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Past perspectives on the present era of abrupt Arctic climate change

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Abrupt climate change is a striking feature of many climate records, particularly the warming events in Greenland ice cores. These abrupt and high-amplitude events were tightly coupled to rapid sea-ice retreat in the North Atlantic and Nordic Seas, and observational evidence shows they had global repercussions. In the present-day Arctic, sea-ice loss is also key to ongoing warming. This Perspective uses observations and climate models to place contemporary Arctic change into the context of past abrupt Greenland warmings. We find that warming rates similar to or higher than modern trends have only occurred during past abrupt glacial episodes. We argue that the Arctic is currently experiencing an abrupt climate change event, and that climate models underestimate this ongoing warming.

The Arctic is currently warming on average more than twice the global mean, with some regions experiencing even higher rates. Additionally, sea-ice extent is decreasing in all months, which is accompanied by significant sea-ice thinning[1–4]. This ongoing change has both local and remote impacts on the climate system, influencing the local surface energy budget as well as large-scale ocean and atmospheric circulation patterns[5–14] and ecosystems[15,16].

Is the speed of recent observed Arctic change unprecedented? How do these trends compare with the most pronounced abrupt changes recorded in the palaeoclimate record? Are there similarities between current and past changes in terms of triggering mechanisms? We present answers to these questions by comparing ongoing and projected change with examples of abrupt changes recorded in Greenland ice cores.

Estimated current rates of change and the spatial patterns of trends in ongoing Arctic warming can be obtained by analysing ERA-Interim reanalysis data[17]. Annual mean temperature trends over the Arctic during the past 40 years show that over this period, where satellite data are available, major portions have warmed by more than 1 °C per decade (Fig. 1a, red colours and outlined portion; a warming of 4 °C within 40 years is hereafter referred to as 1 °C per decade). The most pronounced warming is seen over the Eurasian sector of the Arctic Ocean and adjacent land areas, with the highest rates of change in the Barents Sea and over Svalbard, where rates of change are twice the mean of the Eurasian Arctic.

The spatial pattern of the warming can be compared with the trend in Arctic sea-ice cover over the same period (Fig. 1b). Areas with high rates of temperature change closely match the regions with high rates of sea-ice loss, emphasizing the expected link between high-amplitude warming, high rates of temperature change and concurrent sea-ice retreat. A natural question that follows from this observation is are these rates of change comparable to the abrupt changes identified in the palaeoclimate record?

Abrupt climate changes, as seen in Greenland

We next turn to the records of abrupt change in the Greenland ice-core record and compare these with modern Arctic changes.

Last glacial D–O events. During the last glacial period (120,000–11,000 years ago), more than 20 abrupt periods of warming, known as Dansgaard–Oeschger (D–O) events, took place[18,19]. Their impacts can be detected globally in palaeo-archives[20], but their most marked expression is seen in the deep Greenland ice-core records[21–23]. These are the classic and most discussed examples of abrupt climate change, characterized by a series of rapid and high-amplitude warming events over Greenland followed by a more gradual return to cold conditions[18,19]. They show that key elements of the climate system are capable of changing abruptly—in particular, in the Arctic region—but with major repercussions throughout the climate system[24–26]. Here, we compare present rates of change with those of the past, acknowledging the differences in background climate state (last glacial versus modern era of global warming), differences between their forcing mechanisms (greenhouse gas-driven change in the contemporary Arctic versus unforced change in the past) and differences in the geographical positioning of the changes. In addition, we note that many of the proposed mechanisms driving D–O events involve sudden changes in the strength of the Atlantic Meridional Overturning Circulation (AMOC) and associated ocean–atmosphere heat flux[27,28], with sea-ice retreat a critical aspect driving the event rapidity and amplitude[29–33]. Here, however, we focus primarily on the rates of change rather than the physical mechanisms of the processes involved. A recent review of the dynamics can be found in ref. [34].

Quantifying the amplitude of the abrupt warmings recorded in ice cores is done by calibrating the water isotope palaeothermometer with absolute temperature change estimates derived from measurements of gas fractionation[35–37]. The most comprehensive

