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Arctic warming amplifies climate change and its impacts

ScienceBrief Review

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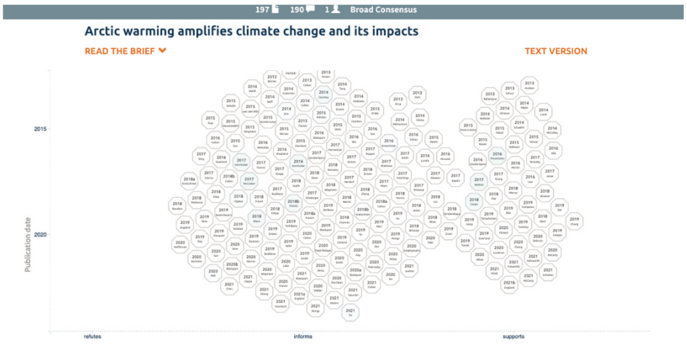
Approach. This ScienceBrief Review examines the evidence linking Arctic warming to the amplification of climate change impacts in Arctic, boreal and mid-latitude regions. It synthesises findings from more than 190 peer-reviewed scientific articles gathered using ScienceBrief. The Brief and evidence can be explored at: https://sciencebrief.org/topics/climate-change-science/arctic.

Summary. The Arctic region has warmed at least twice as much as the global average, leading to a number of environmental consequences. The extent and thickness of sea-ice have decreased and rates of permafrost thaw have increased in recent decades. The impacts of rising mean annual temperatures have been exacerbated by an increase in heatwaves this century. Wildfires are releasing greenhouse gases, while the loss of sea ice is reducing the amount of solar energy reflected by the Earth’s surface. These changes amplify climate change and its impacts. Permafrost thaw will further amplify climate change. There is ongoing debate about how changes in the Arctic energy balance influence patterns of extreme weather in the mid-latitudes.

Key points

The evidence shows that disproportionate warming in the Arctic leads to sea ice decline, land-glacier melt, permafrost thaw and wildfires and that some of these trends exert amplifying feedbacks to climate change. Arctic amplification and mid-latitude extreme weather have been shown to occur contemporaneously, but there is active debate among researchers whether the cause and effect of multiple physical processes has been robustly demonstrated.

- Observed Arctic warming anomalies have led to a decline in summer Arctic sea ice extent, up to 60% below the 1980s average (Overland et al., 2019).
- Arctic permafrost has begun to thaw in multiple regions, due to warming, with an average +6.8 cm thickening of seasonally thawed permafrost (Hayes et al., 2014).
- Greenhouse gas emissions from future permafrost thaw are projected to increase under all future emissions scenarios, forming an important amplifying feedback to climate change. The scale and pace of this feedback is uncertain (+12 GtC to +174 GtC), representing +0.05°C to +0.5°C of additional warming by 2100 (Schaefer et al., 2014; Koven et al., 2015; Schneider von Deimling et al., 2015; Schuur et al., 2015).



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Snap shot of the Brief at the time of publication showing broad consensus among the evidence analysed. Click here to visit the Brief.

- Arctic wildfires have become more frequent in response to more frequent and longer periods of fire weather (Masrur et al., 2018; Box et al., 2019; Justino et al., 2021). Wildfire frequency and intensity are projected to increase in the future (Coogan et al., 2019).
- Climate models project that Arctic sea ice-free summers could occur by 2050 under a high (RCP8.5) future emissions scenario (Landrum et al., 2020).

Background. Arctic amplification - the warming of the Arctic region at over twice the global average amount - has been occurring for a number of decades (Overland et al., 2016; Box et al., 2019; Cohen et al., 2020; AMAP, 2021). Numerous impacts are linked to this, including reduced sea-ice extent, more frequent summer heatwaves and wildfires, as well as permafrost thaw releasing greenhouse gases (Schuur et al., 2015; Box et al., 2019; Tanski et al., 2019; Dobricic et al., 2020).

There is a growing body of literature linking Arctic amplification and mid-latitude extreme weather (autumn/winter cold waves, snow storms and spring/summer heatwaves), via changes to large-scale atmospheric circulation (Vihma et al., 2014; Cohen et al., 2014, 2020, 2021; Coumou et al., 2018; Overland et al., 2021). While there appear to be increases in both Arctic and mid-latitude extremes over some timeframes, the causal mechanisms and their relative strength remain uncertain (Cohen et al., 2014, 2018a,b, 2020, 2021; Francis, 2018b; Blackport et al., 2020a, 2020b; Blackport & Screen, 2021). For further discussion see Box 1.

Box 1: Recent mid-latitude extreme weather - forced response to Arctic warming or internal variability?

