UNIVERSITY OF ALBERTA

Why are the Arctic ice caps changing?

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Martin Sharp from the University of Alberta provides a compelling insight into the issue of precisely why the Arctic ice caps are changing

It is now well established that ice caps and glaciers across the Arctic are, by and large, losing mass more rapidly than they have done at any previous time during the period of record - which goes back nearly 60 years in some regions. An obvious question to ask is why and how is this happening? To answer this question, we need to look at how the climate in the Arctic is changing, how climate variability can generate periods when rates of melting are unusually high and how various feedback mechanisms may amplify the direct effect of climate warming on glaciers and ice caps.

Climatic drivers of glacier change

Since the early 1960s, the Arctic has warmed in both the summer (May to October) and winter (November to April) months (Overland et al., 2017), though warming has been more rapid in the winter months than in the summer (when melting occurs at the glacier surface). The winter warming since the 1960s exceeds 4 degrees Celsius in the Russian Arctic Islands and is more than 2 degrees Celsius over much of Alaska, the Canadian Arctic Archipelago, Svalbard and Northern Scandinavia. Although the summer warming is more muted, because it is limited by the melting temperature of the ice, which is often reached at the surface in summer, it exceeds 2 degrees Celsius in the Canadian Arctic Archipelago and is more than 1 degree Celsius in other glaciated regions of the Arctic. As a result, it has driven increases in the rates at which ice caps and glaciers across the Arctic are melting.

Meltwater production

The total amount of meltwater produced in each glaciated sub-region of the Arctic depends upon the total area of ice in each region, on the mean summer air temperature in each region and on the rate at which that temperature is changing over time. Rapidly warming regions that contain large areas of glacier ice lose mass most rapidly. Not surprisingly, then, Greenland (with its large continental scale ice sheet) was by far the largest single source of meltwater runoff to the ocean in the Arctic (contributing 257 Gt of water to the ocean each year from 2003-2015), followed by Alaska (70 Gt/yr) and the Canadian Arctic Islands (62 Gt/yr). Arctic Russia, Iceland, Svalbard and Scandinavia together contributed a further 37 Gt/yr (Box et al., 2018).