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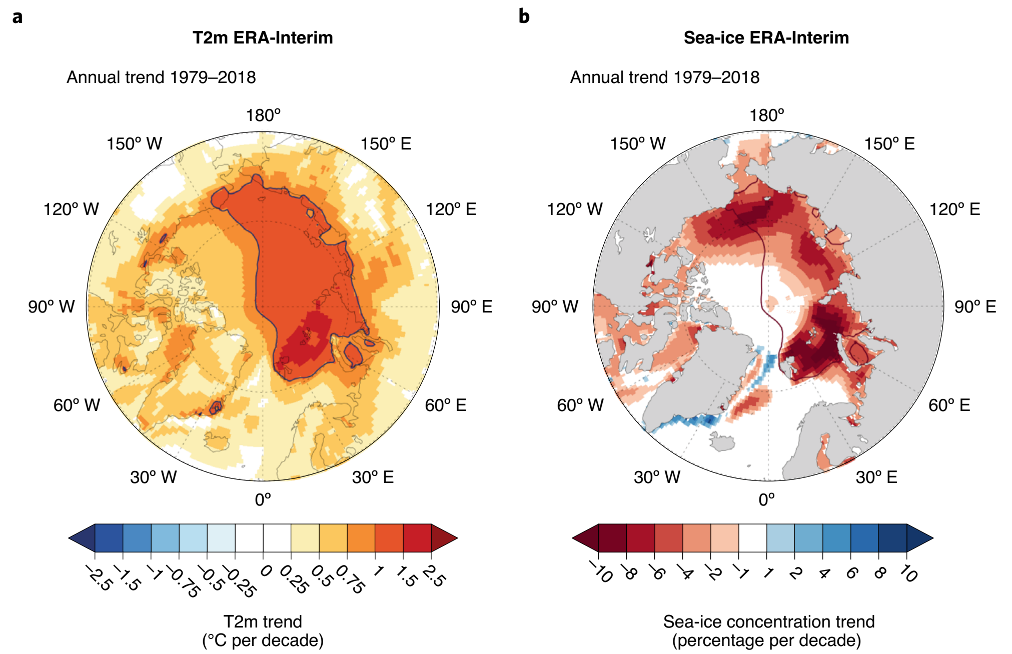

Fig. 1 | Trends in Arctic temperature and sea-ice cover. a, Near-surface air temperature (T2m) trend (°C per decade) over 1979–2018 from ERA-Interim[17,70]. Areas without a statistically significant change (determined using a one-sided Student's *t*-test, with $P < 0.05$ indicating a significant difference) are masked out (no colour). **b**, Sea-ice concentration trend (percentage per decade) over 1979–2018 from ERA-Interim[17,70]. Trends with a magnitude smaller than ±1% per decade are masked out (no colour). The blue and maroon contour lines in the panels signify the area from Fig. 1a with a near-surface air temperature trend greater than 1 °C per decade. The trends are calculated for the entire 40-yr period and expressed as the change per decade.

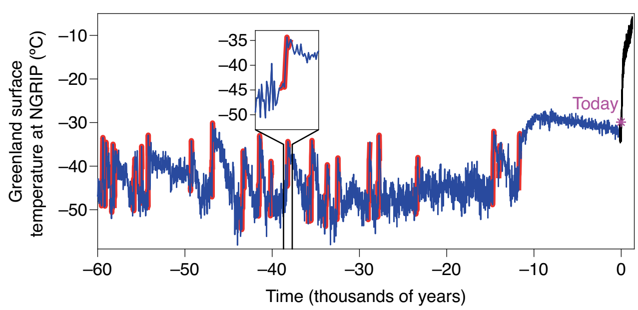

Fig. 2 | Greenland temperature record over the past 60,000 years. Past and future temperatures at the NGRIP deep ice coring site on the Greenland Ice Sheet. The blue lines indicate reconstructed past temperatures based on ice-core water isotope data calibrated using the methodologies in refs. [38,75]; red lines indicate periods of sustained temperature increases of 1 °C per decade or higher over 40 years within a 100-yr period and without a return to cold temperatures; and the black line indicates simulated temperatures at NGRIP from the EC-Earth model forced by RCP 8.5 emissions[72], with present-day simulated temperatures indicated by a purple asterisk. Inset: example of an abrupt temperature increase (D–O event) in more detail.

calibration[38] has been used to convert North Greenland Ice Core Project (NGRIP) ice-core $\delta^{18}O$ data, available at 20-yr resolution, to estimates of surface temperatures at NGRIP during the past 60,000 years (Fig. 2). Using the high-resolution isotope record provides optimal temporal resolution, whereas the absolute temperature from the lower-resolution ice-core gas record is used for calibration, giving a well-calibrated record of absolute temperature change at a reasonable resolution for analysis. The water isotope data used to estimate the duration of the transition in the NGRIP ice core diffuse to some degree with depth, but even at the deepest part of the NGRIP core this diffusion amounts to only a couple of years. Hence this is not a concern for the analysis presented here.

To identify periods in the palaeoclimate record with rates of change similar to or higher than that in the modern Arctic in Fig. 1, we use a criterion of at least 1 °C per decade sustained for 40 years along the Greenland ice-core record. The Greenland ice-core data are used because this is the only quantitative record of past atmospheric temperature with a high-enough temporal resolution that allows for comparison with ongoing trends. The time periods in the NGRIP record that satisfy the present-day warming criterion are highlighted in red in Fig. 2. Remarkably, only the abrupt D–O events and the glacial termination meet this criterion. No other periods of the Greenland ice-core temperature record exhibit similar rates of change as those of the modern Arctic, while some D–O events have even higher rates of change, up to 2.5 times those of this criterion (Supplementary Table 2).

