found that, for the period 1985–2020, overcast sky cases (8–10 tenths) in the Arctic were observed most frequently in summer and autumn (54%) and least frequently in winter (38%), with 47% being the annual mean. We can conclude that there is a strong seasonal cycle in Arctic cloud cover, with summer being cloudier than winter. The frequency of overcast sky shows a dramatic rise from April to May and a subsequent, but slower decline from October to

November, which is consistent with Chernokulsky et al. (2019). May and October are short transition seasons between the winter and summer cloud distributions, which is consistent with the finding of Makshtas et al. (1999). Based on this, we chose February and August as representative months for winter and summer, respectively, and May and October as transition seasons. Also, we found that the Arctic is cloudier over the ocean than over land. This finding is consistent with Chernokulsky and Mokhov (2012), who showed that total cloud cover is observed more frequently over the ocean and less over land.

It has been found that, in the central part of the Arctic Basin, cloud amount tends to fall in two ranges of 0–2 tenths (clear sky) and 8–10 tenths (overcast sky) and the frequency distribution of cloud amount in the winter in the Arctic is not a Gaussian but a bimodal U-shaped β-distribution (Voskresenskii and Bryazgin 1988; Makshtas et al. 1999). The common practice of quantifying cloud amount with only its average value (at least for spatial scales of less than a thousand kilometres) is not correct, as, for typical cloud distributions over sea-ice, the mean value is the least likely value (Makshtas et al. 1999). In this case, it seems appropriate to describe the spatial and temporal variability of total cloud cover in the Arctic in terms of the frequency of overcast (8–10 tenths) sky condition, as was used in previous studies (Vasilieva and Svyashchennikov 2003; Svyashchennikov et al. 2011).

We also found a difference between the modes of total cloud amount in the Arctic in winter and summer. In winter (from November to April), there are two practically equal maxima in the distribution of total cloud cover, one for 0–2 tenths and a second for 9–10 tenths, and the frequency distribution is U–shaped. Also, cloud amounts in the 3- to 8-tenths bins have a comparatively consistent distribution in winter. May and October are short transition seasons between the winter and summer cloud distributions. In summer (from June to September), overcast sky conditions dominate and the distribution is J–shaped. As in winter months, there are very few occurrences of sky conditions with 3–8 tenths total cloud cover.

Trends in total cloud cover in the Arctic in 1985–2020

To analyse long-term trends in total cloud cover in the Arctic for the period 1985–2020, as for mean monthly air temperature trends, we mapped trend values in the frequency of overcast sky conditions obtained from linear regression equations on the study region for each station for each month of the year and presented them as the percentage change over 10 years. Figure 2 illustrates geographical patterns of changes in the frequency of overcast sky conditions over the Arctic for February, May, August and October for the period 1985–2020.

As seen in Figure 2, trends are not uniform over the entire Arctic, but they do aggregate into large regions of similar signs. We found two areas of positive trends in the frequency of overcast sky conditions in the Arctic from October to April for the period 1985–2020. The first region is located in the North Atlantic and extends from about 20° W to 90° E, including the waters of the Greenland, Barents and Kara Seas. The other region covers an area from 150° W to 150° E and includes the waters of the East Siberian, Chukchi and Beaufort Seas. It can be assumed that these two regions connect while reaching the North Pole. One of the "barriers" that separates these areas is a quite extensive area of large negative trends in the frequency of overcast sky conditions in the Laptev Sea (also including the territory of the New Siberian Islands) and to the south of its coast towards the continent that exists from December to March. In general, this area is well defined throughout the year, except for October and November. It is probable that this area of negative trends is a consequence of the expansion of the influence of the Asian anticyclone to the north in winter and subsequent intensified arrival of cold dry air from Eurasia through 70° N between 80° E and 150 °E, which may lead to negative trends in surface temperature and a decrease in the total cloud cover in north-eastern Russia in winter. This is also an interesting topic for further research.

Alekseev et al. (2019), in their study, showed that, during the cold part of the year (from October to April), the deviations from zonal averages of multiyear average surface air temperature and water vapour content values in the area of 60–90°

