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LETTER

Increasing occurrence of heat waves in the terrestrial Arctic

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Abstract

Heat waves in the Arctic may strongly impact environment and local communities. Recently several indices have been proposed for monitoring environmental changes in the Arctic, but heat waves have not been addressed. By applying a structured approach for evaluating occurrences of periods with exceptionally high temperatures, this study demonstrates that in the last decades there was an increase of heat wave occurrences over the terrestrial Arctic. The increase is mainly over the Canadian Arctic Archipelago and Greenland that are surrounded by ocean undergoing a sea-ice melting trend, while the Eurasian Arctic shows no significant change in heat wave occurrence. Since 2002 the probability of experiencing heat waves in the Arctic has been similar or even higher than in the middle and low latitudes and heat waves have already started to increasingly threaten local vegetation, ecology, human health and economy.

1. Introduction

Global warming is especially pronounced in the Arctic manifested as the Arctic amplification (AA) process with the warming rate that is about two times faster than in the rest of the globe (AMAP 2017). The rapid warming of the Arctic strongly impacts its environment and local population. One of the most pronounced environmental manifestations of AA is the reduction of sea ice cover in summer (AMAP 2017). The sea ice melting is a consequence of global warming, but it also produces a number of feedbacks. The ocean over areas without sea-ice warms more rapidly, because its darker surface absorbs much more solar radiation, while the enhanced evaporation over the ocean free of sea-ice moistens atmosphere strongly enhancing downward infrared radiation, and warmer ocean further increases the warming of the surrounding atmosphere (Screen and Simmonds 2013, Lee et al 2017). Strong effects of AA with feedbacks have been observed also over the land (e.g. Bonne et al 2015). The permafrost in the Arctic is thawed at the unprecedented rate (Schuur et al 2015) triggering a number of challenges and threats for regional and local environment and local communities. The thawing exposes large deposits of carbon in the permafrost to bacterial decomposition and may produce large additional emissions of carbon dioxide and methane into the atmosphere (Schuur et al 2015). It further weakens the stability of residential houses and infrastructures producing large economic losses and costs for local communities (Walker and Peirce 2015, Shiklomanov et al 2016). The thawing of permafrost may also release viruses and threaten animal and human health (e.g. Revich and Podolnaya 2011) or suddenly release long-term accumulated pollutants (e.g. Schuster et al 2018).

Contemporary with the slow and persistent increase of mean regional temperature, several heat waves have been occasionally observed in different areas of the Arctic. In July 2010 the exceptionally strong heat wave over Central Russia, that led to a death toll of 55 000 persons and economic loss of US $15 billion (Simmonds 2018), extended far to the north reaching southern boundaries of the Arctic (Russo et al 2015). In July 2012 near-surface temperatures were particularly high over Greenland causing the unprecedented melting rate of the Greenland ice sheet and permafrost thawing (Neff et al 2014, Bonne et al 2015). A strong heat wave occurred in July 2014 in Scandinavia and, although it was weaker than the major Scandinavian heat wave from 1972 and European heat wave from 2003, it could have a strong impact on the local population health (Russo et al 2015). In July 2018 global media linked a heat wave
over Scandinavia and Siberia to exceptionally large forest fires covering large areas of northern Sweden\(^1\) (Euronews 2018). The connection between AA and forest fires in the Arctic may, however, be more complex, because Earl and Simmonds (2018) found that forest fires became less frequent slightly south of the Arctic in eastern Europe and western Russia and there was no significant trend over Alaska and Canada.