Present and future warming on Greenland

It is important to recognize that the D–O events in the palaeoclimate record of Fig. 2 represent temperatures over the interior Greenland Ice Sheet, while the contemporary warming in Fig. 1 is highest in the central Arctic and across the Arctic Ocean. We therefore include the degree to which central Greenland may warm under a high-end, unmitigated emissions scenario for comparison. An estimate of future warming using an Earth system model (the European Community Earth System Model (EC-Earth)) under the extended representative concentration pathway (RCP) 8.5 scenario[39,40] at the NGRIP ice coring site is shown in Fig. 2. We choose this model experiment because it lasts until the year 3200 and thus affords a long-term perspective of the Greenland Ice Sheet's response to a high-end emissions scenario. The simulated long-term future warming is of similar amplitude to the D–O events of the past but at a substantially slower rate that does not exceed the 1 °C per decade threshold. This implies an abrupt full-Arctic warming trend may not be reflected in the rate of warming in the Greenland Ice Sheet interior, despite its presence in other regions experiencing sea-ice loss. This is likely due to the elevated location and the position of most of Greenland to the south, and upstream and upwind, of the Central Arctic.

Glacial abrupt changes in models and reconstructions

To set these results into a future perspective, we compare the observed and reconstructed temperature changes for the present and the past (Figs. 1 and 2) with model simulations of past and future changes. Climate model and proxy data reconstructions of the transitions from cold (stadial) to warm (interstadial) periods during D–O transitions of the last glacial are shown in Fig. 3. A reconstruction of the mean abrupt surface temperature changes over Greenland is obtained by stacking a number of abrupt transitions recorded in the NGRIP ice core[19,41], centred by their temporal midpoints as recorded in the NGRIP water isotopic record. In order to objectively define this midpoint, we apply a ramp-fitting method (A. Grinsted and S. O. Rasmussen, personal communication) based on probabilistic inference using an ensemble Markov Chain Monte Carlo (MCMC) sampler[42]. Similar to refs. [43,44], such an approach is based on the assumption that the abrupt shifts observed in the ice core $\delta^{18}O$ record can be characterized as a ramp or linear change from one stable state to the other, for which the onset, midpoint and end can be precisely quantified, as well as the associated uncertainties.

Focusing on the sequence of events from DO5 to DO9, we use the ramp-fitting method on a 500-yr time window around the date corresponding to the onset of each of those transition events, as identified visually by ref. [19]. These are compared to simulated temperature changes over central Greenland from the Norwegian Earth System model (NorESM[45,46]) in an experiment with glacial boundary conditions set to a period 38,000 years ago when D–O events were prevalent[47]. A cold, stadial situation with extensive sea-ice cover was established by a relatively strong forcing by freshwater hosing imposed on the equilibrium (interstadial) simulation, after which the forcing stopped and the model relaxed back to its warm, interstadial state[48] (see Supplementary Text 1 for details of the experiment). The modelled transition from a cold state with extensive sea-ice cover to one with less sea ice compares well in amplitude, rate of change and duration with the mean reconstructed temperature changes from the Greenland ice core (Fig. 3), with a peak rate of change exceeding 2 °C per decade over central Greenland (Fig. 4a). The model simulation lies clearly inside the range of individual events over Greenland, while the mean ice-core change has somewhat higher amplitude and rate of change than the model experiment. The rapid temperature increase of the model corresponds with a simulated rapid retreat of Nordic Seas and Labrador Sea sea-ice extent (Fig. 4b), in agreement with observed transitions found in sea-ice proxy data from a marine sediment core in the Southeastern Nordic Seas[33]. The regional temperature impact of the simulated sea-ice retreat from the model experiment in Fig. 3 is documented in Fig. 4a,b. This shows widespread high rates of temperature change associated with the sea-ice loss during the transition out of a cold stadial period, with rates of change that in areas exceed those found in Fig. 1 for recent decades.

By matching dated tephra (volcanic ash) layers found in the Greenland NGRIP ice core to the same tephra layers in the marine sediment record, it has recently been shown that the initial retreat of sea ice in the south-eastern Nordic Seas precedes the start of the atmospheric warming recorded in the Greenland ice cores[33]. During the interstadial warm phase of D–O events, sea ice is absent in the eastern Nordic Seas, the ocean stratification is weak, and the upper and intermediate layers of the ocean are well-ventilated[31,33]. When forced with either reduced transport of heat by inflowing Atlantic water or increased freshwater input to the surface ocean, sea ice is re-established in model simulations of the Nordic Seas, initiating the next cold stadial period[49,50].