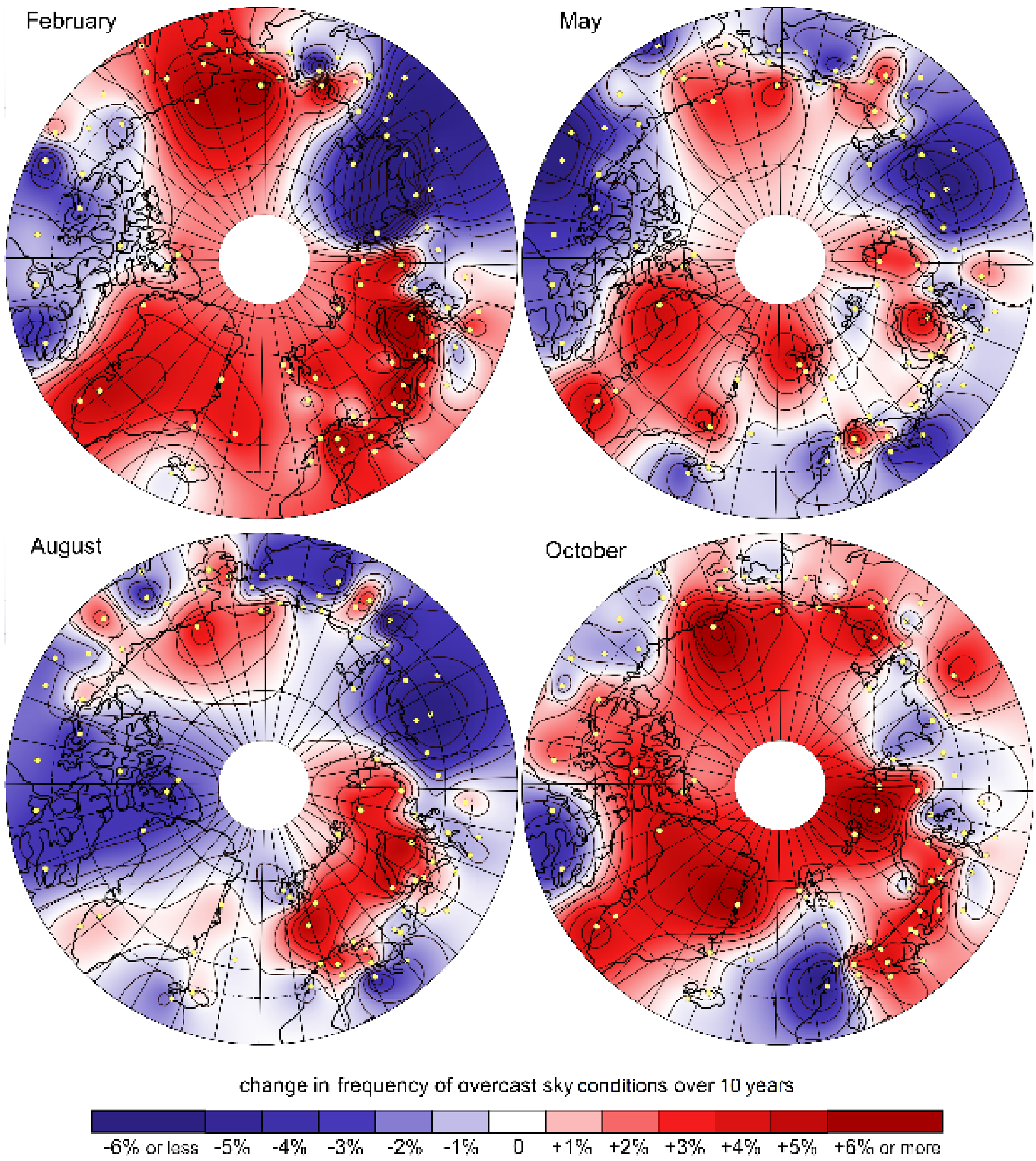

Fig. 2. Changes in frequency of overcast sky conditions in the Arctic in 1985–2020. Dashed circles show the Arctic circle; black circles show latitude lines at 70° N and 80° N. Small yellow dots indicate stations.

N show positive anomalies in the regions adjacent to the North Atlantic and Pacific Ocean latitudinal segments (sectors of 0–80° E and 200–230° E along 70° N, respectively), which were identified as the Atlantic and Pacific gates for heat influx into the Arctic, respectively. Earlier, Voskresensky and Bryazgin (1988) noted that the high frequency of overcast sky conditions in the western and eastern parts of the Russian Arctic coast in winter is associated with the predominance of moist air masses originating from the Atlantic and Pacific Oceans. Many researchers also mentioned the transport of moisture and heat through the Atlantic and Pacific gates (Bengtsson et al. 2011; Woods et al. 2013; Kim and Kim 2017).

Using simplified calculations for the period 1979–2014 on individual isobaric surfaces, Alekseev et al. (2016) also found that the contribution of water vapour transport to the variability of its total content in winter in the region of 70–90° N is 59% and explains 90% of the trend for 1980–2014. It is probable that the influx of moist air masses through the Atlantic gate is one of the main factors of the significant increase in the frequency of overcast sky conditions observed in the Barents and Kara Seas throughout the year, especially from October to February, when one of the highest trends in the increase in frequency of overcast sky conditions in the Arctic is observed. It is worth noting that the area in which heat influxes through the Atlantic gate most strongly influence the Arctic winter temperature extends from the Norwegian Sea to the East Siberian Sea with maxima of influence over the Barents and Kara Seas extending towards the Laptev Sea and north to the North Pole (Alekseev et al. 2016).