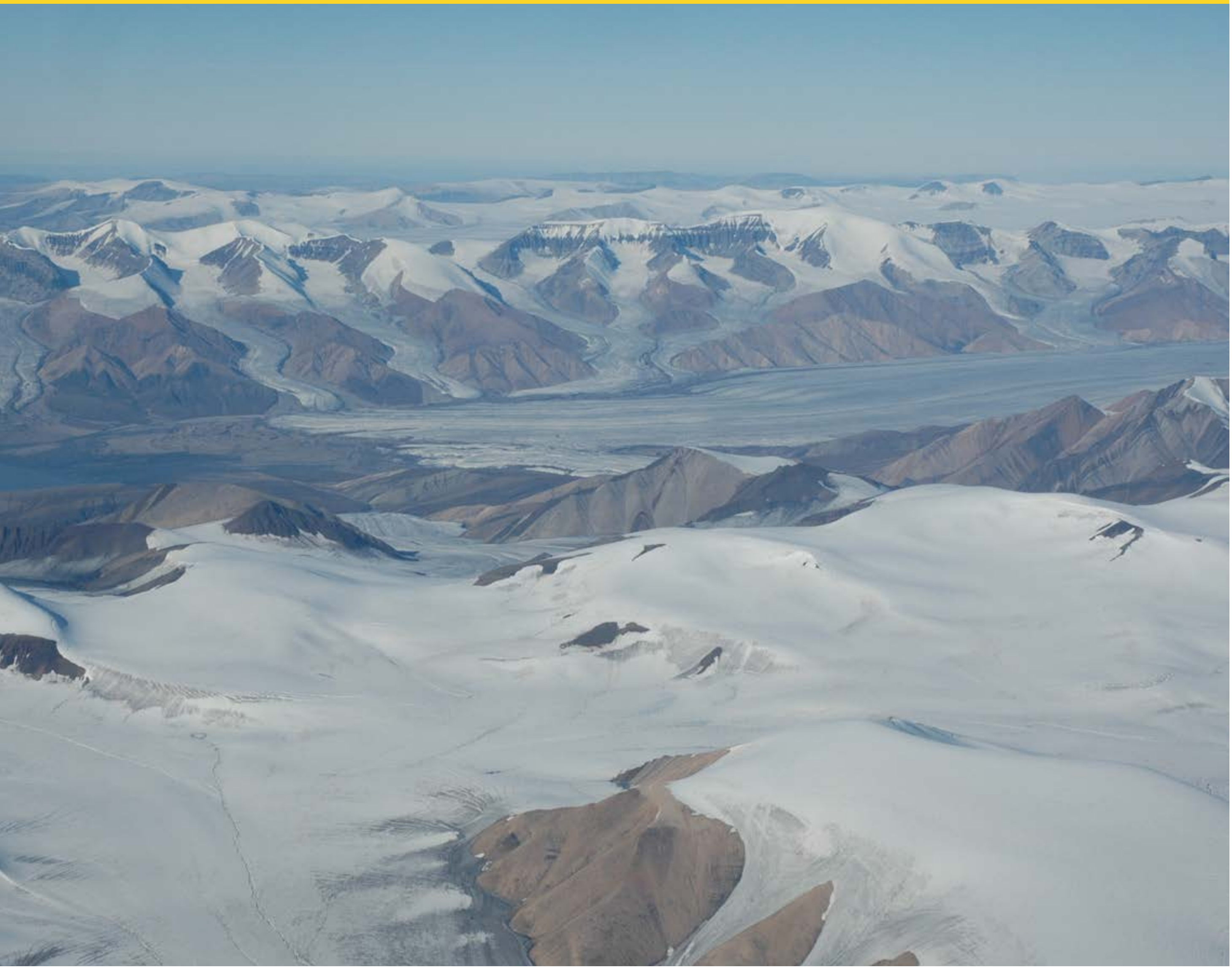
The relative importance of natural and anthropogenic forcings

Attribution studies designed to determine why the climate is warming and why glaciers are losing mass suggests that the signature of anthropogenic forcings on the climate, (such as increasing concentrations of greenhouse gases in the atmosphere) is clearly detectable in the records of the mass balance of glaciers in Alaska, Arctic Canada and Greenland during the period 1991-2010 and that it is probably also apparent in Iceland and Scandinavia. The anthropogenic contribution to the global rate of glacier mass loss from 1991-2010 was estimated to be 69 +/-24% by Marzeion et al., (2014). Factors that add to this anthropogenic contribution include land-use changes, changing concentrations of anthropogenic aerosols in the atmosphere and emissions of greenhouse gases, like carbon dioxide and methane, which have increased the concentrations at which these gases occur in the atmosphere.

The role of snow/ice albedo feedback in ice cap melting

The direct impact of both natural and anthropogenic climate forcings on glacier mass balance is modified by various feedback effects. The most notable of these is the so-called “snow-ice-albedo feedback”. The albedo of a surface is a measure of the fraction of the incoming solar radiation that is reflected from the surface on which the radiation is incident. The albedo of fresh, dry, snow can be as high as 97% (in which case only 3% of the incident radiation is available to warm or melt the snow surface) but it drops to around 74% for a melting snow surface and to around 40% for a melting glacier ice surface. Albedo decrease increases the fraction of the incoming solar radiation that is available for melting snow and ice. Hence rates of surface melting tend to increase when the reflective winter snow cover is removed, exposing glacier ice with a lower albedo.