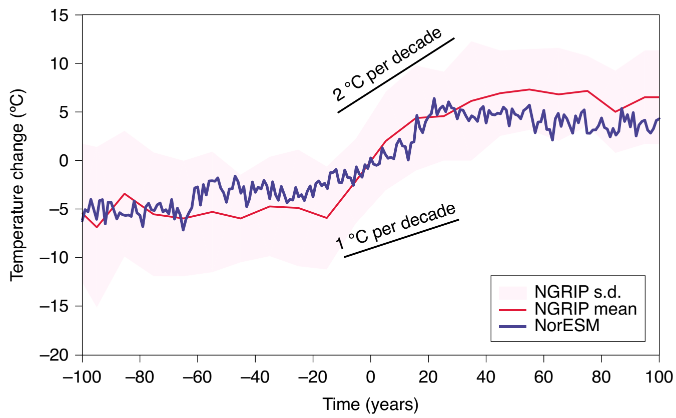

Fig. 3 | Comparison of reconstructed and modelled Greenland abrupt changes. Marine Isotope Stage 3 (MIS3) surface temperature change at the summit of Greenland across a forced stadial-to-interstadial transition, as simulated by NorESM (with boundary conditions representing the period 38,000 years before present) compared to a stacked oxygen isotope-based temperature record from NGRIP DO event 5 to DO event 9 (40,000–32,000 years before present). The red shading represents the NGRIP standard deviation (s.d.) based on $\pm 1\sigma$ for each 10-yr period. The inserted thin lines indicate for reference the slopes of 1 °C and 2 °C per decade, respectively.

The close correspondence between the simulated and measured rapid transition in Greenland temperature gives confidence that key physical mechanisms governing the abrupt transitions are captured by the climate model. In the past, both models and data indicated that disappearing sea ice precedes abrupt temperature change, and this has also been evident for the past 40 years (Fig. 1). Glacial abrupt changes in Greenland temperature have been simulated by a range of models with varying degrees of complexity; for examples, see refs. [29–31,51–54]. A common feature in all of these models is the occurrence of abrupt changes in sea-ice extent under glacial boundary conditions. Recent studies suggest, however, that large unforced abrupt changes in sea ice can also occur in some models forced with pre-industrial boundary conditions[55,56]. This poses the question: if abrupt changes in sea-ice cover are an inherent feature of the coupled climate system, could this also cause abrupt changes in Arctic temperature in the near future?

Models underestimate the high rates of Arctic change

For comparison, the simulated trends in twenty-first century temperature and sea-ice cover from NorESM forced by RCP 8.5 are shown in Fig. 4c,d. Regions predicted to exceed surface air temperature increases of 1 °C per decade are restricted to the central Arctic and are associated with areas of rapidly decreasing sea-ice cover. This suggests that projected Arctic temperature change under a high-end emissions scenario is of comparable magnitude to rates of change in Greenland temperature recorded during D–O events. Here, temperature trends during D–O events (Fig. 4a) exceed those observed in recent decades in some Arctic regions (Fig. 1a) and in the RCP 8.5 scenario simulation (Fig. 4c), though there are also differences such as the colder background climate of the glacial, and the location of sea-ice loss. The higher trends in the palaeoclimate simulation are probably an effect of the much larger sea-ice cover. Furthermore, the high rates of temperature change are associated with areas of strong reductions in sea-ice cover. Taken together with