The pronounced increase in frequency of overcast sky conditions in the East Siberian, Chukchi and Beaufort Seas throughout the year may also be a consequence of heat and moisture transport through the Pacific gate, which, in turn, can be a consequence of the observed increase in the convective cloud types in the Eurasian European Arctic, which was also mentioned by Chernokulsky and Esau (2019). Transition from stratiform to convective cloud types opens a significantly larger fraction of the surface to absorb solar radiation, which leads to more shortwave solar radiation reaching the darker open water surface.

Overall, positive trends in the frequency of overcast sky conditions are observed over the Arctic Ocean and its seas (except for the Laptev Sea) throughout the year. Negative trends in some parts of the Arctic Ocean during the summer months are almost negligible, and they prevail over the continental parts of the Arctic while reaching rather large values over the Canadian Arctic Archipelago and the Asian part of the Russian Arctic, which is seen in Figure 2 for February, May and August. However, in October and November, almost the entire Arctic shows a significant increase in frequency of overcast sky conditions, except for the Norwegian Sea and some local areas.

Trends in downward longwave and shortwave radiation at Ny-Ålesund station in 1985–2020

Longwave radiation fluxes play a key role in the formation of the Arctic climate, especially in winter. In recent decades, there has been an increase in longwave radiation fluxes at high latitudes and the primary factors contributing to trends in downward longwave radiation fluxes are cloud fraction, cloud-base height and precipitable water (Francis and Hunter 2007).

Cloud radiative effect over the Arctic varies seasonally. Many studies agree that clouds have a warming effect during all season except summer (Curry and Ebert 1992; Intrieri et al. 2002; Eastman and Warren 2010). In the cold and dark part of the year (from late autumn to early spring), an increase in water vapour content in the atmosphere (as well as its part represented as clouds) in the absence of incoming shortwave solar radiation contributes to surface heating by the absorption and re-emitting of more longwave radiation from the Earth's surface by clouds, and due to high surface albedo associated with snow and ice. In contrast, in summer, clouds act to cool the surface by reflecting and scattering incoming shortwave radiation (which the underlying surface would do under clear-sky conditions when surface albedo is relatively low).

According to the SHEBA (Surface Heat Budget of the Arctic) programme, the annual average surface cloud forcing in the Arctic for shortwave radiation was estimated at -10 Wm^{-2}, and for longwave forcing at 38 Wm^{-2} (Intrieri et al. 2002). The net cloud radiative forcing at the Arctic surface can reach about 20 Wm^{-2} in winter despite nearly zero incoming solar radiation, which is due to the strong longwave radiative effect of Arctic clouds (Shupe and Intrieri 2004).

To study trends in longwave radiation fluxes and their subsequent comparison with changes in the frequency of overcast sky conditions, we analysed the long-term changes in the longwave radiation fluxes using ground-based radiation measurements at the Ny-Ålesund station from 1992 to 2020.

Figure 3 shows trends in downward longwave and global radiation fluxes and trends in the frequency of overcast sky conditions at the surface for all months for Ny-Ålesund station in 1992–2020. According to Figure 3, longwave downward radiation fluxes exhibit significant positive trends from October to February at the highest decadal rates of 12.7 Wm^{-2}, 12.3 Wm^{-2} and 10.9 Wm^{-2} in October, January and February, respectively. Correspondingly, in the same period, the frequency of overcast sky conditions also increased dramatically in response to a positive trend in the frequency of overcast sky conditions. It is worth noting that the observed increase in frequency of overcast sky conditions contributes to an increase in the downward longwave radiation fluxes in winter, when shortwave radiation fluxes at the surface are very small or almost zero.

From April to June, as well as in September, we found a significant reduction in the global radiation at the highest decadal rate of 13.4 Wm^{-2} in May. It corresponds with an increase in frequency of overcast sky conditions that also has its peak in May at a decadal rate of 5.7%. In contrast, the slight decrease in frequency of overcast sky conditions in July and August contributes to an increase in global radiation fluxes.

The downward longwave radiation fluxes in July and August remain positive, despite the decrease in the frequency of overcast sky conditions, since the largest downward longwave radiation fluxes per year are observed during these months at the Ny-Ålesund station, amounting to 310.9 Wm^{-2} in July and 305.4 Wm^{-2} in August. It can be concluded that cloud cover has a negative shortwave radiation effect (which is visible from April to June) at the Ny-Ålesund station, causing an increase in downward longwave radiation fluxes at the same time. However, in the absence of global radiation fluxes, in winter, the interannual variability of total cloud cover correlates strongly with longwave radiation fluxes, since the downward longwave radiation fluxes then are less than in summer and they are the only source of radiation during the polar night.