There is ongoing debate around the causes and strength of possible links between Arctic warming and mid-latitude extreme weather. The key areas of debate stem from the following:

- **Observational studies have suggested that mid-latitude extreme weather is linked to Arctic amplification** through declining Arctic sea ice extent and/or increased autumn snow cover, with changes to atmospheric circulation playing an important role (Francis & Vavrus, 2012; Francis et al., 2015; Coumou et al., 2015, Cohen et al., 2016, 2018a, 2018b, 2021).
- **Observational studies are unable to demonstrate causality** and rely on statistical relationships that could equally be a cause of, or response to, variability in mid-latitude atmospheric circulation (Blackport & Screen, 2021). Satellite observations have a relatively short time series (~40 years), so that observed analyses are subject to considerable sampling uncertainties (Kolstad & Screen, 2019; Warner et al., 2020).
- **Recent climate modelling and analysis points towards atmospheric circulation driving temperature anomalies, with Arctic sea ice responding.** Coupled climate model experiments simulate both observed sea ice decline and mid-latitude cold waves, but only when coinciding with atmospheric-driven heat loss (Blackport et al., 2019). Lead-lag analysis of modelling simulations demonstrates that atmospheric circulation drives surface temperature and pressure anomalies that precede reduced sea ice extent, suggesting sea ice extent responds to, and does not drive, mid-latitude extreme winter weather (Blackport et al., 2019; Blackport & Screen 2021). Although lead-lag analysis of some observations and metrics imply Arctic variability leads, rather than follows, severe winter weather in the US (Cohen et al., 2018b).
- **In recent years, the strength of observed relationships between Arctic amplification and mid-latitude extreme weather may have weakened**, compared to the trends calculated earlier in the decade (Blackport et al., 2020a, 2020b), although some robust trends are still reported (Cohen et al., 2021). Atmospheric waviness may have declined in recent years (Blackport et al., 2020a), although there is also contrasting evidence (Martin, 2021), while Arctic amplification has continued, possibly suggesting forcing by something other than Arctic amplification, such as tropical forcing, or internal variability, or intermittency (Kolstad & Screen, 2019; Siew et al., 2020; Warner et al., 2020).
- **Modelling studies, needed to demonstrate causality and quantify links between Arctic amplification and mid-latitude extreme weather, have been inconclusive, with a broad spectrum of results presented** (Cohen et al., 2018b, 2020), including positive, weak/neutral and negative phase North Atlantic Oscillation (Overland et al., 2016). While individual models can show strong linkages between Arctic amplification and mid-latitude winter cold anomalies (Cohen et al., 2021), many large model ensembles show only a weak connection (Blackport et al., 2019).
- **Model simulations could underestimate the response of mid-latitudes to Arctic amplification**, due to underestimated signal (Scaife & Smith, 2018), or by forcing with sea ice loss only, such as in Blackport et al. (2019), rather than inclusion of all aspects of Arctic amplification (Francis et al., 2017; Labe et al., 2020). An additional hypothesis is that models with limited vertical extent or resolution may not resolve important stratospheric-tropospheric interactions (Sun et al., 2015; Zhang et al., 2018; Cohen et al., 2021). Although in some models, these interactions were intermittent and/or suffer cancelling regional effects when results are viewed at pan-Arctic scale (Sun et al., 2015; Siew et al., 2020).
- **Large natural atmospheric variability and a weak signal from forced changes to sea ice extent means large model-ensembles and long simulation lengths are needed to confidently detect the modelled response**, due to its low signal-to-noise ratio (Screen et al., 2018; Blackport & Screen, 2021; Peings et al., 2021; Xu et al., 2021). Characterising short-term (2-4 week) variability is important for metrics such as jet-stream waviness, so should not be overlooked by seasonal or longer averaging (Coumou et al., 2018).
- **Observational studies suggest Arctic amplification is linked to occurrences of mid-latitude summer heatwaves through modification of atmospheric circulation patterns.** While there have been fewer studies of links in summer than in winter, these studies suggest various hypotheses to explain how atmospheric circulation varies, including: a weakened poleward tropospheric pressure gradient, reducing storm tracks and the westerly jet stream and shifting their position (Coumou et al., 2015, 2018). An alternative hypothesis is that atmospheric (Rossby) waves are amplified by Arctic amplification and can promote blocking and prolonged weather systems, enabling extremes to occur (Coumou et al., 2014, 2018; Kornhuber et al., 2016; Mann et al., 2017). Modelling of indirect measures suggest the future strength of this effect, known as quasi-resonant amplification, could be driven by the interplay between rising greenhouse gas and falling aerosol concentrations (Mann et al., 2018). The Arctic amplification signal in quasi-resonant amplification may have emerged from natural variability in the last decade (Mann et al., 2017).
- **The future trend in mid-latitude extreme weather is likely to be driven by the interplay of Arctic and tropical teleconnections** (remote influences), both of which exert remote influences on mid-latitude extreme weather (McCusker et al., 2017; Coumou et al., 2018).