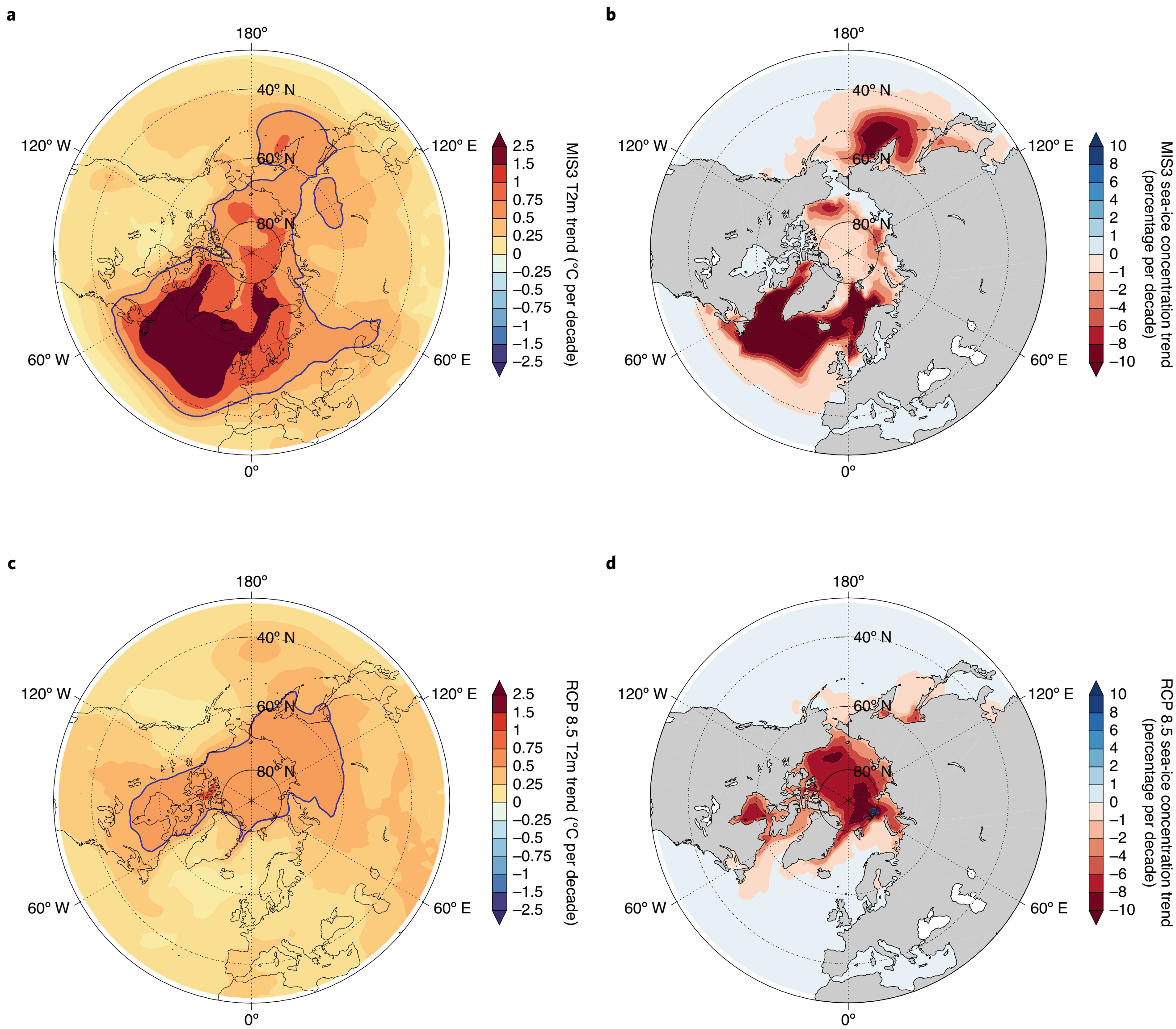

Fig. 4 | Past and future rapid temperature trends. a–d, Comparisons of simulated past and future changes. **a**, MIS3 surface decadal temperature trend across a stadial-to-interstadial transition, as simulated by the NorESM climate model. **b**, Sea-ice trend in percentage area change from the same model as in **a**. **c**, Decadal temperature trend under RCP 8.5 (2061–2100), as simulated by the NorESM model. **d**, Rates of change of sea-ice cover for the same experiment as in **c**. The blue contour lines in panels **a** and **c** signify the area with a near-surface air temperature trend greater than 1 °C per decade.

the observed recent Arctic warming in Fig. 1, this implies lower rates of temperature change in regions not experiencing diminishing sea-ice cover, including the summit of the Greenland Ice Sheet and coastal Greenland (Figs. 1 and 2).

Having established a close relationship between sea-ice changes and rapid contemporary Arctic and past Greenland warming, we ask to what extent state-of-the-art Earth system models simulate trends of similar magnitude. We have analysed the CMIP5 (ref. [57]) models across the RCP 2.6, 4.5 and 8.5 scenarios during 1979–2100, overlapping with the interval covered by the reanalysis data used in Fig. 1. The consistency of the simulated Arctic warming among CMIP5 models is displayed in Fig. 5. By combining information from the CMIP5 historical (1979–2005) and future (2006–2100) scenario periods, this analysis allows for the time evolution and magnitude of sea-ice reduction to differ among models and assumes trends will vary depending on individual model sea-ice cover. In this way, it enables a comparison to the period of the reanalysis data (Fig. 1) identifying models that pass the abruptness criterion (1 °C per decade) at any point during the period 1979–2100.

We find that the abrupt change threshold is surpassed in several models in regions of the Arctic, more extensively in the high-emissions scenario (RCP 8.5) relative to the lower-emissions scenarios (RCP 2.6 and 4.5). However, the observed warming trend in the reanalysis data over the Arctic in recent decades is more abrupt and covers a substantially larger area (Fig. 1) than in the models (Fig. 5), even through the twenty-first century (with the possible exception of RCP 8.5). In RCP 2.6, which has a mean temperature change in line with the 2 °C target of the Paris Agreement[58], less than half of the models show abrupt changes, with rates as high as those observed during the last 40 years. From this, we infer that climate models underestimate the abruptness of the recent changes observed in the Arctic, and that high rates of change in temperature manifest themselves earlier and are more widespread in observations than those predicted by CMIP5 models. This is also