In general, from 1992 to 2020, a steady increase in the frequency of overcast sky conditions is observed at the Ny-Ålesund station throughout the year with a maximum decadal increase of 7.7% in January. Positive trends in the frequency of overcast sky conditions correspond to an increase in longwave downward radiation fluxes in all months the year; however, the largest increase is observed from October to February at a maximum decadal rate of 12.7 Wm^{-2} in October. Global radiation fluxes decreased throughout the year, except for July and August, when negative trends in total cloud cover are observed.

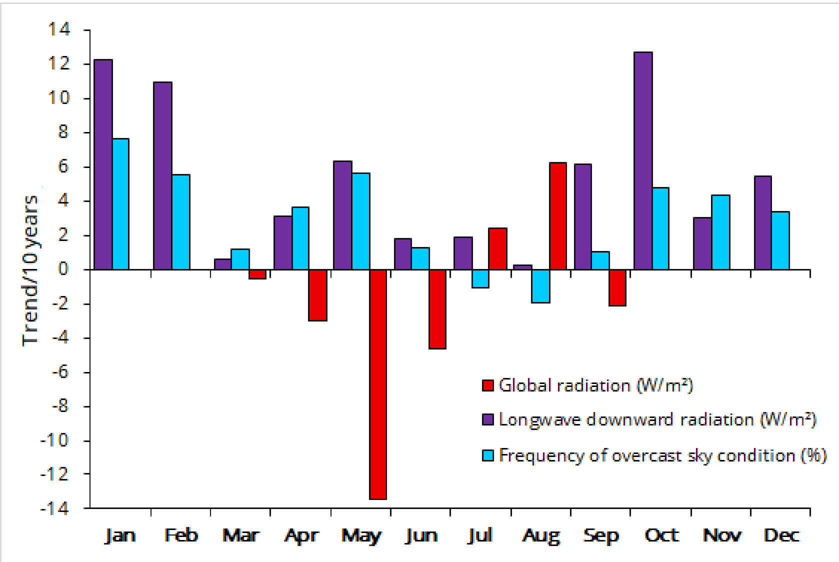

Fig. 3. Trends in global radiation and longwave downward radiation, and changes in frequency of overcast sky conditions in 1992–2020 at Ny-Ålesund station

Conclusions

The present study has examined long-term trends in total cloud cover and trends in mean monthly air temperature and downward shortwave and longwave radiation in the Arctic for 1985–2020. The analysis of mean monthly air temperature trends in the Arctic indicates that the Arctic has indeed been warming up since 1985, but the signs and magnitudes of trends vary in time and location. The strongest warming has occurred in the Barents and Kara Seas in winter. However, there are a few instances of cooling trends in surface temperature in north-eastern Russia in winter, as well as in northern central Russia in March and June.

The analysis of the frequency of overcast sky conditions shows that the total cloud cover exhibits a substantial variation both between seasons and from year to year. We found two areas of positive trends in the frequency of overcast sky in 1985–2020 in the period from October to April over the Arctic. One is in the North Atlantic, which extends from about 20° W up to 90° E and includes the waters of the Greenland, Barents and Kara Seas. The other area covers an area from 150° E up to 150° W and includes the water area of the East Siberian, Chukchi and Beaufort Seas, which may be the result of the inflow of warmer and wetter air masses by atmospheric heat and moisture transport through the latitudinal segments called the Atlantic and Pacific gates. Positive trends in overcast sky conditions dominate over the Arctic Ocean and its seas (with the exception of the Laptev Sea) throughout the year. Negative trends prevail over the continental parts of the Arctic.

The analysis of downward longwave and global radiation fluxes trends and their comparison with the changes in the frequency of overcast sky conditions at the surface for Ny-Ålesund station in 1992–2020 showed that, in the cold seasons (from October to February), longwave downward radiation fluxes exhibit significant positive trends due to the increasing cloud cover. From April to June, the increasing total cloud cover results in a decreasing trend in global radiation fluxes. In contrast, in July and August, the slight decrease in frequency of overcast sky conditions contributes to an increase in global radiation fluxes. The summer trends of downward longwave radiation fluxes are not significant, although they remain positive. It can be concluded that the cloud cover at the Ny-Ålesund station has a negative shortwave radiation effect from April to June, causing an increase in downward longwave radiation fluxes at the same time. However, in the absence of global radiation fluxes in winter, the interannual variability of total cloud cover correlates strongly with longwave radiation fluxes, since the downward longwave radiation fluxes are less during that time than in summer, and they are the only source of radiation during the polar night. Whether these trends will remain stationary, accelerate or decrease is an open question.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Author contributions

Study design: PS, AD; data collection: PS, AD; statistical analysis: PS, AD; result interpretation: PS, AD; manuscript preparation: PS, AD; literature review: PS, AD.

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