



Interconnected Disaster Risks
2020/2021

Arctic Heatwave

Authors: Davide Cotti and Zita Sebesvari

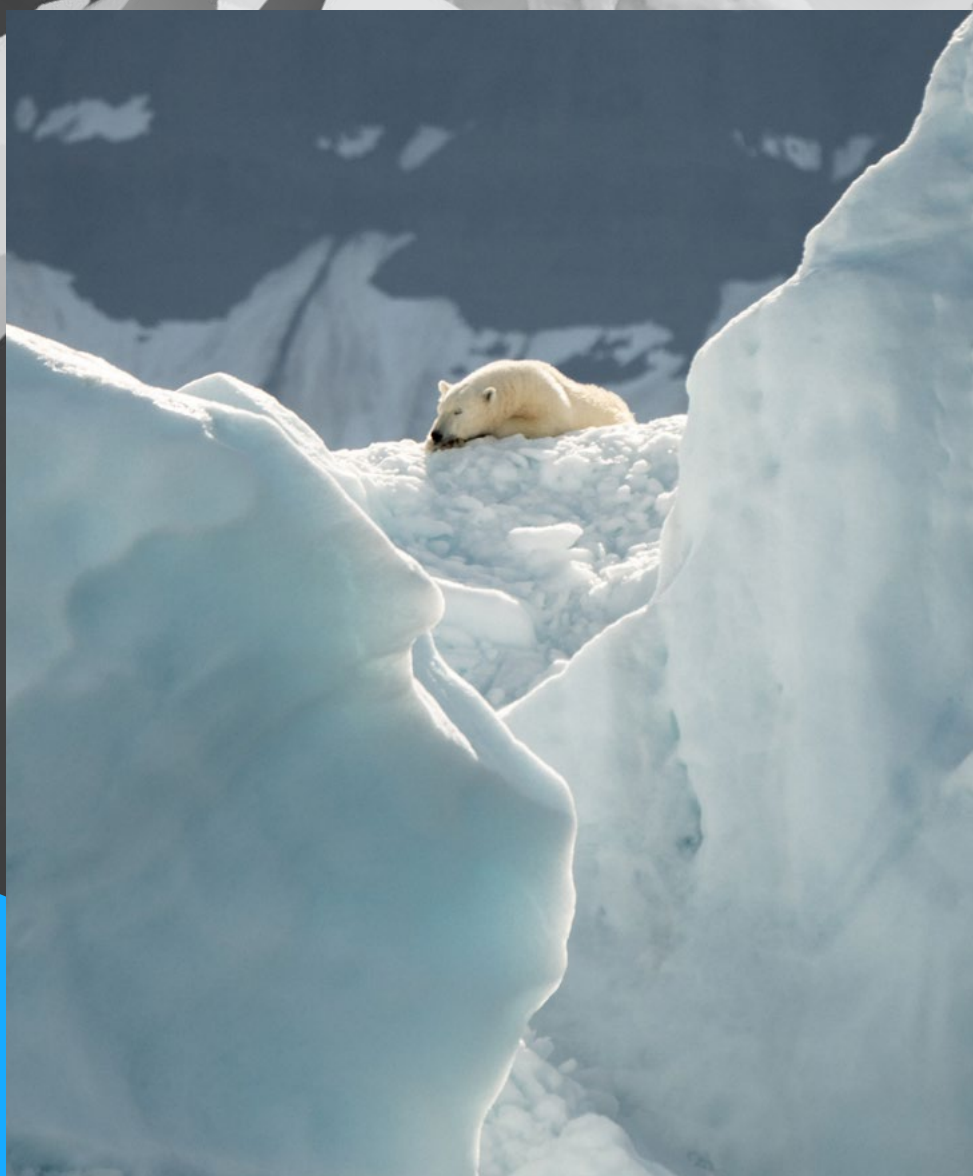


Table of Contents

1. Event	3
2. Impacts	5
Permafrost thawing	5
Wildfires	9
Atmospheric circulation and mid-latitude extremes	10
Greenland ice sheet	12
Impacts on local communities	13
Impacts on ecosystems and wildlife	14
3. Drivers	15
Arctic Amplification	15
4. Root causes	19
5. Solutions	20
References	23

1. Event

In the summer of 2020, the ice cover in the Arctic Ocean reached its second lowest value since records began in 1979 (NASA, 2020). On 20 June, a record Arctic temperature of 38°C was measured in the Russian town of Verkhoyansk, which lies north of the Arctic Circle (ESA, 2020). Only a few weeks earlier, a fuel tank broke down close to the Siberian town of Norilsk and released 20,000 tonnes of diesel after one of its pillars collapsed due to the thawing of the permafrost soil beneath it (The New York Times, 2020). Between May and September 2020, wildfires have ravaged eastern Siberia, affecting both forests and peatlands in permafrost areas, with a total extent of 14 million hectares of burnt landscape (Witze, 2020).

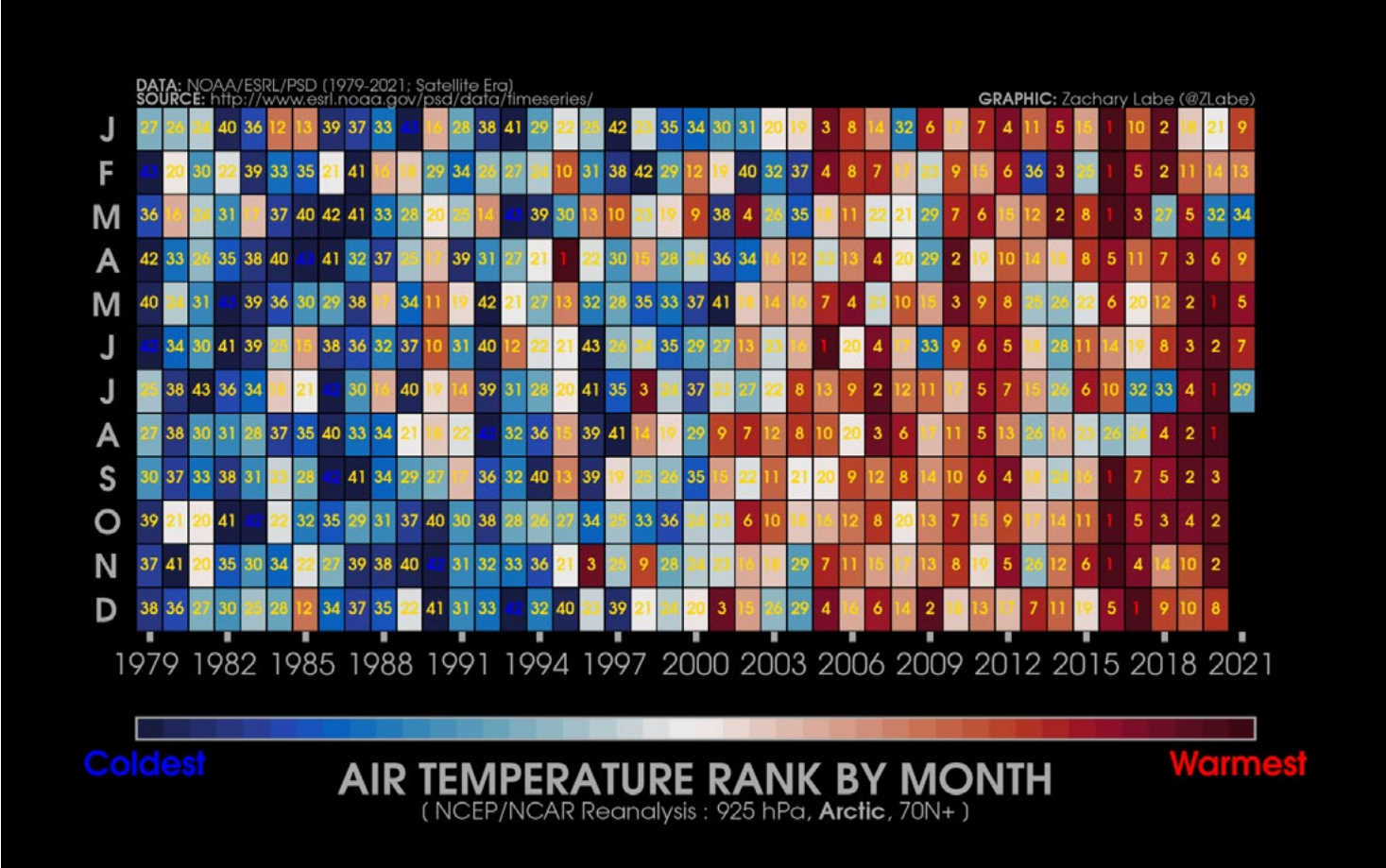


Figure 1: Air temperature rank by month (1979–2021), from Labe (2020). The ranking shows how almost every month has experienced a maximum of average temperature between 2015 and 2020 compared to the reference period, with 2020 showing a striking concentration of maxima in spring, summer and fall.