The occurrence of heat waves over the Northern Hemisphere has increased in the last decades with respect to the beginning of the twentieth century (e.g. Russo et al 2014). Heat waves may strongly impact population by increasing the mortality (Gasparrini and Armstrong 2011) and may stress ecosystems (e.g. Marchand et al 2005). It can be expected that in the Arctic negative impacts may be even stronger, because living habits are based on temperatures that only in short summer periods rise over the freezing level (e.g. AMAP 2017). Microbes may start to proliferate at temperatures above 0°C (Schuur et al 2015) and these conditions may especially develop during heat waves when temperatures become higher than usual for several consecutive days. As a consequence, heat waves that are particularly long may expose carbon stored in the permafrost to microbial activity enhancing atmospheric sources of carbon dioxide and methane and strongly stress and damage residential houses and commercial infrastructures. Heat waves might also accelerate the reduction of sea-ice thickness in coastal areas endangering the commuting over the sea-ice or participating in traditional activities like fishing and hunting.

Heat waves typically appear occasionally and cover limited geographical areas. Magnitudes of temperature anomalies and their duration might be attenuated in the Arctic with respect to the middle latitudes, because partly additional heat is used for the accelerated melting of sea-ice and thawing of permafrost. Although Arctic temperatures rise more rapidly than the global mean, the occurrence of heat waves in summer may be equally or even less frequent that in the middle and low latitudes. This means that, while the occurrence of several heat waves in the Arctic has been documented recently, their significance and increase of the frequency still have to be established and related to heat waves in the rest of the Northern Hemisphere.

Several new indicators have been proposed to monitor the changing environmental conditions in the Arctic. They may combine the variability of several parameters representing climate change in the Arctic (Box et al 2019, Overland et al 2019), combine scientific and indigenous knowledge to study marine mammals (Moore and Hauser 2019), represent trends of different parameters expressing the sea-ice change in the Arctic Ocean (Bliss et al 2019, Gerland et al 2019), and apply the frost index to estimate methane release from the permafrost (Geng et al 2019), assess lake ice dynamics (Arp et al 2018) and eroding permafrost coasts (Jones et al 2018) for representing the strength of the Arctic warming (Arp et al 2018), evaluate the strength of the Arctic Ocean halocline for estimating the state of the Arctic Ocean (Polyakov et al 2018) and estimate the variability of cold atmospheric mass over the Arctic (Kanno et al 2019). The changing frequency and intensity of heat waves might provide an additional indicator of the current change of Arctic environmental conditions that may be directly related to changes affecting Arctic terrestrial ecosystems and local population.

This study estimates the variability and intensity of heat waves in the Arctic since 1979. It compares the occurrences of heat waves in the Arctic with their occurrences in the middle and low latitudes in the Northern Hemisphere in order to evaluate the relationship between heat waves and recent enhanced warming in the Arctic.

2. Method

2.1. Atmospheric reanalysis

Atmospheric fields are obtained from ERA-Interim, a 4-dimensional variational analysis (4D-Var) with a 12-h analysis window (Dee et al 2011). The spatial resolution of the reanalysis data set in the Arctic is less than 30 km. Atmospheric reanalysis combine in situ and remote observations with model simulations to produce estimates of atmospheric states and their accuracy may strongly depend on the availability of in situ observations that may be scarce in the Arctic. By comparing several data sets, it has been demonstrated that all atmospheric reanalysis in the Arctic show significant biases with respect to independent in situ observations (Lindsay et al 2014, Graham et al 2019). There is also a large spread in estimates of linear trends of near-surface temperature. Here we evaluate near-surface temperature trends and heat waves only over land in summer months (June–July–August). We assume that, due to the availability of a larger number of in situ observations of near-surface temperatures over land in summer, estimates from atmospheric reanalysis used for our study are more accurate than the estimates for the whole Arctic that include less observed ocean and colder seasons with a lower number of in situ observations.

This study used the ERA-Interim reanalysis, although the Arctic System Reanalysis (ARS) (Bromwich et al 2018) provide more detailed fields with the horizontal resolution of 15 km and use more information from observations. ERA-Interim starting in 1979 spans a longer period than ARS starting in 2000. In this way ERA-Interim covers the period of enhanced sea-ice melting in the Arctic after 2000 and the two preceding decades. ERA-Interim also provides global fields

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\(^1\) https://euronews.com/2018/07/20/how-unusual-sweden-s-wildfire-problem-is
that could be used for comparing intensity and frequency of heat waves in the Arctic with the lower latitudes.