Observations

Arctic amplification of climate change

Clear evidence from observations and climate models demonstrates rapid warming of the Arctic since the late 20th century due to human-caused climate change (Francis et al., 2017; Overland et al., 2019, England et al., 2021). Record winter temperature anomalies 2015-2018 have contributed to a ~60% reduction in Arctic sea ice extent, compared to the 1980s average, and a 75% reduction in September (annual minimum) sea ice since 1979 (Overland et al., 2019).

Arctic warming has intensified the hydrological cycle, resulting in increases in precipitation, humidity, river flow, and glacier melt (Box et al., 2019). These effects have impacted Arctic ecosystems through changing the distribution of animals, plants, pollinators, nutrient supply and plant resistance to disease and impacting carbon-cycling (Box et al., 2019). The impact on evapotranspiration and clouds are less well known because of regional and seasonal variations, large data gaps in space and time and inter-model variations (Vihma et al., 2016).

Permafrost degradation

Rising Arctic temperatures and increased rainfall are leading to expanding areas of permafrost thaw, where soil, rock and ice that had been frozen for more than 2 years thaw for at least part of the year (Box et al, 2019; Overland et al., 2019). This active layer with annual freeze/thaw cycles is deepening: for example, in northeast Greenland the observed active layer depth increased, on average, by +1.6 cm per year from 1997-2010 (Lund et al., 2014), while modelling for the whole Arctic region simulated an average +6.8 cm thickening of active layer depth between 1970 and 2006 (Hayes et al., 2014). Measurements from the Canadian Arctic show rates of permafrost thaw +150% to +240% above the long-term average, representing 90 cm of ground subsidence between 2003-2016 (Farquharson et al., 2019).

Abrupt degradation of permafrost by thermokarst processes (soil collapse as ice pockets thaw) or by coastal erosion, can release greenhouse gases much faster than warming alone (Schuur et al., 2015; Streletskaya et al., 2018) because metres of permafrost are disturbed over days to weeks, rather than centimetres per year during surface warming (Turetsky et al., 2019). Rising ocean temperatures, increasing energy and declining sea ice extent have the potential to destabilise submarine permafrost and gas hydrates - frozen methane and seawater (Ruppel et al. 2017). Generally, greenhouse gases released from submarine permafrost are thought to be contained within the water column (Ruppel et al. 2017), but there are localised cases of methane venting to the atmosphere (Sapart et al., 2017), so ongoing monitoring is required (Ruppel et al. 2017).

Widespread thawing of Arctic permafrost releases greenhouse gases to the atmosphere, acting as an amplifying feedback to climate change. Permafrost and peatland soils are rich stores of carbon, locked in the ground by the ice (Chaudhary et al., 2020). As permafrost thaws, the organic carbon is converted to carbon dioxide (CO_2) or methane (CH_4) by microbial decay, which can be emitted to the atmosphere (Schuur et al., 2015; Turetsky et al., 2019, 2020; Hopple et al., 2020). This emission of additional greenhouse gases due to initial warming is an example of a feedback that amplifies climate change (Webster et al., 2014). This is discussed in greater detail by the ScienceBrief Review about carbon cycle - climate feedbacks. Carbon cycle modelling for the period 1970-2006 simulates a total emission of around 3.7 GtC[a] to the atmosphere from thawed permafrost (Hayes et al., 2014).

Some evidence suggests that rates of carbon emissions from permafrost thaw are greater in cooler, northerly locations than in warmer, southerly locations (Raudina et al., 2018; Serikova et al., 2019; Heffernan et al., 2020). It's possible these observations reflect localised differences in variables such as soil type, moisture content, or alternative sources of greenhouse gas emission. These observations support calls for more extensive data collection and better modelling (Schuur et al., 2015; Turetsky et al., 2019).

Wildfires

Wildfires in Arctic tundra and boreal forest ecosystems have become increasingly frequent and more intense in recent decades, predominantly due to climate change, as well as more minor factors (McCarty et al., 2021). Increases in lightning activity have been identified in the Arctic during 2010-2020 (Holzworth et al., 2021) and the fire danger index shows an increasing trend between 2000-2016, with significant upward trends in Eurasia and Siberia (Justino et al., 2021). These climate-driven trends indicate that both the frequency of natural ignition opportunities and the readiness of vegetation and organic soils to burn have increased in recent decades. The frequency of wildfires has correspondingly increased in the Arctic over the last four decades (Box et al., 2019). Examples of record-breaking wildfires in Siberia in 2019, 2020 (McCarty et al., 2020, 2021; Witze, 2020), and further fires in 2021, have occurred during heatwaves, as have a number of record-breaking fire seasons in the high latitudes of North America (Scholten et al., 2021). Satellite observations (2001-2015) indicate tundra wildfires are clustered spatially and temporally, with variability in their occurrence and intensity linked to climate variability (Masrur et al., 2018). In Canadian boreal forests, the satellite observed burned area increased +11% per year between 2006-2015 (Coops et al., 2018). Increases in summer heat and flammability of organic peat soils also mean that fires burn for longer and emit more carbon (Walker et al., 2020; Scholten et al., 2021). In particular, warm-dry periods in summer months coincide with the majority of wildfire occurrences, while warm-dry periods between late spring and mid-summer increase wildfire occurrence and intensity (Masrur et al., 2018).