Box 1: The Arctic Circle

The Arctic region is a vast and diverse landscape and ecosystem, home to almost four million inhabitants, scattered in eight countries. Most commonly, the Arctic Circle, i.e. the latitude above which the sun does not set on the summer solstice (longest day of the year) and does not rise on the winter solstice (shortest day of the year), is employed to set the boundaries of the Arctic region (Klimenko, 2019). However, next to the Arctic Circle multiple definitions and consequent boundaries for the region are in use, using either the climatic (e.g. the 10°C July isotherm) or biome-related characteristics (e.g. the Arctic tree line) or organizational and governance matters for the delineation (e.g. the area of interest for the Arctic Monitoring & Assessment Programme, a working group of the inter-governmental soft law body Arctic Council), resulting in a fluid geographical extent of recorded and possible impacts. However, the consequences of rising temperatures are felt across all these landscapes.



2. Impacts

Permafrost thawing

Permafrost – ground that remains frozen for at least two consecutive years (Shakhova and others, 2019) – occupies a quarter of the Northern Hemisphere (Wang and others, 2019). However, recent heatwaves have triggered thawing of permafrost layers located both on continental soil (ESA, 2020) and beneath marine sediments in the continental shelf (subsea permafrost) (Shakhova and others, 2019).

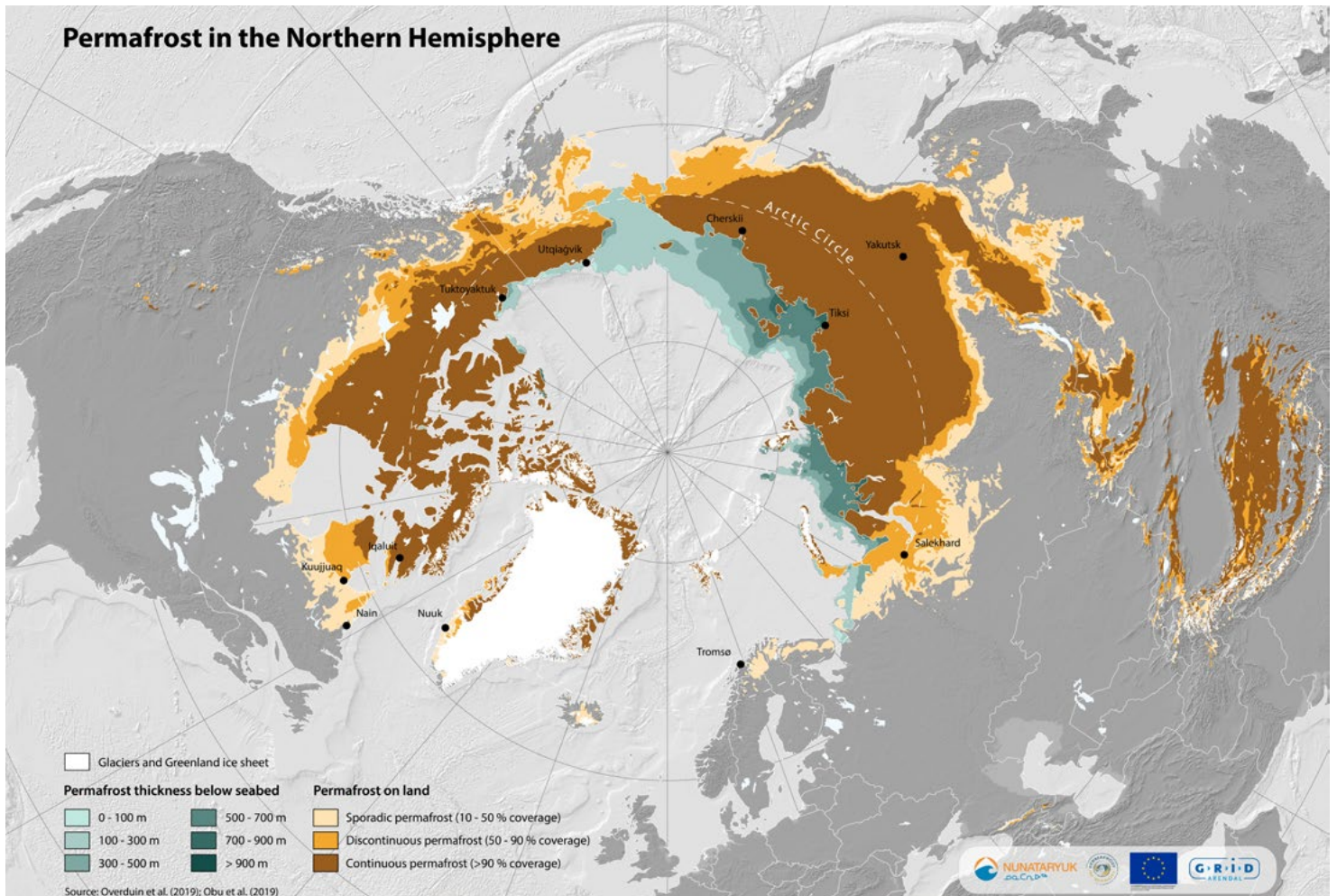


Figure 2: Permafrost in the Northern Hemisphere (GRID - Arendal, 2020). The map shows the location and types of permafrost across the Arctic region.

Thawing can occur in two main patterns: gradual or abrupt. Gradual thaw is a slow process which affects centimetres of soil in long timeframes and is characterized by a slow penetration rate (Turetsky and others, 2019). This type of thawing has been occurring for decades, affecting large portions of the continental permafrost. However, recent observations have confirmed that the Arctic territory is experiencing more and more abrupt thaws – extremely fast processes that involve several metres of soil in a matter of years or even days (Turetsky and others, 2020). According to Turetsky and others (2019), 20 per cent of frozen lands are susceptible to abrupt thawing. Such abrupt thawing in 20 per cent of permafrost areas is expected to affect half of all the carbon stock contained in the permafrost, as a result of increased erosion which could expose deep permafrost – further accelerating thawing (Turetsky and others, 2020).



Figure 3: An example of thermokarst in Siberia, from the Copernicus Sentinel-2 mission (ESA, 2019).

The consequences of gradual and abrupt thawing of terrestrial permafrost is relevant on the local scale in terms of landscape stability, as frozen soil is what holds the landscape together at higher latitudes (Turetsky and others, 2019). Thawing has already resulted in the formation of thermokarst, i.e. massive landscape alterations generated by thaw-induced disruptions of soil continuity, such as gullies, craters and lakes (Dickie, 2020). These major alterations of soil conditions cause instability for infrastructure already in place, which is generally not designed to withstand such changes (Polovtseva, 2020). A particularly impactful example of this was the collapse of the fuel tank in Norilsk, Siberia, in May 2020, which released 20,000 tons of diesel. The tank had been made unstable by the subsiding soil due to thawing permafrost (The New York Times, 2020). While this infrastructure collapse received particular attention in the media, many more transportation and industrial infrastructures are exposed to risk of functional collapse in the Arctic. Hjort and others (2018) have calculated that an average of 69 per cent of “pan-Arctic infrastructure is located in areas where near-surface permafrost is projected to thaw by mid-century,” with railways being particularly affected, followed by residential infrastructures and pipelines, collectively affecting 3.6 million people directly.

In addition to disruptions of the local environment, consequences from changes in the permafrost are likely to have global repercussions. Arctic permafrost stores large quantities of carbon, which have accumulated in a period ranging from a few hundred to several thousand years (Treat & Frohling, 2013), therefore pre-dating human emissions from modern industrial activities. The release of this carbon reserve is particularly concerning as it may significantly exacerbate climate change (IPCC, 2019). This phenomenon, known as the Permafrost Carbon Feedback (PCF), is feared to effectively reduce the chances of meeting the objectives established by the international climate treaties (Schaefer and others, 2014; Natali and others, 2021). The northern permafrost region is thought to contain approximately 1,460 to 1,600 billion metric tonnes of organic carbon – twice as much as is currently contained in the atmosphere (Schuur, 2019). Of this, at least 130 billion tonnes of organic carbon (equivalent to more than 10 years of human emissions) is stored in the so-called Yedoma deposits that formed during the last ice age (Turetsky and others, 2019). Since this carbon was captured prior to the modern industrial era, its release would amount to a net contribution to human-induced carbon emissions, with no offset mechanisms in place. Yedoma deposits, in particular, have at times being characterized as the “sleeping giants” of the carbon cycle (Strauss and others, 2017). Conservative estimates predict 200 billion tonnes of carbon could be released to the atmosphere from the gradual thawing of

the permafrost alone in the next 300 years, while an additional 60 to 100 billion tonnes could be added by abrupt thawing (Turetsky and others, 2019)¹. The IPCC Sixth Assessment Report concluded with high confidence that the loss of carbon following permafrost thaw is irreversible at centennial timescales (IPCC, 2021).

In addition to terrestrial permafrost, scientists are beginning to investigate the potential of carbon release from subsea permafrost – the frozen soil located under the sea floor in the Arctic Ocean. While it appears to be more stable in terms of its response to climatic changes, research suggests that carbon emissions from this type of soil might already be influencing the global carbon cycle (Sayedi and others, 2020). Though this field is severely understudied and there are many uncertainties, reviews of the current knowledge tentatively concluded that the sub-sea permafrost could account for one fifth of terrestrial deposits (Sayedi and others, 2020).