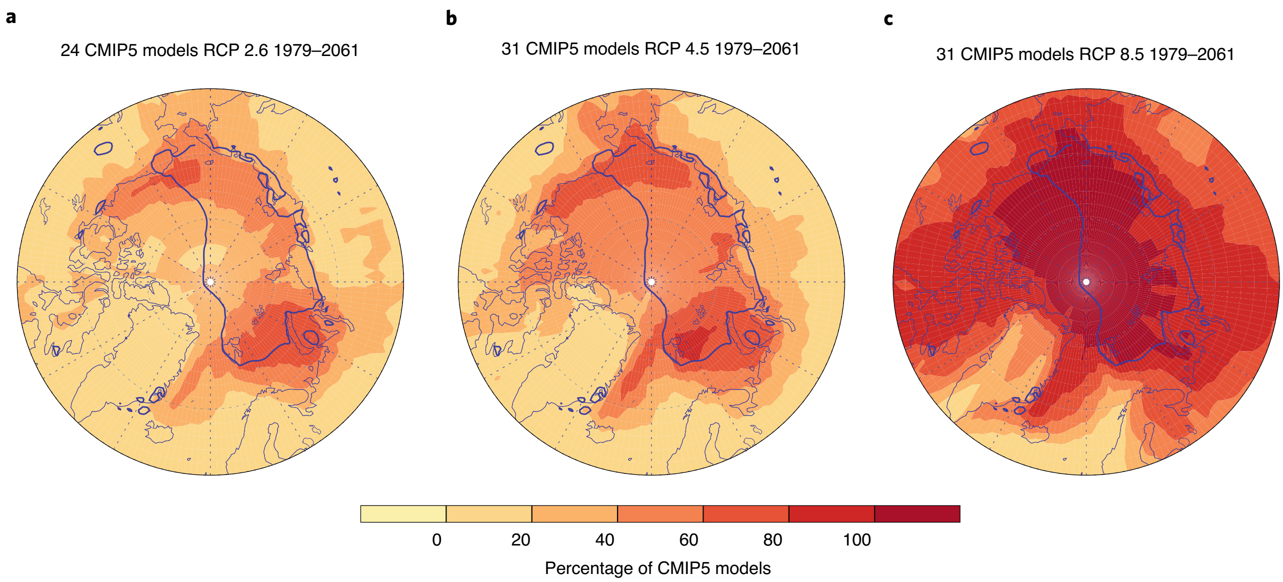

Fig. 5 | Arctic temperature trends under different forcing scenarios. Areal distribution of the percentage of CMIP5 models reaching a near-surface air-temperature trend greater than 1 °C change per decade sustained for 40 years at some point in time during the period 1979–2100 in the RCP 2.6 (left), RCP 4.5 (middle) and RCP 8.5 (right) scenarios, respectively. The number of models represented are 24, 31 and 31, respectively. For comparison, the blue lines show the areas with increases exceeding 1 °C per decade sustained over 40 years (from Fig. 1).

corroborated by the finding of Flato et al.[59] that most of these models are unable to capture recent accelerated sea-ice loss. This is the case both for the entire Arctic and for the eastern Arctic, where most of the recent warming has taken place (Supplementary Fig. 1). Note we also highlight trends in the NorESM model compared with the rest of the CMIP5 ensemble (Supplementary Fig. 1).

While the D–O simulation with NorESM captures abrupt warming, the physical mechanisms behind sea-ice reduction during a D–O event and today's Arctic decline are very different—in one case internally driven, in the other radiatively forced. NorESM returns to a warm climate state when freshwater hosing ceases in the D–O experiment. As discussed in the previous section, several models display abrupt changes in sea-ice extent under glacial conditions, though in general, models are unable to capture the forced response of ongoing sea-ice decline in the central Arctic.

In order to assess whether this shortcoming of the models can be understood in terms of their climate sensitivity, we rank them according to the size of the area experiencing abrupt change under the RCP 2.6 and 4.5 scenarios, and list their equilibrium climate sensitivity (ECS), calculated following the methods outlined in ref. [60] (Supplementary Table 1). We find a weak dependence of the degree of abrupt Arctic temperature change on climate sensitivity; the higher climate sensitivity, the larger the area experiencing abrupt warming. Only models with relatively high climate sensitivity display rapid warming (>1 °C per decade), except in RCP 8.5. However, there are some models with high climate sensitivity that do not display such rapid warming, regardless of forcing. Taken together, this suggests that climate model sensitivity is important for representing the ongoing rapid changes in the Arctic in the lower-end scenarios: models with higher climate sensitivity are more likely to simulate Arctic temperature trends in agreement with observations.

More broadly, this illustrates that while large-scale sea-ice decline is central to creating widespread rapid warming signals in both present-day and glacial settings, the underlying mechanisms behind sea-ice decline may differ, either because they are different mechanisms altogether or because key Arctic processes are inadequately represented in the CMIP5 ensemble.

Abruptness of current changes in the Arctic

Abrupt climate change has been defined as "a transition of the climate system into a different mode on a time scale that is faster than the responsible forcing"[61]. It is also described as a nonlinear response to an external forcing, but as noted in IPCC Fifth Assessment Report[28], abrupt changes could also arise from internal mechanisms of the ocean, atmosphere and sea-ice systems in the absence of external forcing. Many palaeoclimate archives document climate changes that happened at rates considerably exceeding the average rate of change for longer-term averaging periods prior to and after this change, with the D–O events representing the clearest examples. A variety of mechanisms have been suggested to explain the emergence of abrupt changes. Most of them invoke the existence of thresholds in the underlying dynamics of one or more Earth system components. Both internal dynamics and external forcing can in theory generate abrupt changes in the climate state, and abrupt behaviour has also been detected in unforced model simulations[32,56].