Future projections

Arctic amplification of climate change

Future Arctic warming and intensification of precipitation and humidity are projected during the 21st century, resulting in continued reduction of Arctic sea ice extent (Overland et al., 2019). For example, under a medium future emissions scenario (RCP4.5), Arctic winter temperature is projected to increase +5.8±1.5°C by 2050 and +7.1 ±2.3°C by 2100 (Overland et al., 2019). Precipitation and humidity are expected to rise due to enhanced moisture-holding capacity of a warmer atmosphere, increased evaporation from warmer waters that are no longer covered by sea ice, as well as enhanced moisture transport from lower latitudes (Vihma et al., 2016). By 2100 under a high emissions scenario (RCP8.5) Arctic precipitation is projected to increase between +50% and +60% (Bintanja, 2019). Sea ice extent is projected to decline such that, under RCP4.5, the Arctic Ocean may be sea ice-free in late summer before the

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[a] 1 gigaton (GtC) = 1 billion tons carbon = 10^{15} grams of carbon; 1 GtC = 3.664 $GtCO_2$

end of the 21st century (Overland et al., 2019). The Arctic may be transitioning away from a frozen state, or may already have, with surface temperature and precipitation-phase (rain or snow) emerging as a new climatic state by the mid 21st century, under RCP8.5 (Landrum et al., 2020).

Permafrost degradation

Continued future warming is projected to thaw, destabilise and erode far more permafrost, emitting large volumes of carbon to the atmosphere. Two sets of model projections suggest a 20% reduction in permafrost area in the Northern Hemisphere, by 2040, irrespective of future emissions scenario, which only impacts loss rates in the second half of the 21st century (Overland et al., 2019). Modelling simulates carbon emissions due to permafrost thaw between +12 GtC and +174 GtC, by 2100, depending on emissions and modelling scenario, which represents approximately +0.05°C to +0.5°C of additional 21st century warming (Schaefer et al., 2014; Koven et al., 2015; Schneider von Deimling et al., 2015; Schuur et al., 2015). This would require carbon emissions to be reduced by between a further -6% and -17% to limit warming to well below 2°C (González-Eguino et al., 2016). Extended modelling simulations suggest that permafrost thaw will accelerate, perhaps more than doubling emissions by 2300 (Schuur et al., 2015). In addition, CH_4 emitted during permafrost thaw is modelled to represent an equivalent +10% to +40% increase in radiative forcing (warming) by 2100 (Koven et al., 2015; Schneider von Deimling et al., 2015), further reducing remaining carbon budgets.

Wildfires

Simulations project increased fire danger in some Arctic regions due to extended or more frequent periods of fire weather, greater intensity of fire weather or increases to burned area (Wotton et al., 2017; Coogan et al., 2019).

Projections of future mean annual fire activity and its interannual variability vary strongly across ecosystems (Kitzberger et al., 2017; Young et al., 2017). Alaskan Arctic tundra and boreal forest edge environments are projected to experience the largest increases in fire hazard, where the 30 year fire probability is projected to increase four-fold by 2100 under RCP6.0 (Young et al., 2017). Future warming of Siberian permafrost landscapes may increase fire frequency (Ponomarov et al., 2016) in what had traditionally been a low flammability landscape. In addition to changes in heatwave, drought frequency and fire danger, the bioclimatic response of vegetation growth (fuel production) to future changes in climate is considered a major control on the future fire regime of high-latitude ecosystems (Walker et al., 2020).

This ScienceBrief Review is consistent with the IPCC Sixth Assessment Report (AR6 WG1) Chapter 10 (Cross Chapter Box 10.1, 2021), which assessed rapid Arctic warming at more than twice the global average and 25% reduction of autumn Arctic sea ice, compared to the last 40 years, as *very likely*§ and with *high confidence*§, the result of human-caused greenhouse gas emissions. However, regarding links between mid-latitude extreme weather and Arctic amplification, there is *low to medium confidence*§ in the mechanisms involved and their degree of influence, particularly due to apparent differences between observational and modelling studies.

§*See an explanation of IPCC calibrated language.*

References

The full Brief and references can be explored on ScienceBrief with the following link: https://sciencebrief.org/topics/climate-change-science/arctic, where the search filter can be used for e.g. Author name or keyword.

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