The surface albedo can be as low as 12% if the ice is covered in rock debris that has either melted out of the ice or been deposited onto the glacier surface by processes, such as rock falls and landslides from surrounding valley walls. Such debris typically absorbs more incident solar radiation than the more reflective snow and ice surfaces. In Iceland, the fallout of ash from volcanic eruptions has a similar effect, as may particulate fallout of black carbon from forest fires in areas like Alaska. There is also increasing evidence that melting glacier surfaces are colonised by pigmented microbes (the pigments provide protection against ultraviolet radiation) and that this also darkens these surfaces, as does ponding of meltwater on the glacier surface - something that is spreading to progressively higher elevations on ice caps in Arctic Canada. Local variability in surface melt rates may also occur in response to variations in



the micro-topography of the melting surface which affect whether and for how long a given area of the surface is illuminated by or shaded from, incident solar radiation.

As snow accumulates on a glacier surface over winter and buries any surficial rock debris, the albedo increases and the glacier surface becomes very reflective of solar radiation. This, along with the fact that the snowpack tends to be very cold at the end of winter and must be heated to the melting point before melting can resume, makes it (initially) hard to melt the snow in spring. However, as the snow cover starts to melt and thin, the grain size of the snow tends to increase, liquid water accumulates in the snow and particulate matter (like dust) released by melting may accumulate on its surface. Eventually, the snow disappears, thereby exposing the underlying glacier ice and the glacier surface becomes increasingly darker, absorbs more solar radiation, heats up and, eventually, melts. Summer snowfall events which bury a previous melting surface temporarily raise the surface albedo and slow down the rate of surface melting until the snow has been completely melted and glacier ice has been re-exposed at the surface. These processes result in an annual cycle of glacier mass change in which mass is added to a glacier by snowfall in winter and removed from it by melting in summer. As the climate warms over time, the period during which summer melting can occur tends to become longer and the amount of melting during that period may increase. Unless this extra melting is offset by greater snowfall in winter, the glacier will lose mass over time.

Mortimer and Sharp (2018) reported that the mean summer surface albedo of glaciers in Canada's Queen Elizabeth Islands (QEI) (as measured using NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) sensors, decreased from 2001 to 2016 at a mean rate of 0.029 +/-0.025 per decade, while the mean July albedo decreased more rapidly (-0.05+/- 0.031 per decade). The largest decreases in albedo were observed at low elevations around the ice cap margins between 2007 and 2012. There appeared to be a correlation between the mean summer black sky albedo and the mean summer North Atlantic Oscillation Index, which suggests that changes in patterns of atmospheric circulation over the region were influencing the surface albedo of the ice caps. There was also a negative correlation, for the period 2001-2016, between the mean summer surface temperature of the QEI ice caps and their black sky albedo, which suggests that positive ice-albedo feedback may be helping to accelerate rates of mass loss from glaciers in this region.

Internal accumulation

One factor that may complicate this story is that, because the surface snow is the first to be melted when air temperatures rise above the melting temperature in the spring, the first meltwater produced will percolate downwards into underlying snow that has yet to be warmed to the pressure melting temperature. It will then refreeze, releasing latent heat that helps to warm the snowpack to the melting temperature. This refreezing process, known as internal accumulation, will, however, delay the runoff of this fraction of the summer meltwater as the ice it produces must be melted again before water can run off. In areas where this occurs over multiple years, substantial ice bodies may form within the firn layer of the glacier or ice cap. As these ice bodies are buried over time by snowfall, they form an aquitard within the firn layer that prevents deep percolation of meltwater into the firn.

Mass loss by slush flows and slush avalanches

If this process persists over multiple summer seasons, the aquitards can become very thick and spatially extensive and meltwater may be ponded above them in the overlying firn and snow. If the upper parts of the firn and the overlying snowpack become water-saturated then, on sloping surfaces, they may fail and start to move downslope as slush flows, or slush avalanches that can travel considerable distances, accumulating mass by erosion as they go. These flows can cut significant channels into the snow and firn above the aquitards and these may, in turn, attract meltwater inflow from surrounding areas of the firn body. This meltwater may further erode the channels created by the slush flows and turn them into stream channels that play an important role in evacuating meltwater from higher elevation regions of the ice caps. Up-glacier expansion of meltwater drainage systems to regions of ice caps that had no surface drainage in the past is now being observed as surface melting extends to progressively higher elevations and as the formation of large ice bodies in the firn both warms the firn by the release of latent heat of fusion and increases the probability that it becomes water-saturated.