Nevertheless, the only times over the past 60,000 years that Greenland temperature change exceeded 1 °C per decade was during abrupt D–O events; no other interval in the ice-core temperature record displays a 40-yr period or longer with such high rates of change. By this measure, we argue that changes occurring during modern Arctic warming and past D–O events can together be defined as abrupt, and we view the present as an era of abrupt climate change in the Arctic.

While both the current and past records discussed here reflect atmospheric temperature change, the palaeoclimate record represents temperature in the interior Ice Sheet, while current Arctic change is occurring over or proximal to the region of sea-ice loss. As the warming spread from the region of sea-ice loss, it is worth noting that the past warming over the regions of sea-ice loss during D–O events has likely been higher than what is sampled in the ice core[30]. Similarly, it is also worth noting from Fig. 2 that the recent warming over central Greenland does not qualify as abrupt according to this criterion. Disappearance of sea-ice cover appears to be a prerequisite for abrupt change, common to both the glacial and modern cases. The rates of change in D–O events were on average higher than those of the present Arctic, and the area of

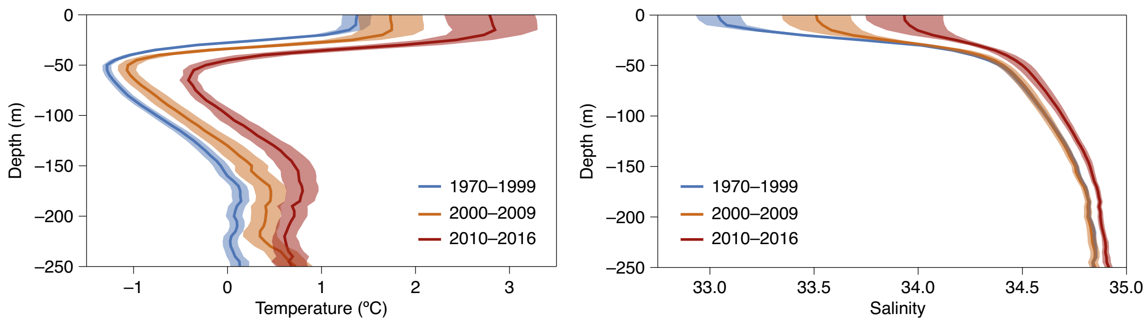

Fig. 6 | Evidence for ongoing Atlantification in the Arctic. Atlantification of the European Arctic: observed temperature (left) and salinity (right) profiles for the Northern Barents Sea from 1970–2016, showing warming and salinification as sea ice in the European Arctic is reduced (reproduced from ref. [67]). Line denotes mean values; shading indicates the standard error of the mean (s.e.m.).

sea-ice loss potentially higher, as indicated in model experiments. During D–O events, the warming originating from an ice-free surface ocean reached 3 km above sea level in central Greenland due to the location of the open ocean to the south and east of the Ice Sheet. Modern changes in the Arctic are apparently not affecting Greenland in a similar fashion, potentially because the sea-ice loss is occurring upstream of Greenland[62].

Another difference is the mechanism driving the warming. A destabilization of Arctic Ocean stratification has not been observed in contemporary climate, though this appears to have happened at the onset of the D–O warmings[31,33,63], enabling warmer subsurface waters to be lifted to the surface. If this occurred in the modern Arctic, such an event would exacerbate Arctic warming and force longer-term change, as discussed below. So far, the abrupt temperature change over the Eurasian Arctic appears to be primarily a result of radiative feedbacks occurring within relatively little change to ocean circulation.

A potential mechanism for future abrupt Arctic change

A key factor for maintaining extensive Arctic sea-ice cover is the strong stratification of the underlying water column: sea ice is protected from the warm and salty Atlantic layer underneath by a fresh surface layer and a strong halocline[64,65]. We pose the question: could the ongoing warming and sea-ice loss abruptly transform areas of the Arctic Ocean into a permanently ice-free ocean, potentially with deep mixing? Currently, deep oceanic convection only occurs in the Nordic Seas and Labrador Sea, and is inhibited in the Arctic Ocean by stable surface stratification. With a few exceptions, CMIP5 model simulations do not initiate deep convection within the Arctic Ocean under future warming scenarios. However, current state-of-the-art Earth system models have a poor representation of Arctic Ocean stratification[66], and it is therefore questionable whether future projections adequately describe the risk of such a change. In high-end emissions scenarios, most models predict a seasonally ice-free Arctic sometime in the second half of the twenty-first century in response to the change in radiative forcing. The areas that have or will exceed the threshold value of abrupt change in the twenty-first century under low-, mid- and high-emissions scenarios are shown in Fig. 5. These models retain a stable stratification of the surface layer in the Arctic throughout the twenty-first century due to higher surface temperature and lower salinities from an enhanced hydrological cycle and seasonal melting of sea ice. The rates of change and timing would be very different if the stratification were to break and areas of the Arctic Ocean started to convect in a manner similar to the D–O events[31,33].