The form in which carbon is released from the permafrost deposits is also extremely consequential depending on its global warming potential. Methane is much more effective than carbon dioxide as a greenhouse gas – it is up to 86 times stronger on a 20-year time scale (IPCC, 2015). Therefore a large atmospheric release of methane could constitute a significant increase to climate change positive feedbacks (Strauss and others, 2017). In the case of permafrost, carbon could be released in the form of methane through the decomposition of organic matter by microbes ‘reactivated’ by higher temperatures under anaerobic conditions (such as in thermokarst lakes [Gray, 2018] or in sub-sea permafrost [Shakhova and others, 2019]). However, large uncertainties persist in assessing the dynamics of organic matter decomposition in permafrost (Strauss and others, 2017). Additionally, Froitzheim and others (2021) have found that significant releases could also come from thermogenic methane deposits (e.g. reservoirs of methane captured in ice in the form of hydrates) that could be released to the atmosphere in case of permafrost thawing, a phenomenon registered in north Siberia in connection with the 2020 heatwave.

Due to lack of data, the dynamics of PCF are not yet fully considered in the IPCC climate projections presented in the AR5 report ², and therefore much uncertainty remains as to how current estimates of greenhouse gas concentrations (which are the ones used to negotiate emissions targets) might have to be modified to account for this feedback mech-

1 These estimates do not consider the possible counterbalancing effect from offsets through vegetation changes such as the northward expansion of the tree line (Turetsky and others, 2019).

2 However, information on the PCF is being included and characterized in the IPCC reports, with gradual thawing being featured in the 2018 Special Report on Global Warming of 1.5 °C and abrupt thawing in the 2019 Special Report on the Ocean and Cryosphere in a Changing Climate (Turetsky and others, 2019).

anism (Schaefer and others, 2014). Turetsky and others (2020) predict that the inclusion of abrupt thawing alone in permafrost carbon release models could produce a twofold increase in projected emissions, and there are already signs that some tundra regions are shifting from being carbon sinks to carbon sources (Natali and others, 2019).

Wildfires

Over the mainland, and especially in Siberia, increased temperatures have resulted in the occurrence of widespread wildfires, affecting both forests and peatlands (Witze, 2020). While the triggering events of the fires can be traced back to lightning and human accidents (such as campfires and prescribed burnings that became uncontrollable) (Greenpeace, 2020), prolonged high temperatures during winter provide favourable conditions for the spread of the fires by creating drier forest and peatland fuel (McCarthy and others, 2020). In 2020, as consequences of above-average winter temperatures, the fire season began in early May rather than as it usually does in July, allowing for a much larger timeframe for the development of wildfire fronts (Witze, 2020). This is in line with recent trends, which have seen an increase in frequency, burned area and emissions from wildfires, and a decrease in the return interval (Kharuk and others, 2021).

The dynamics of Arctic wildfire cycles under climate change are complex. Kharuk and others (2021) observe that a prolonged spring and summer can result in an expansion of the tree-growing season, while higher temperatures induce an increase in Gross Primary Productivity³. Studies have shown that Siberian forests affected by wildfires have a significant rate of survival, meaning up to half of the trees do not die during the wildfire and forests are able to recolonize the landscape. This can result in a particularly efficient carbon offset mechanism, given the observed vigour of vegetation re-growth after fire events. In fact, the Siberian forests managed to retain their role as a net carbon sink from 2000 to 2019 despite the large increase in wildfire events (Kharuk and others, 2021). However, the presence of peatlands increases the complexity of fire regimes in the Arctic (Witze, 2020). In this carbon-rich ecosystem, fires can smolder undetected as flameless combustion under the surface of the peat for months or even years, then reemerge in springtime, in a phenomenon sometimes referred to as “zombie” fires (McCarthy and others, 2020). Peatlands are considered the most carbon-dense ecosystems on Earth (Witze, 2020), and therefore their

³ Gross primary productivity indicates the total uptake of carbon dioxide (CO₂) by plants during photosynthesis (Cai and others, 2021)

combustion can mobilize very large quantities of carbon dioxide, especially in combination with permafrost thaw (Hugelius and others, 2020). Moreover, as regrowth of peatlands is extremely slow compared to that of forests, no offset mechanism is available to naturally recapture the carbon emitted during their combustion, which is then permanently lost to the atmosphere (Witze, 2020).

In addition to disrupting the local landscape, Arctic wildfires are drivers of the global carbon cycle change due to direct and indirect contributions to global greenhouse gas emissions (USGCRP, 2018). Direct fire emissions resulting from the combustion of carbon-rich vegetated land cover in the Arctic releases large quantities of carbon (Veraverbeke and others, 2021). Scientists from the Copernicus Atmosphere Monitoring Service (CAMS) have estimated that during the summer of 2020, wildfires across the Arctic Circle released 244 million tonnes of carbon dioxide (European Commission, 2020), equivalent to a third of all carbon emissions registered for the entire country of Canada in 2019. In addition to direct emissions, however, wildfires can also further contribute to global climate change through post-fire soil carbon dioxide emissions. Changes in soil temperature and moisture from wildfires can result in a deeper active layer in the permafrost (Veraverbeke and others, 2021), thus mobilizing older carbon deposits stored in the soil. Natali and others (2021) assert that in the next few decades, thawing and decomposition of organic matter following wildfires could become the major source of Arctic carbon emissions.

Atmospheric circulation and mid-latitude extremes

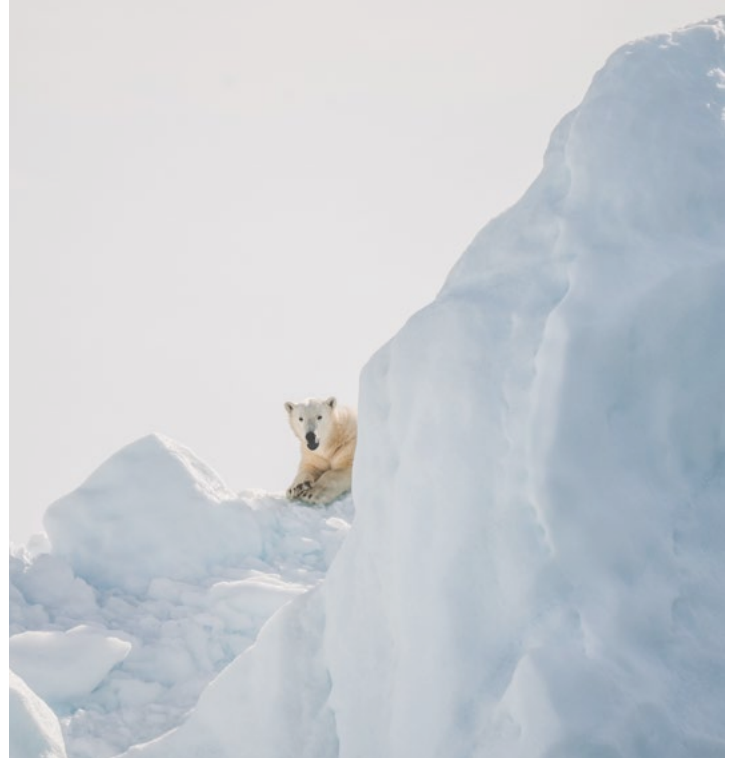
A new regime of Arctic temperatures may have profound impacts on the climate of other latitudes as well. In fact, climate at mid-latitudes is influenced by complex atmospheric processes in the Arctic (Barnes & Screen, 2015; Francis & Vavrus, 2012). The pattern of the polar jet stream is of particular relevance. Jet streams are “meandering streams of fast-moving air” (Voiland, 2013), which play an important role in regulating atmospheric circulation at the global level. The polar jet stream, in particular, is the result of the interface between denser cold air masses at the poles and warmer and looser subtropical air masses, resulting in a tropospheric belt of winds flowing eastward (Machens, 2013). The polar jet stream is responsive to changes in the polar vortex – a strong circulation of winds

forming in the stratosphere above the North Pole (Lindsey, 2021). When infiltrated by upward tropospheric waves, the polar vortex experiences a marked increase in temperatures (generally known as sudden stratospheric warming), which results in a slower wind speed and ultimately a disruption of its circulation (Lindsey, 2021). This in turn weakens the polar jet stream, leading to a more meandering north-south flow (Francis & Vavrus, 2015). This altered pattern allows “[...] warm air to penetrate farther north and cold air to plunge farther south” (Lei & Wei, 2020, p. 1), therefore creating the conditions for different extreme events at different mid-latitude locations, such as heatwaves in Europe (Zhang and others, 2020) and cold spells in North America (Castet, 2021), like the one that affected Texas in February 2021. The climate pattern created by the alternation of a stable and contained polar jet stream with a more meandering and farther-reaching one is known as Arctic Oscillation (NOAA, 2020). While these processes are well known, scientists are still debating if and how the warming temperatures in the Arctic (especially during winter, when the polar jet stream is generally at its strongest) actually affect mid-latitude extremes. Francis & Vavrus (2015) assert that rapid arctic warming, which is connected to climate change through a process called Arctic Amplification (see below), can generate a wavier jet stream and the ‘negative’ phase of the Arctic oscillation. However, other researchers find that alteration to the Arctic oscillation can be explained by natural variability, without reference to human-induced climate change (Henson, 2021). Overland and others (2021) suggest that temperature anomalies may only interact with jet stream patterns (e.g. amplifying or counteracting them) rather than causing them. Scientific consensus on the effect of Arctic Amplification to mid-latitude weather patterns has not been reached yet (Cohen and others, 2014; Cohen and others, 2020; Barnes & Screen, 2015; AMAP, 2021).