In the study the Arctic is defined as the area north of the Arctic circle, that is from 66°N on the ERA-Interim grid. Over Europe and Western Siberia this latitude is close to the AMAP defined boundary of the Arctic (e.g., AMAP 2017), while over the Eastern Siberia and North America it is positioned north of the AMAP boundary. The arbitrary choice of the southern boundary of the Arctic might impact the results of the study, because the terrestrial part of the Arctic is significantly reduced towards the North Pole.

2.2. Heat wave magnitude index daily
As in many other studies (Alexander et al 2006, Perkins and Alexander 2013, Russo et al 2015), here a heatwave is defined as a period of at least three consecutive days for which daily maximum temperature on each day exceeds the 90th percentile threshold of climatological daily maximum temperatures, centred on a 31 day window, for the base period 1981–2010. Heat wave magnitude is estimated by means of the Heat Wave Magnitude Index daily (HWMId, Russo et al 2013, 2016). The index calculation is based on three stage processes:

1. The first stage is the calculation of daily heat wave magnitude of each single day composing a heat wave as follow:

$$M_d \left( T_d \right) = \begin{cases} \frac{T_d - T_{50y25p}}{T_{50y75p} - T_{50y25p}} & \text{if } T_d > T_{50y25p} \\ 0 & \text{if } T_d \leq T_{50y25p} \end{cases}\,$$

where $T_d$ is the daily maximum temperature on the $d$th day of the heatwave. $T_{50y25p}$ and $T_{50y75p}$ are the 25th and 75th percentiles of the distribution (31 values) of maximum $T_d$ of each year in 1979–2015.

2. The second stage is the calculation of heat wave magnitude of all heat waves in a year or season: the magnitude of each individual heat wave within each year or season (Mhw) is defined as the sum of the daily magnitudes $M_d$ of the consecutive days composing a heat wave. In each year or season there may be several heat waves with different Mhw.

3. The third stage is the calculation of the HWMId. The maximum value of Mhw occurring within a given summer, which we take to represent the largest heat wave in that year or season, is then defined as HWMId at that grid point for that summer.

With this definition HWMId represents only the strongest heat wave in the year with the intensity representing the integral of daily temperature extremes during the heat wave normalized by a value representing the temperature variability at each geographical location. In case there are no heat waves in a specific year the HWMId has a value equal to zero. The HWMId is an integrated standardized measure of heat wave intensity that allows the comparison of heatwave intensity between different climatic regions (see Russo et al 2014, 2015, 2016), and is therefore particularly useful to compare heatwaves with other variables as done in this study. The HWMId has been calculated by mean of the R code recently included in the ‘extRemes’ functions of the R package called ‘extRemes’ (Gilleland and Katz 2011).

2.3. Statistical significance
Linear slopes are calculated by the Sen–Kendall method (Sen 1968) and the statistical significance is estimated by the Mann–Kendall test (Mann 1945). The statistical significance is set to the 0.05 level.

3. Heat waves in the arctic
The recent trend of summer near-surface temperatures in the Arctic, shown in figure 1, is spatially very heterogeneous. In North-Eastern Canada, Greenland, Scandinavia and Eastern Siberia temperatures rise at rates that are more than two times larger than the rates in surrounding areas. Over the Arctic Ocean the warming rate is slower, likely because the additional heating is used for melting sea ice, and over the ice free ocean heat anomalies are mixed in the ocean interior. Less rapid heating over land may be explained by anomalies in atmospheric circulation that may locally determine advection of warm air from the south and cold air from the north (Screen et al 2018).