In the Fram Strait and Northern Barents Sea, observations over the last decades show a dramatic increase in the meridional ocean heat transport, which—combined with greenhouse gas-induced radiative forcing—has led to reduced sea-ice cover[67,68]. The future strength of this ocean heat transport depends on the strength of the different limbs of the northward transport of warm Atlantic water into the European Arctic, which, to a large extent again, depends on the atmospheric circulation[65] and on the heat carried by these currents.

Associated with this heating, there is also increased salinity in this region (Fig. 6) due to higher-salinity water flowing in from the Atlantic and meltwater from melting sea ice being transported further inside the Arctic Ocean. This Atlantification of the European sector of the Arctic Ocean suggests a situation similar to the initiation of warm D–O transitions, where increased ocean heat flux and sea-ice retreat at the entrance to the Nordic Seas lead to a subsequent phase of strong convection and ventilation[33]. One may speculate that further Atlantification of the Arctic may initiate instability and convection. Our reconstructed estimates of the stratification in the Nordic Seas during D–O cycles, however, point to warmer subsurface waters than observed in the current Arctic Ocean, implying the stratification was less stable in the past than today[63,69]. Thus, we are likely not yet at the threshold[49,63] that could generate overturning. In order to evaluate the realism of such a future scenario with convection inside the Arctic Ocean, improved models and better observations of Arctic stratification are needed as well as more highly resolved freshwater fluxes in models and their future Arctic Ocean pathways. The lessons from the past clearly show that the combination of sea-ice loss and associated ocean physics carry a potential for abrupt changes and threshold exceedance that can sustain sea-ice loss and associated atmospheric warming over centuries. Based on current Earth system models, we cannot rule out similar mechanisms becoming active in the Arctic in the following decades.

Conclusions

Using a criterion based on the speed of near-surface air temperature warming over the past four decades, we find that the current Arctic is experiencing rates of warming comparable to abrupt changes, or D–O events, recorded in Greenland ice cores during the last glacial period. Both past changes in the Greenland ice cores and the ongoing trends in the Arctic are directly linked to sea-ice retreat—in the Nordic Seas during glacial times and in the Eurasian Arctic at present. Abrupt changes have already been experienced and could, according to state-of-the-art climate models, occur in the Arctic during the twenty-first century, but climate models underestimate current rates of change in this region. Among the various emissions scenarios in CMIP5, only for those with mitigation pathways commensurable with Paris Agreement targets does the Arctic avoid abrupt future change. To constrain future risks of abrupt and sustained warming, improved observations and model representation of Arctic Ocean circulation, stratification, salinities and freshwater budgets are needed.

Data availability

For Fig. 1, The ERA-Interm data are available from https://www.ecmwf.int/en/forecasts/datasets/archive-datasets/reanalysis-datasets/era-interim (ref. [70]). For Fig. 2, NGRIP data are from http://www.iceandclimate.nbi.ku.dk/data/2010-11-19_GICC05modelext_for_NGRIP.xls (ref. [71]). For Figs. 3 and 4, the NorESM Marine Isotope Stage 3 simulation is available through the Norwegian Research Data Archive: https://doi.org/10.11582/2020.00006 (ref. [48]). The NorESM RCP 8.5 simulation is available from the CMIP5 ESGF archive: https://esgf-node.llnl.gov/projects/cmip5/ (ref. [72]). The data of 40-year near-surface air temperature (TAS) trend to make Fig. 5 are available at: https://doi.org/10.5281/zenodo.3631549 (ref. [73]). Data for Supplementary Fig. 1 are available at: https://doi.org/10.5281/zenodo.3631409 (ref. [74]). The model data for calculation of these 40-year TAS trends are downloaded from: https://esgf-node.llnl.gov/projects/cmip5/ (ref. [72]). Files to reproduce Figs. 1–5 can be found in Supplementary Data.

Code availability

Code used to generate the figures can be downloaded from the project website: https://ice2ice.w.uib.no/publications/ and from GitHub: https://github.com/ice2ice-synthesis/Nature-Climate-Change-perspective.git. Files to reproduce Figs. 1–5 can be found in Supplementary Data.

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Author contributions

E.J., J.H.C., T.D., K.H.N. and B.M.V. developed the synopsis and drafted the manuscript with input from P.L.L. C.G., K.H.N., M.S., B.M.V., S.Y. and M.S. provided the figures. M.B., C.G., E.C., M.F.J., H.A.K., H.S. and E.S. provided model and observational data. All authors contributed to the writing and revision of the text. E.J. coordinated the drafting of the manuscript and the final version.

Competing interests

The authors declare no competing interests.

Additional information

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