A modified polar jet stream is also believed to influence storm activities, in combination with other factors. On one side, the reduced subtropical-polar thermal gradient may contribute to a weakening and decreased frequency of extra-tropical cyclones, which feeds from the interaction of warm and cold air masses on the polar front (Voiland, 2013). Moreover, research suggests also that the probable increase in wind shear (a measure of speed and direction of winds and an important component in the formation of storms) is likely to prevent the organization of heat and moisture into a storm (Voiland, 2013). On the other hand, however, the projected slowing down of the polar jet stream may also induce storms that do form to have a slower motion, thereby resulting in more stationary landfalls which are expected to discharge larger volumes of precipitations in potentially inhabited coastal areas (Voiland, 2013).

Greenland ice sheet

Greenland hosts the second largest ice sheet on Earth, storing a quantity of water that, if melted, would contribute to global mean sea level rise of more than seven metres (Tedesco and others, 2019). Scientists have been monitoring the loss of ice volume in the past decades, finding alarming trends of reduction (IPCC, 2019). In addition to contributing to sea level rise, the influx of cold freshwater into the North Atlantic from the melting of the Greenland ice sheet is expected to result in large disturbances and consequential weakening of the Atlantic Meridional Overturning Circulation (AMOC) (IPCC, 2019), an event which experts consider capable of triggering other globally-relevant environmental tipping points, such as the transition of the Amazon rainforest to savannah state (Wunderling and others, 2021). Although the surface melt of the Greenland ice sheet is influenced by increased surface air temperature (Hanna and others, 2021), the dynamic of this response is complex. In 2020, the very high summer temperatures did not generate a proportional record-setting ice loss, showing instead a lower melt extent compared to other summers in the 2010–2020 period (Scambos and others, 2020).



Impacts on local communities

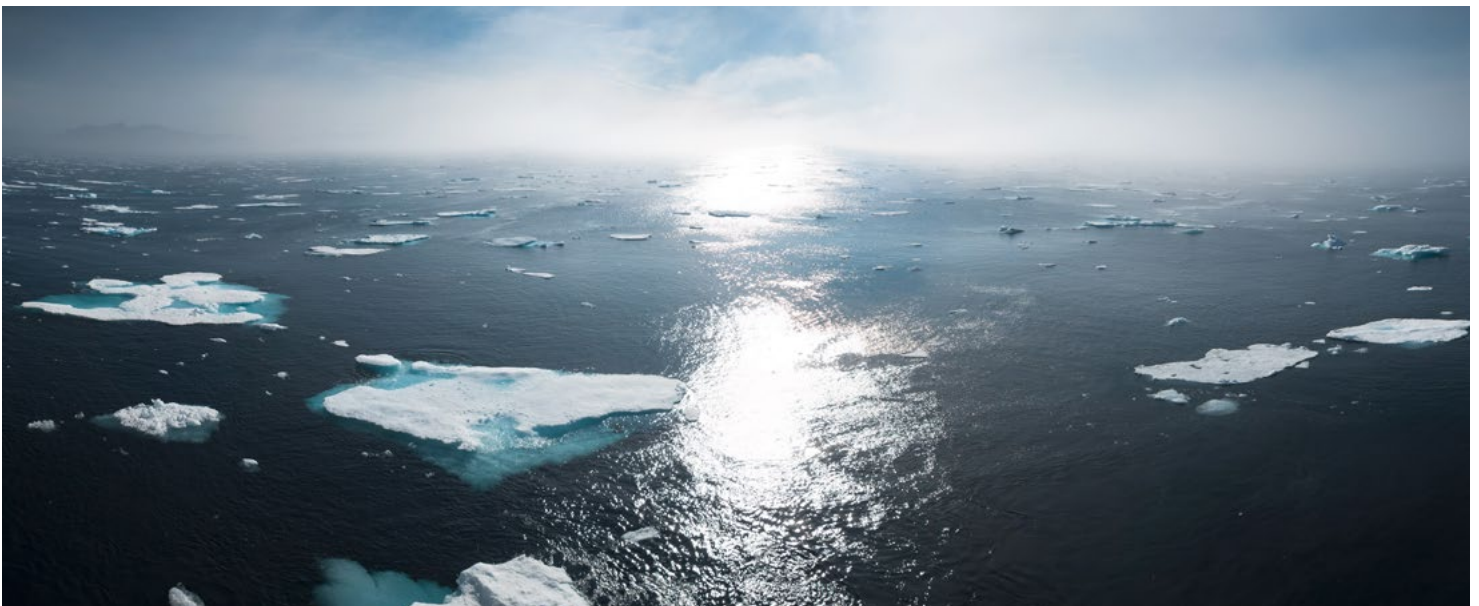
The drastic environmental changes described above have major repercussions on the lives and livelihoods of Arctic inhabitants. Communities of this region are extremely diverse, ranging from indigenous lowland coastal groups relying on maritime resources (primarily located in Alaska, Canada and Greenland), to indigenous herders (characteristic of the Fennoscandia and Russian region), to more sedentary settlers dependent on activities in non-primary sectors (typical of the Russian region).

For some traditional indigenous communities depending on hunting and gathering, the availability of traditional food sources has been affected by recent environmental changes such as the decrease in sea ice coverage (AMAP, 2021) – a primary element for accessibility to marine mammals and fish for indigenous fishing communities in Alaska (Inuit Circumpolar Council – Alaska, 2015). Alaskan communities are already experiencing hunting failures and have required interventions from the federal government to secure enough food for their populations (Struzik, 2016). In some areas, access to fresh or clean water has also become a concrete concern, as freshwater resources are being affected by changes in precipitation patterns and melting permafrost (Klimenko, 2019). Human security in the Arctic is also severely affected by exposure to natural hazards connected to environmental change. For instance, more than 85 per cent of Alaskan native settlements are faced with flooding and erosion, which can translate into severe consequences when factoring in the remoteness of these communities and the subsequent difficulties in timely disaster response (AMAP, 2021). Some communities in Siberia are already experiencing permanent inundations caused by permafrost thawing, and are facing the prospect of having to relocate entire villages (MacFarquhar & Ducke, 2019). Other potential threats might come from health hazards, particularly from insect (Kharuk and others, 2021) and zoonotic disease outbreaks (Oliva & Fritz, 2018), release of pollutants (Dobricic and others, 2020; AMAP, 2021), and exposure to extreme heat – a condition of which the population has little experience of and knowledge to cope with and adapt to (Ciavarella and others, 2021).

Impacts on ecosystems and wildlife

The rapid changes in climatic conditions are heavily impacting ecosystems and biodiversity in the fragile Arctic environment. Polar bears, one of the most iconic species of the region, are under stress by diminished availability of sea ice, forcing them to change their feeding behaviour (CAFF, 2013). According to some estimates, only a few Arctic polar bear sub-populations would be able to survive in the region by 2100 under a high-emission scenario (Molnár and others, 2020).

Higher temperatures and more frequent precipitations can also trigger more complex transformations in terrestrial environments, including an increase in plant biomass (US-GCRP, 2018). Moreover, northward migration of more temperate plant and animal species is already under way (CAFF, 2013), and is expected to progressively increase competition at the expense of unique Arctic species (IPCC, 2019). Sea ice retreat is also triggering changes in maritime environments; for instance, in recent decades net primary production has increased by almost 30 per cent in the Arctic Ocean (Lei & Wei, 2020; Schuur, 2019), but this also includes the appearance of toxic algae (Lei & Wei, 2020). In addition, increasing carbon dioxide concentration in the atmosphere leads to higher amounts of carbon dioxide dissolving into the ocean causing ocean acidification. Ocean acidification also changes the characteristics of Arctic marine environments, although its long-term effects on marine biodiversity are still not fully understood (AMAP, 2018).



3. Drivers

Arctic Amplification

Arctic Amplification is a key phenomenon in understanding the environmental processes at play in the Arctic. With this term, researchers refer to the observed accelerated trend of temperature changes at higher latitudes; data shows that temperatures in the Arctic region have increased twice as fast compared to mid-latitudes (Lei & Wei, 2020). The Arctic will continue to warm more than the global surface temperature and there is high confidence that the rate of warming will remain more than two times the rate of global warming (IPCC, 2021). Multiple mechanisms contribute to this phenomenon, including local forcing⁴ such as snow, albedo, cloud and ice insulation feedbacks, and remote forcing such as atmospheric and ocean heat, and atmospheric moisture transportation (Cohen and others, 2020).