Starting from 2001 heat waves occurred over the whole Arctic including the areas that do not show large increase of summer temperatures (figure 2). One such area is Western Siberia where heat waves appeared more than once between 2006 and 2015. In this area they occurred also between 1986 and 1990 and their appearance after 2006 may not necessarily represent an increase. On the other hand, heat waves in Greenland became more intense and widespread only after 2001 where they seem to coincide with the general rise of temperatures in summer.

In order to evaluate the relationship between the rise of near-surface temperatures in summer and heat waves, figure 3 shows temporal evolution of mean near-surface temperatures over land and heat wave indices averaged over land area in four quadrants in the Arctic. The figure also shows their linear slopes and the correlation between the two signals. The correlation may only provide a rough indication of the relation between Arctic warming and heat waves, because strong heat waves may increase the mean summer temperature in a particular year. In the first quadrant, that includes Scandinavia and Western Siberia, there is
a significant rise of near-surface temperatures, but intensive heat waves were also occurring at the beginning of the analysis period and there is no significant change in heat waves intensity during the last decades. The two signals are positively correlated indicating that, nevertheless, the Arctic warming could be related to heat waves. Similarly to the first quadrant, in the second quadrant covering Eastern Siberia near-surface temperatures rise significantly, but heat waves also seem to be intensive in the first half of the analysis period and their trend is not significant. The correlation between the two signals is similar to the first quadrant and, although, the occurrence of heat waves does not change significantly, the Arctic warming might be related to their variability. In the third quadrant covering Alaska and north-western Canada near-surface temperatures rise less rapidly than over the Eurasian continent, but heat waves become more frequent during the last decades. The correlation is lower than in the first two quadrants indicating that in this part of the Arctic the increase of heat waves could be due to the influence from the lower latitudes or changes in the atmospheric circulation. In the fourth quadrant covering North-Eastern Canada and Greenland near-surface temperatures increase continuously and heat waves become more intensive in the second half of the analysis period. In this quadrant the increase is particularly evident after 2000, and the correlation is much higher than in the other three quadrants indicating that the near-surface temperature rise could provide conditions favourable for the increase of heat wave occurrences.

It seems that over the Eurasian part of the Arctic the rise of near-surface temperatures is not connected to the frequency of heat waves, while over North America and Greenland heat waves become more frequent as near-surface temperatures become higher. Several environmental processes and distinct geographical positions of areas affected by heat waves might contribute to this difference. The Eurasian continent is larger than the North American continent and terrestrial areas in the Eurasian Arctic are often distant and southward from the ocean. Figure 2 shows that in almost all pentads heat waves in the Arctic over Eurasia often spread also over the middle latitudes indicating that they may be related to atmospheric disturbances that are not limited to the Arctic. On the other hand, the Canadian Arctic Archipelago and coastal areas of Greenland are mostly surrounded by seas and oceans that separate them from the middle latitudes, and they may be more influenced by local oceanographic conditions. In these areas the warming in summer may be more dependent on the direct radiative forcing (Screen et al 2012) and the slow

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**Figure 1.** Linear trends of temperatures at 2 m above ground (10^{-2} °C yr^{-1}) in summer (June–July–August) over the Arctic from 1979 to 2015. Dots indicate areas with statistically significant values (p = 0.05), and the thick dashed line 66°N. In the Arctic significant trends are mostly restricted to land areas.
decadal rise of the mean near-surface temperature in summer might set more favourable conditions for the occurrence of heat waves. A significantly increasing decadal trend of sea-ice melting is observed in Hudson and Baffin Bays (Bliss et al. 2019) and this process might be related to increasing heat waves in the surrounding areas.