Arctic contributions to changes in global mean sea level

The array of processes that contribute to ice cap melting also determine the rates at which Arctic glaciers are adding water to the global ocean and contributing to the rise in global mean sea level, which is one of the biggest potential hazards associated with global climate warming (although warming of the ocean itself, which results in thermal expansion of ocean waters, is also a factor). Box et al. (2018) estimated that the total contribution of Arctic glacier and Greenland ice sheet melt to global mean sea level change from 1971-2017 was 23 +/- 12.36 mm. This is the sum of regional contributions from Greenland (10.61mm), Alaska (5.71 mm), Arctic Canada (3.21 mm), Scandinavia (0.08 mm), Svalbard (1.12 mm), Iceland (0.82 mm) and the Russian High Arctic (1.45 mm). Uncertainties associated with these individual regional estimates range from 0.33mm (Svalbard) to 2.16 mm (Alaska) and 7.31 mm (Greenland). However, the rates of water

input to the ocean from glaciers in several of the regions of the Arctic changed significantly between the periods 1986-2005 and 2005-2015. The rates increased over time for Greenland, Arctic Canada, Scandinavia and Iceland but decreased over time for Alaska, Svalbard and the Russian Arctic. For the whole Arctic, they increased from 8.30 to 12.36 mm (Box et al., 2018). ✺

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The fight against climate change: We all foot the bill for a warmer Arctic

Joseph Cook, Vice President of the UK Polar Network (UKPN) Committee argues that we all foot the bill for a warmer Arctic in the fight against climate change

2019 is shaping up to be a watershed year in the fight against climate change. Coordinated international school strikes – whose figurehead Greta Thunberg has already been nominated for a Nobel Prize – and national movements such as the Extinction Rebellion have highlighted the urgent need for climate action. Major “scientainment” programmes such as the BBC’s “Climate Change: The Facts” and Netflix’s “One Planet” demonstrate that climate consciousness is rapidly becoming mainstream. The Governor of the Bank of England, Mark Carney, has recently made the economic dangers of climate change clear to bankers, warning the City to “take climate change seriously or lose money”, indicating that the message is finally permeating into influential institutions. Nevertheless, in a system where several degrees of warming are already “baked-in”, policy still severely lags environmental urgency and governments are distracted by various national crises, it remains to be seen whether this positive rhetoric translates into meaningful action and whether it does so rapidly enough to mitigate the worst effects of future climate change.

Immediate, meaningful action is critical to avoid further exacerbating the social, economic and environmental stresses that we will now inevitably face as our climate warms. While we often report climate change in terms of global averages, the effects of climate warming are felt more strongly in some places than others. The Arctic, in particular, is warming at more than twice the global average rate because the sensitive sea ice, glaciers and snow that cover large parts of the Arctic amplify warming trends. This happens because snow and ice are highly reflective and act like a mirror bouncing solar energy back into space. When temperatures rise that snow and ice become less reflective and when it melts away completely, it reveals dark land or ocean. This makes the planet less reflective, meaning more heat is available for warming the Earth. The effects of this are felt acutely in the Arctic but also ripple through global weather systems, economies, infrastructures and human societies. The Arctic is a sensitive victim of climatic change but at the same time a powerful accelerator of climate impacts worldwide, meaning we all pay the price for a warmer Arctic.