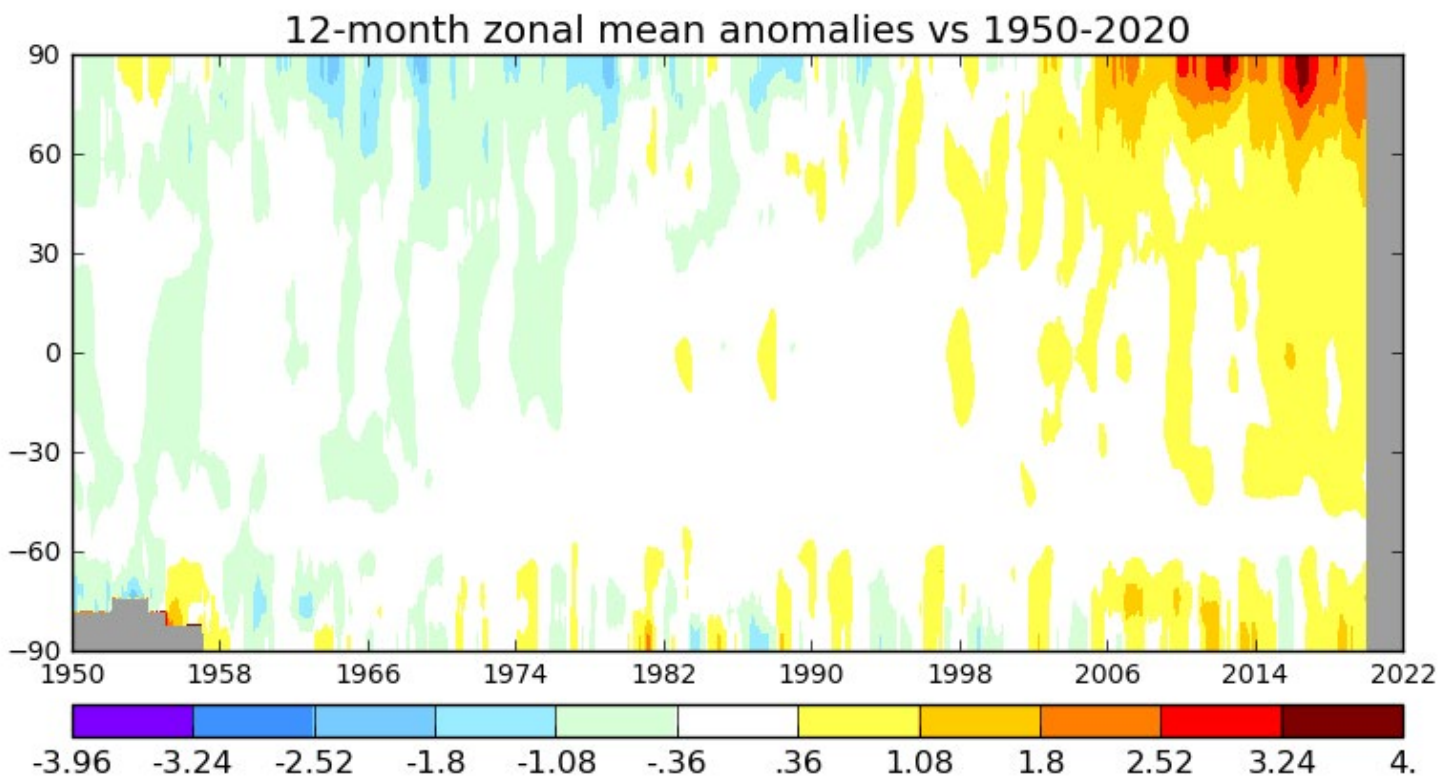


Figure 4: Average annual temperature anomalies at different latitudes (baseline period: 1950–2020). The picture was generated through the NASA GISS Surface Temperature Analysis (v4) online tool, from NASA (2021). The Arctic region (top-right corner) shows the highest increase.

⁴ “Forcing” refers to factors that can alter the climate system (<https://www.climate.gov/maps-data/primer/climate-forcing>)

Sea ice dynamics, in particular sea ice concentration (SIC) and sea ice thickness (SIT), are an important factor for Arctic Amplification (Landrum & Holland, 2020). Ice and snow are very effective reflective surfaces for solar radiation, a phenomenon known as the albedo effect. In fact, snow-covered sea ice surfaces can reach 80 per cent reflectance, compared to 7 per cent of an ice-free ocean (Cohen and others, 2020). The loss of sea ice and continental snow cover thus results in larger absorption of sunlight, favoring more rapid and intense direct increase of temperatures at high latitudes (Cohen and others, 2020). This phenomenon triggers a positive feedback loop across the summer-winter ice cycle: prolonged reduction of sea ice during summer results in increased absorption by the dark ocean surface and therefore a storage of latent heat which delays sea ice growth in the winter months (Cohen and others, 2020). Recent studies have estimated that winter cloud cover is also an important contributing factor to Arctic Amplification, in a feedback process with sea ice cover (Cohen and others, 2020).

Far from being stable in terms of extent, the ice sheets undergo seasonal cycles of growth and usually reach their maximum extent around the month of March, which signals the end of the long Arctic winter. Conversely, the lowest extent is generally observed towards the end of summer in September, after six months of direct sunlight. At no time in recorded history has the Arctic been completely free of ice for any portion of time (Labe, 2020). However, the continuous satellite monitoring of ice cover over the Arctic Ocean reveals a downward trend since the first records, in 1979 (AMAP, 2021). Landrum & Holland (2020) observed that the mean sea ice extent decreased by 31 per cent between 1979 and 2018. Even more alarmingly, the baseline used for the construction of models is generally based on the data collected since the beginning of satellite observations, in 1979. This is concerning, as changes in sea ice extent are thought to have occurred at a much faster pace in the latter part of the 20th century compared to historical patterns, and therefore the baseline might not be representative of previous long-term conditions (Landrum & Holland, 2020).

While the seasonal extent of sea ice is one important indicator of the state of the Arctic ice cap, another important aspect is the dynamics of ice thickness (Labe and others, 2018). In fact, thicker ice sheets are important thermic regulators: they limit the exchange of heat between ocean and the atmosphere, while also decreasing the transmission of

solar radiation (Mallett and others, 2021). Thick ice generally survives the melting season, thus creating multi-year ice formations, which in turn helps the creation of new ice during winter. Following the changes in recent decades, the Arctic Ocean is now dominated by much younger ice. The presence of old multi-year ice (> 4 years old) declined by 95 per cent between 1985 and 2018 (Lei & Wei, 2020).