On the other hand, after 2010 heat waves increased over continental parts of Greenland (figure 2) that are high above the sea level and where heat waves may be less influenced by the surrounding ocean. This indicates that also other factors than sea-ice melting may contribute or may be more important for the occurrence of heat waves in North-East Canada and Greenland. It has been found that the enhanced melting of the ice sheet in 2012 and similar historical events in Greenland were simultaneously related to several processes producing the anomalous transport of warm and humid air masses from the middle latitudes and to high ocean temperatures south of Greenland (Neff et al. 2014). This indicates that Arctic heat waves may be primary driven by anomalous transport of warm and humid air from the middle latitudes, but while in the past the presence of sea-ice and colder ocean could attenuate the temperature variability, the ongoing sea-ice melting may expose terrestrial areas of North-East Canada and Greenland to the stronger influence of warm and humid air masses occasionally transported from the middle latitudes.

The increase of heat waves in the North American part of the Arctic is not continuous, because in 2013 and 2014 heat waves were less intense than in 2012 and 2015 (figure 3). In particular, in 2013 a weaker heat wave over the Canadian Arctic Archipelago and Greenland happened concomitantly with a very strong heat wave over the western part of the Eurasian Arctic.

Figure 2. Occurrence of heat waves in pentads from 1981 to 2015. Values represent cumulative heat wave indices in each pentad. In order to present pentads years 1979 and 1980 are omitted from the figure. The thick dashed line indicates 66°N.
The discontinuous change of heat waves in different areas of the Arctic may indicate that in the near future heat waves might increase also in the other areas of the Arctic or decrease in its North American part that currently seems to be mostly affected.

The percentage of area covered by heat waves over the northern hemisphere increased during the analysis period (figure 4). The increase of areas covered by heat waves over the middle and low latitudes was especially marked starting from 2010. In the high latitudes the increase started already from 2002 and heat waves covered larger percentages of land area. In particular, in 2007 and 2010 the probability for experiencing the heat wave anywhere in the Arctic was larger than 10%
and at some latitudes in the Arctic it was larger than 30%. In general, after 2000 the probability of heat waves in the Arctic was larger than in the middle and low latitudes. Between 75°N and 80°N it reached 20%, meaning that on average in these latitudes one could experience strong heat waves in three summers during the 15 years long period. Figures 2 and 3 show that the increase of the occurrence probability was mainly due to heat waves occurring over the Canadian Arctic Archipelago and Greenland.

4. Conclusions

By evaluating the occurrence of heat waves, the study shows that in the last decades there was an increase of heat waves in the terrestrial Arctic. Although near-surface temperatures raised over the most of the terrestrial Arctic, the increase of heat waves happened almost exclusively over North-Eastern Canada and Greenland, while it did not change significantly over the Eurasian continent. The increase over North-Eastern Canada and Greenland appears simultaneously with sea-ice melting and warming of the surrounding ocean and further research is necessary for understanding the relationship between sea-ice melting, ocean heating and increasing occurrences of heat waves.

Heat waves in the Arctic were occasionally recorded before the period of the study, like the heat wave in July 1972, impacting Norway, Sweden, Finland and Russia (Russo et al. 2015). On the other hand, there is no indication of decadal trends of heat wave occurrences in the past that would be comparable to the current increase. Here we further show that since 2002 the probability to experience heat waves in the Arctic has been larger than the probability in the middle and low latitudes. By considering a number of negative effects on the environment and local population that heat waves may produce in the Arctic, it may be concluded that they have already started to increasingly threaten local ecology, human health and economy. In the future the evaluation of the frequency and intensity of heat waves by the heat index may provide an additional information on the intensity of the warming in the Arctic and its influence on the local ecosystems and communities. As a standardized index that is applied at other latitudes, the heat wave index may be also used for comparing the severity of environmental changes in the Arctic with respect to other parts of the globe.

Data availability statements

ERA-Interim analysis are freely available from the ECMWF data server (https://ecmwf.int/en/forecasts/reanalysis-datasets/era-interim). The R code for calculating heat waves is freely available as the ‘hwmid’ functions of the R package ‘extRemes’ (https://cran.r-project.org/web/packages/extRemes/index.html). The heat wave data that support the findings of this study are available from the corresponding author upon reasonable request.

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