The Arctic is where most of the ice and snow in the northern hemisphere are concentrated. It is where most of our glaciers rest in mountain valleys and where the continent-sized Greenland Ice Sheet sits high atop the ancient continental crust. Both the glaciers and the ice sheet are shrinking, losing billions of tonnes of ice each year due to warming temperatures. This is a major issue because it adds water to the oceans, rising sea levels. This is not a localised problem.

Higher sea levels mean coastal areas and flood plains becoming uninhabitable, increased coastal and riverbank erosion, loss of land for agriculture, housing, utilities and businesses as well as storm surges that penetrate further inland causing more damage. It has been estimated that sea level rise alone could wipe $14 trillion from the global economy every year by the year 2100 if we continue on our current rate of carbon emission (Jevrejeva et al. 2014). It has recently been estimated that by the end of the century Arctic warming will contribute $66.9 trillion to the global economic costs of climate change under emissions scenarios expected under current national pledges (Yumashev et al. 2019). Almost four million people live in the Arctic region with cultures, traditions and livelihoods finely tuned to the cold environment that are threatened by climate warming. At the same time, warmer temperatures provide some opportunities, for example, retreating glaciers, ice caps and ice sheets will enable access to new areas for mineral, oil and gas prospecting and new shipping routes. However, while beneficial for local economies, extracting these resources will be environmentally damaging and exacerbate a global climate crisis, raising sensitive geopolitical issues.

Changes to Arctic ice influence the weather locally and at lower latitudes, including over major population centres in northern Europe and North America. Because ice is cold, it influences the pressure of air masses above it, controlling the shape, position and strength of the jetstream and polar vortex. Extreme weather events will continue to increase in frequency and magnitude as the Arctic ice continues to retreat, exacerbating both floods and droughts and associated phenomena, such as wildfires and landslides, with the inevitable loss of life and damage to homes, businesses and infrastructures. This is not only happening in distant, uninhabited Arctic icescape but it is already happening to all of us, the world over. Even those who do not directly suffer the direct impacts of these environmental hazards will suffer through rising costs of insurance, living costs and a weaker global economy.

The ecological costs of a warming Arctic are also high, with indigenous, cold-adapted species pushed ever closer to extinction by a rapidly changing environment and a northwards shift of invasive species. Grizzly bears have been observed migrating north into areas previously occupied only by polar bears and Arctic foxes. A further ecological cost is that cold oceans acidify more rapidly than warmer ones, threatening marine wildlife, especially those species that rely upon low acidity, carbonate-rich water for building shells. The rapidly declining Arctic sea ice is fundamental to the survival of seal and polar bear. Furthermore, as the polar bear habitat shrinks, these animals are forced into more frequent human contact. Melting glaciers are also releasing contaminants into rivers, oceans, lakes and soils to be taken up by plants and consumed by animals, concentrating up the food chain meaning amplified doses are ultimately consumed by humans.

Arctic warming costs us all dearly. The Arctic itself is a threatened landscape, sensitive and vulnerable to the stresses we place upon it by burning fossil fuels. Strong connections exist between the Arctic and the lower latitudes. Through temperature rise, the Arctic is vulnerable to distant carbon emissions, but at the same time, humans at lower latitudes are vulnerable to environmental hazards amplified in the Arctic. These strong mutual connections mean protection and stewardship of the threatened Arctic begins with environmentally responsible behaviour at home. The costs of a warming Arctic are financial, humanitarian and ecological and are borne by everyone on the planet. Costs will increase as temperatures continue to rise. There must be a global movement towards leaving fossil fuels underground and relying upon renewable energy, while also generating less waste and adopting climate-conscious behaviours. There are still uncertainties in the feedbacks amplifying Arctic warming and the sensitivity of glaciers and ice sheets to climatic change that must be addressed as a matter of urgency. Understanding and monitoring how the Arctic is changing is key to accurately forecasting the timescales of change enabling proper management and mitigation measures to be put in place in a timely fashion. Because of the fundamental importance of Arctic processes to human societies globally, Arctic research must remain an international priority.

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