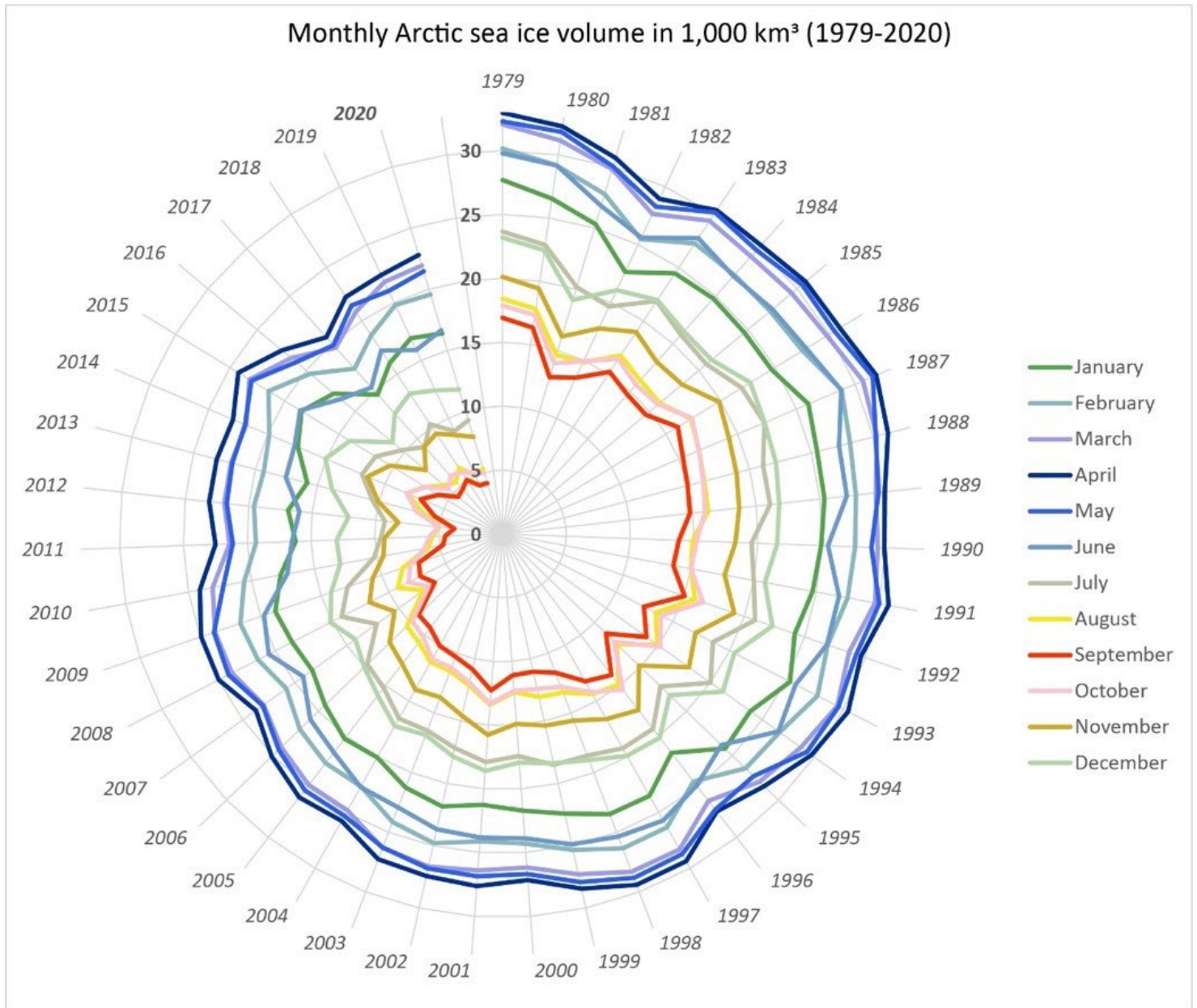


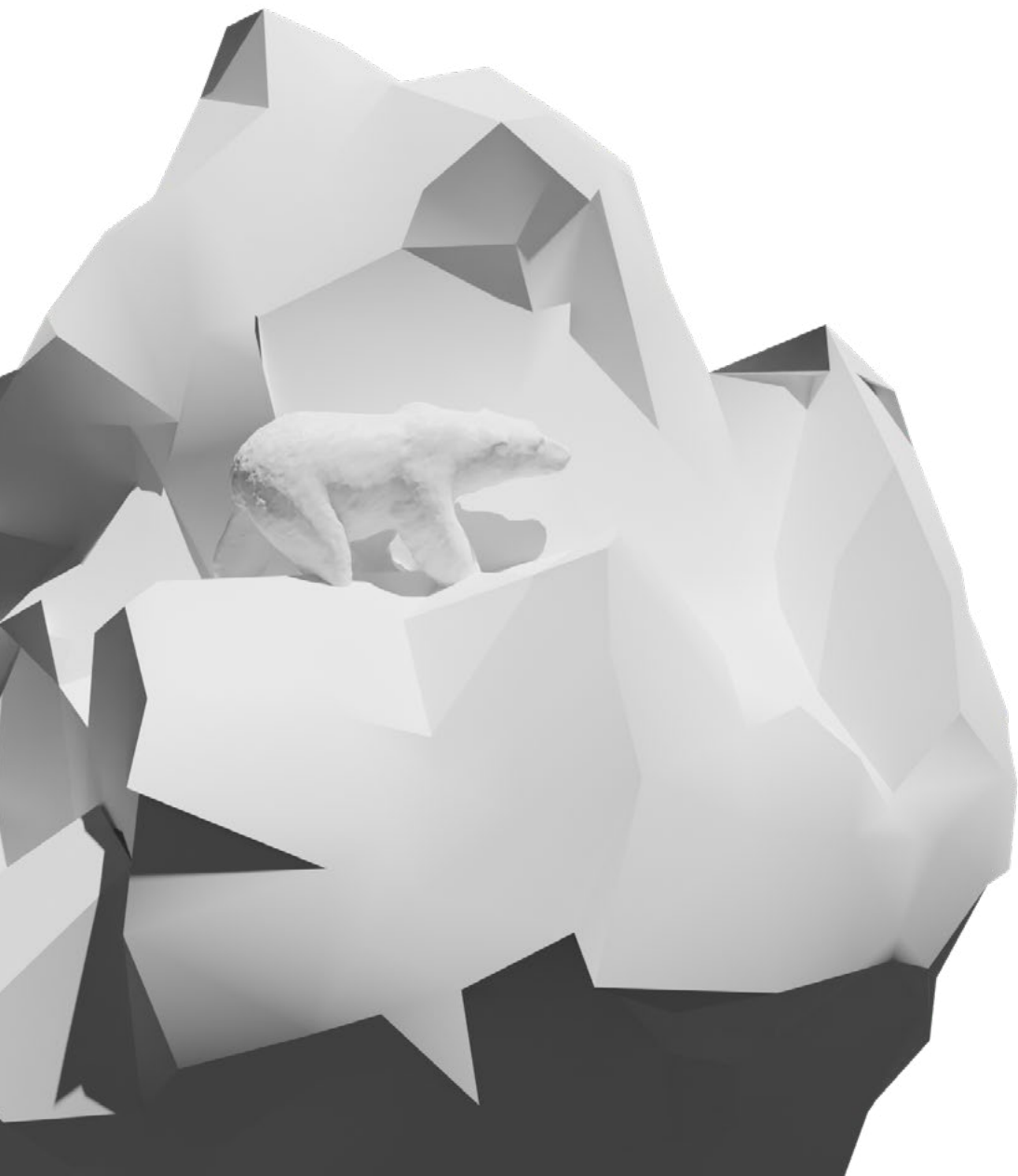
Figure 5: The chart plots the average ice volume by month in the Arctic between 1979 and 2020. Values are expressed as 1,000 cubic kilometres. Data was obtained from the Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS, 2021). The chart is modified after the Arctic Death Spiral chart by Andy Lee Robinson – for further details see Horton (2021).

Researchers consider the threshold of 1 million cubic kilometres as the boundary to consider the Arctic Ocean as ice free (Landrum & Holland, 2020). In 2012, the total volume of sea ice fell under 4 million cubic kilometres for the first time. In 2020, this threshold was breached again, reaching 3.74 million square kilometres on 15 September (NASA, 2020). Figure 5 summarizes the 1979–2021 trends of sea ice volume by plotting all the monthly average values by year. The result is a concentric spiral, where for all months a clear and rapid decreasing trend is visible. If this trend continues unabated, according to IPCC (2019) the first occurrence of an ice-free summer in the Arctic Ocean could materialize before 2050 in a high-emissions scenario, although other estimates suggest an even shorter timeframe (Diebold & Rudebusch, 2021). The IPCC Sixth Assessment Report concluded that the Arctic will likely be practically sea ice free in September at least once before 2050 (IPCC, 2021). Reaching the first Arctic ice-free summer on human record – sometimes referred to as a Blue Ocean Event (McKay, 2019) – is widely considered an important climate tipping point, although much uncertainty remains as to how much and how fast it will contribute to further global changes (McKay, 2019). The prospect of an ice-free Arctic, on the other hand, has sparked interest for several national actors, given the opportunity offered by new transportation routes and the potential for extractive industries (Klimenko, 2019).



4. Root causes

Given the extreme susceptibility of the Arctic environment to changes in global temperatures, human-induced climate change is widely considered the main cause for the rapid changes and abrupt impacts in the Arctic (IPCC, 2019; IPCC, 2015). In a regional study focusing on the 2020 heatwave in Siberia, Ciavarella and others (2021) were able to demonstrate that such an event would be extremely unlikely without human influence on the global climatic processes through emission of greenhouse gases. The Sixth Assessment Report of the IPCC concludes that human influence is very likely the main driver of both the observed reductions in Arctic sea ice since the reference period of 1979–1988 and the decrease in the spring snow cover in the Northern Hemisphere since 1950 (IPCC, 2021).



5. Solutions

“There is no uncertainty about the sign of future Arctic change.”

(Overland and others, 2019, p. 11)

Because of the scale and momentum of the processes involved, scientists doubt that current trends of environmental change in the Arctic can be halted or reverted in the short term (Overland and others, 2019). However, future conditions can change dramatically under different emission scenarios, which suggests that strong mitigation policies can still allow us to avert some of the worst consequences at the global scale (Overland and others, 2014). In a study aiming at quantifying changes in the northern permafrost’s capacity for storing carbon under different Representative Concentration Pathway⁵ (RCP) scenarios, McGuire and others (2018) argue that the permafrost region could continue to absorb more carbon than it emits if aggressive mitigation policies are enacted. The importance of the Arctic region as a regulator for the entire global climate system makes it crucial to cut future carbon emissions, as processes and feedbacks taking place at northern latitudes might negatively influence planetary climate stability – even if temperature change is successfully limited to 2°C (Overland and others, 2019). While emissions reduction from industrial activities has to be addressed as a global effort, other mitigation measures can take place within the Arctic region. For example, a reduction in wildfires could help the conservation of the carbon stocks currently stored in plants and soils, although the overall effect on end-of-century climate projections is likely to be limited even under full active fire management practices (USGCRP, 2018).

A new Arctic also means drastic transformation for its current inhabitants. However, despite colossal changes to local environmental conditions, researchers, practitioners and stakeholders place a lot of confidence in the ability of local communities to adapt (Ford and others, 2015; Eerkes-Medrano & Huntington, 2021; AMAP, 2021). Indigenous communities, in particular, have thrived in the region for millennia by forging a culture that incorporates change as an integral feature of the environment, which is then regarded more as a flux than as a stationary entity (Ford and others, 2015). For instance, Eerkes-Medrano & Huntington (2021) report that maritime communities in Alaska were not particularly alarmed during the 2007 sea ice minimum, in stark contrast to the tone of the media coverage of the event. However, a not-insignificant part of the historical adaptation strategies of communities across the Arctic Circle has been the ability to relocate, a condition that is

⁵ The RCP scenarios describe potential pathways of anthropogenic greenhouse gas emissions https://sedac.ciesin.columbia.edu/ddc/ar5_scenario_process/RCPs.html

now severely limited by the presence of international borders and incentives to reside in sedentary settlements (Eerkes-Medrano & Huntington, 2021). In order to ensure adaptation opportunities for the four million inhabitants of the Arctic, more effort in terms of governance response by central institutions is required (Ford and others, 2015), together with a more active participation of local communities in both research and policy design (Ford and others, 2015; Manrique and others, 2018).

Acknowledgements

We'd like to thank Caitlyn Eberle, Jack O'Connor, Oscar Higuera and Saskia Werners for their support in this research.

References

Arctic Monitoring and Assessment Programme (AMAP) (2018). AMAP Assessment 2018: Arctic Ocean Acidification. Tromsø, Norway. Arctic Monitoring and Assessment Programme.

Arctic Monitoring and Assessment Programme (AMAP) (2021). Arctic Climate Change Update 2021: Key Trends and Impacts: Summary for Policy-Makers. Arctic Monitoring and Assessment Programme. DOI: 10.18356/7f7eeb17-en

Barnes, Elizabeth A., and James A. Screen (2015). The Impact of Arctic Warming on the Midlatitude Jet stream: Can It? Has It? Will It? In WIREs Climate Change, vol. 6, No. 3, pp. 277–86. DOI: 10.1002/wcc.337

Cai, Yihan, and others (2021). Gross Primary Production of Dwarf Bamboo, *Sasa Senanensis*, in a Mature Beech Forest with a Substantial Gap-Mosaic Structure. In Journal of Plant Research, vol. 134, No. 2, pp. 209–21. DOI: 10.1007/s10265-021-01262-y

Castet, Christelle (2021). A Cold Snap in Texas... How Unexpected? . URL: www.climateaxa/articles/a-cold-snap-in-texas-how-unexpected

Ciavarella, Andrew, and others (2021). Prolonged Siberian Heat of 2020 Almost Impossible Without Human Influence. In Climatic Change, vol. 166, 1-2, DOI: 10.1007/s10584-021-03052-w

Climate State (2013). NASA: The Polar Jet Stream – Climate State. URL: climatestate.com/2013/05/02/nasa-the-polar-jet-stream/

Cohen, Judah, and others (2014). Recent Arctic Amplification and Extreme Mid-Latitude Weather. In Nature Geoscience, vol. 7. URL: www.nature.com/articles/ngeo2234

Cohen, Judah, and others (2020). Divergent Consensuses on Arctic Amplification Influence on Midlatitude Severe Winter Weather. In Nature Climate Change, vol. 10, No. 1, pp. 20–29. DOI: 10.1038/s41558-019-0662-y

Conservation of Arctic Flora and Fauna (CAFF) (2013). Arctic Biodiversity Assessment: Status and Trends in Arctic Biodiversity. Conservation of Arctic Flora and Fauna: Akureyri, Iceland.

Dickie, Gloria (2020). Arctic Permafrost Moving Toward Crisis, Abrupt Thaw a Growing Risk: Studies. URL: news.mongabay.com/2020/03/arctic-permafrost-moving-toward-crisis-abrupt-thaw-a-growing-risk-studies/

Diebold, Francis X., and Glenn D. Rudebusch (2021). Probability Assessments of an Ice-Free Arctic: Comparing Statistical and Climate Model Projections. In Journal of Econometrics, DOI: 10.1016/j.jeconom.2020.12.007

Dobricic, Srdjan, and others (2020). Increasing Occurrence of Heat Waves in the Terrestrial Arctic. In Environmental Research Letters, vol. 15, No. 2, p. 24022. DOI: 10.1088/1748-9326/ab6398

Eerkes-Medrano, Laura, and Henry P. Huntington (2021). Untold Stories: Indigenous Knowledge Beyond the Changing Arctic Cryosphere. In Frontiers in Climate, vol. 3, DOI: 10.3389/fclim.2021.675805

European Commission (2020). Copernicus Reveals Summer 2020's Arctic Wildfires Set New Emission Records. URL: atmosphere.copernicus.eu/copernicus-reveals-summer-2020s-arctic-wildfires-set-new-emission-records

European Space Agency (ESA) (2019). Permafrost thaw ESA. URL: https://commons.wikimedia.org/wiki/File:Permafrost_thaw_ESA19399520.jpeg

European Space Agency (ESA) (2020). Monitoring the Arctic Heatwave. URL: www.phys.org/news/2020-08-arctic-heatwave.html

Ford, James D., and others (2015). The Adaptation Challenge in the Arctic. In *Nature Climate Change*, vol. 5, No. 12, pp. 1046–53. DOI: 10.1038/nclimate2723

Francis, Jennifer A., and Stephen J. Vavrus (2012). Evidence Linking Arctic Amplification to Extreme Weather in Mid-Latitudes. In *Geophysical Research Letters*, vol. 39, No. 6, n/a-n/a. DOI: 10.1029/2012GL051000

Francis, Jennifer A., and Stephen J. Vavrus (2015). Evidence for a Wavier Jet Stream in Response to Rapid Arctic Warming. In *Environmental Research Letters*, vol. 10, No. 1, p. 14005. DOI: 10.1088/1748-9326/10/1/014005

Froitzheim, Nikolaus, and others (2021). Methane Release from Carbonate Rock Formations in the Siberian Permafrost Area During and After the 2020 Heat Wave. In *Proceedings of the National Academy of Sciences of the United States of America*, vol. 118, No. 32, DOI: 10.1073/pnas.2107632118

Gray, Ellen (2018). Unexpected Future Boost of Methane Possible from Arctic Permafrost. URL: climate.nasa.gov/news/2785/unexpected-future-boost-of-methane-possible-from-arctic-permafrost/

Greenpeace (2020). Siberia a Climate Hotspot: Wildfires Rage Covering Russian Cities in Smoke. URL: www.greenpeace.org/international/press-release/44107/siberia-climate-hotspot-wildfires-russian-cities-smoke/

GRID - Arendal (2020). New Map Shows Extent of Permafrost in Northern Hemisphere. URL: news.grida.no/new-map-shows-extent-of-permafrost-in-northern-hemisphere

Hanna, Edward, and others (2021). Greenland Surface Air Temperature Changes from 1981 to 2019 and Implications for Ice-sheet Melt and Mass-balance Change. In *International Journal of Climatology*, vol. 41, S1, E1336-E1352. DOI: 10.1002/joc.6771

Henson, Bob (2021). Arctic Climate Change May Not Be Making Winter Jet Stream Weird After All. URL: www.washingtonpost.com/weather/2021/07/31/arctic-climate-change-jet-stream-winter/

Hjort, Jan, and others (2018). Degrading Permafrost Puts Arctic Infrastructure at Risk by Mid-Century. In *Nature communications*, vol. 9, No. 1, p. 5147. DOI: 10.1038/s41467-018-07557-4

Horton, Ben (2021). Arctic Death Spiral. URL: www.arcticdeathspiral.org/

Hugelius, Gustaf, and others (2020). Large Stocks of Peatland Carbon and Nitrogen Are Vulnerable to Permafrost Thaw. In *Proceedings of the National Academy of Sciences of the United States of America*, vol. 117, No. 34, pp. 20438–46. DOI: 10.1073/pnas.1916387117

Intergovernmental Panel on Climate Change (IPCC) (2015). *Climate Change 2014: Synthesis Report*. Intergovernmental Panel on Climate Change: Geneva, Switzerland.

Intergovernmental Panel on Climate Change (IPCC) (2019). *The Ocean and Cryosphere in a Changing Climate: A Special Report of the Intergovernmental Panel on Climate Change*. Intergovernmental Panel on Climate Change.

Intergovernmental Panel on Climate Change (IPCC) (2021). *Summary for Policymakers*. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., and others, eds.,

Inuit Circumpolar Council - Alaska (2015). *Alaskan Inuit Food Security Conceptual Framework: How to Assess the Arctic from an Inuit Perspective: Full Technical Report*. Inuit Circumpolar Council - Alaska.

Kharuk, Viacheslav I., and others (2021). Wildfires in the Siberian Taiga. In *Ambio*, DOI: 10.1007/s13280-020-01490-x

Klimenko, Ekaterina (2019). The Geopolitics of a Changing Arctic. SIPRI Background Paper. Stockholm International Peace Research Institute.

Labe, Zachary, and others (2018). Contributions of Ice Thickness to the Atmospheric Response from Projected Arctic Sea Ice Loss. In *Geophysical Research Letters*, vol. 45, No. 11, pp. 5635–42. DOI: 10.1029/2018GL078158

Labe, Zachary (2020). A Sign of the Future: Summer 2020 in the Arctic. URL: polarbearsinternational.org/news/article-climate-change/a-sign-of-the-future-summer-2020-in-the-arctic/

Landrum, Laura, and Marika M. Holland (2020). Extremes Become Routine in an Emerging New Arctic. In *Nature Climate Change*, vol. 10, No. 12, pp. 1108–15. DOI: 10.1038/s41558-020-0892-z

Lei, Ruibo, and Zexun Wei (2020). Exploring the Arctic Ocean Under Arctic Amplification. In *Acta Oceanologica Sinica*, vol. 39, No. 9, pp. 1–4. DOI: 10.1007/s13131-020-1642-9

Lindsey, Rebecca (2021). Understanding the Arctic Polar Vortex. URL: www.climate.gov/news-features/understanding-climate/understanding-arctic-polar-vortex

MacFarquhar, Neil, and Emile Duce (2019). Russian Land of Permafrost and Mammoths Is Thawing. *The New York Times*, 2019. URL: www.nytimes.com/2019/08/04/world/europe/russia-siberia-yakutia-permafrost-global-warming.html

Machens, Chris (2013). NASA: The Polar Jet Stream - Climate State. URL: climatestate.com/2013/05/02/nasa-the-polar-jet-stream/

Mallett, Robbie D., and others (2021). Faster Decline and Higher Variability in the Sea Ice Thickness of the Marginal Arctic Seas When Accounting for Dynamic Snow Cover. In *The Cryosphere*, vol. 15, No. 5, pp. 2429–50. DOI: 10.5194/tc-15-2429-2021

Manrique, David R., and others (2018). Arctic: Traditional Knowledge, Livelihoods and Community Engagement. JRC Technical Reports. Brussels Joint Research Centre.

McCarthy, Jessica L., and others (2020). Arctic Fires Re-Emerging. In *Nature Geoscience*, vol. 13, No. 10, pp. 658–60. DOI: 10.1038/s41561-020-00645-5

McGuire, A. D., and others (2018). Dependence of the Evolution of Carbon Dynamics in the Northern Permafrost Region on the Trajectory of Climate Change. In *Proceedings of the National Academy of Sciences*, vol. 115, No. 15, pp. 3882–87. DOI: 10.1073/pnas.1719903115

McKay, David A. (2019). Fact-Check: Will an Ice-Free Arctic Trigger a Climate Catastrophe? URL: climatetippingpoints.info/2019/04/02/fact-check-will-an-ice-free-arctic-trigger-a-climate-catastrophe/

Molnár, Péter K., and others (2020). Fasting Season Length Sets Temporal Limits for Global Polar Bear Persistence. In *Nature Climate Change*, vol. 10, No. 8, pp. 732–38.

National Aeronautics and Space Administration (NASA) (2020). 2020 Arctic Sea Ice Minimum at Second Lowest on Record. URL: <https://climate.nasa.gov/news/3023/2020-arctic-sea-ice-minimum-at-second-lowest-on-record/>

National Aeronautics and Space Administration (2021). GISS Surface Temperature Analysis (v4). URL: https://data.giss.nasa.gov/gistemp/zonal_means/

Natali, Susan M., and others (2019). Large Loss of CO₂ in Winter Observed Across the Northern Permafrost Region. In *Nature Climate Change*, vol. 9, No. 11, pp. 852–57. DOI: 10.1038/s41558-019-0592-8

Natali, Susan M., and others (2021). Permafrost Carbon Feedbacks Threaten Global Climate Goals. In *Proceedings of the National Academy of Sciences*, vol. 118, No. 21, DOI: 10.1073/pnas.2100163118

NOAA (2020). Arctic Oscillation. URL: www.ncdc.noaa.gov/teleconnections/ao/

Oliva, Marc, and M. Fritz (2018). Permafrost Degradation on a Warmer Earth: Challenges and Perspectives. In *Current Opinion in Environmental Science & Health*, vol. 5, pp. 14–18. DOI: 10.1016/j.coesh.2018.03.007

Overland, James, and others (2019). The Urgency of Arctic Change. In *Polar Science*, vol. 21, pp. 6–13. DOI: 10.1016/j.polar.2018.11.008

Overland, James, and others (2021). How Do Intermittency and Simultaneous Processes Obfuscate the Arctic Influence on Midlatitude Winter Extreme Weather Events? In *Environmental Research Letters*, vol. 16, No. 4, p. 43002. DOI: 10.1088/1748-9326/abdb5d

Overland, James E., and others (2014). Future Arctic Climate Changes: Adaptation and Mitigation Time Scales. In *Earth's Future*, vol. 2, No. 2, pp. 68–74. DOI: 10.1002/2013EF000162

PIOMAS (2021). PIOMAS Arctic Sea Ice Volume Reanalysis. URL: psc.apl.washington.edu/research/projects/arctic-sea-ice-volume-anomaly/

Polovtseva, Maria (2020). A Blessing and a Curse: Melting Permafrost in the Russian Arctic. URL: www.thearcticinstitute.org/blessing-curse-melting-permafrost-russian-arctic/

Sayedi, Sayedeh S., and others (2020). Subsea Permafrost Carbon Stocks and Climate Change Sensitivity Estimated by Expert Assessment. In *Environmental Research Letters*, vol. 15, No. 12, p. 124075. DOI: 10.1088/1748-9326/abcc29

Scambos, Ted, and others (2020). Greenland's 2020 Summer Melting: A New Normal? . URL: nsidc.org/greenland-today/2020/08/greenlands-2020-summer-melting-a-new-normal/

Schaefer, Kevin, and others (2014). The Impact of the Permafrost Carbon Feedback on Global Climate. In *Environmental Research Letters*, vol. 9, No. 8, p. 85003. DOI: 10.1088/1748-9326/9/8/085003

Schuur, Edward A. (2019). Arctic Report Card: Update for 2019: Arctic Ecosystems and Communities Are Increasingly at Risk Due to Continued Warming and Declining Sea Ice. URL: arctic.noaa.gov/Report-Card/Report-Card-2019/ArtMID/7916/ArticleID/844/Permafrost-and-the-Global-Carbon-Cycle

Shakhova, Natalia, and others (2019). Understanding the Permafrost–Hydrate System and Associated Methane Releases in the East Siberian Arctic Shelf. In *Geosciences*, vol. 9, No. 6, p. 251. DOI: 10.3390/geosciences9060251

Strauss, Jens, and others (2017). Deep Yedoma Permafrost: A Synthesis of Depositional Characteristics and Carbon Vulnerability. In *Earth-Science Reviews*, vol. 172, pp. 75–86. DOI: 10.1016/j.earscirev.2017.07.007

Struzik, Ed (2016). Food Insecurity: Arctic Heat Is Threatening Indigenous Life.

Tedesco, Marco, and others (2019). Greenland Ice Sheet. NOAA. URL: arctic.noaa.gov/Report-Card/Report-Card-2019/ArtMID/7916/ArticleID/842/Greenland-Ice-Sheet

The New York Times (2020). Russia Declares Emergency After Arctic Oil Spill. URL: www.nytimes.com/2020/06/04/world/europe/russia-oil-spill-arctic.html

Treat, Claire C., and Steve Frolking (2013). A Permafrost Carbon Bomb? In *Nature Climate Change*, vol. 3, No. 10, pp. 865–67. DOI: 10.1038/nclimate2010

Turetsky, Merritt R., and others (2019). Permafrost Collapse Is Accelerating Carbon Release. In *Nature*, vol. 569,

Turetsky, Merritt R., and others (2020). Carbon Release Through Abrupt Permafrost Thaw. In *Nature Geoscience*, vol. 13, No. 2, pp. 138–43. DOI: 10.1038/s41561-019-0526-0

U.S. Global Change Research (USGCRP) (2018). Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report. Washington, DC

U.S. Global Change Research. DOI: 10.7930/Soccr2.2018

Veraverbeke, Sander, and others (2021). Direct and Longer-Term Carbon Emissions from Arctic-Boreal Fires: A Short Review of Recent Advances. In *Current Opinion in Environmental Science & Health*, vol. 23, p. 100277. DOI: 10.1016/j.coesh.2021.100277

Voiland, Adam (2013). In a Warming World, Storms May Be Fewer but Stronger: Scientists Investigate How Climate Change Affects Extreme Weather. URL: earthobservatory.nasa.gov/features/ClimateStorms

Wang, Chenghai, and others (2019). Most of the Northern Hemisphere Permafrost Remains Under Climate Change. In *Scientific reports*, vol. 9, No. 1, p. 3295. DOI: 10.1038/s41598-019-39942-4

Witze, Alexandra (2020). Why Arctic Fires Are Bad News for Climate Change. In *Nature*, vol. 585, pp. 336–37.

Wunderling, Nico, and others (2021). Interacting Tipping Elements Increase Risk of Climate Domino Effects Under Global Warming. In *Earth System Dynamics*, vol. 12, No. 2, pp. 601–19. DOI: 10.5194/esd-12-601-2021

Zhang, Ruonan, and others (2020). Increased European Heat Waves in Recent Decades in Response to Shrinking Arctic Sea Ice and Eurasian Snow Cover. In *npj Climate and Atmospheric Science*, vol. 3, No. 1, DOI: 10.1038/s41612-020-0110-8

Photo Credits

© Unsplash/Annie Spratt, cover, p.12

© Unsplash/William Bossen, p. 4

