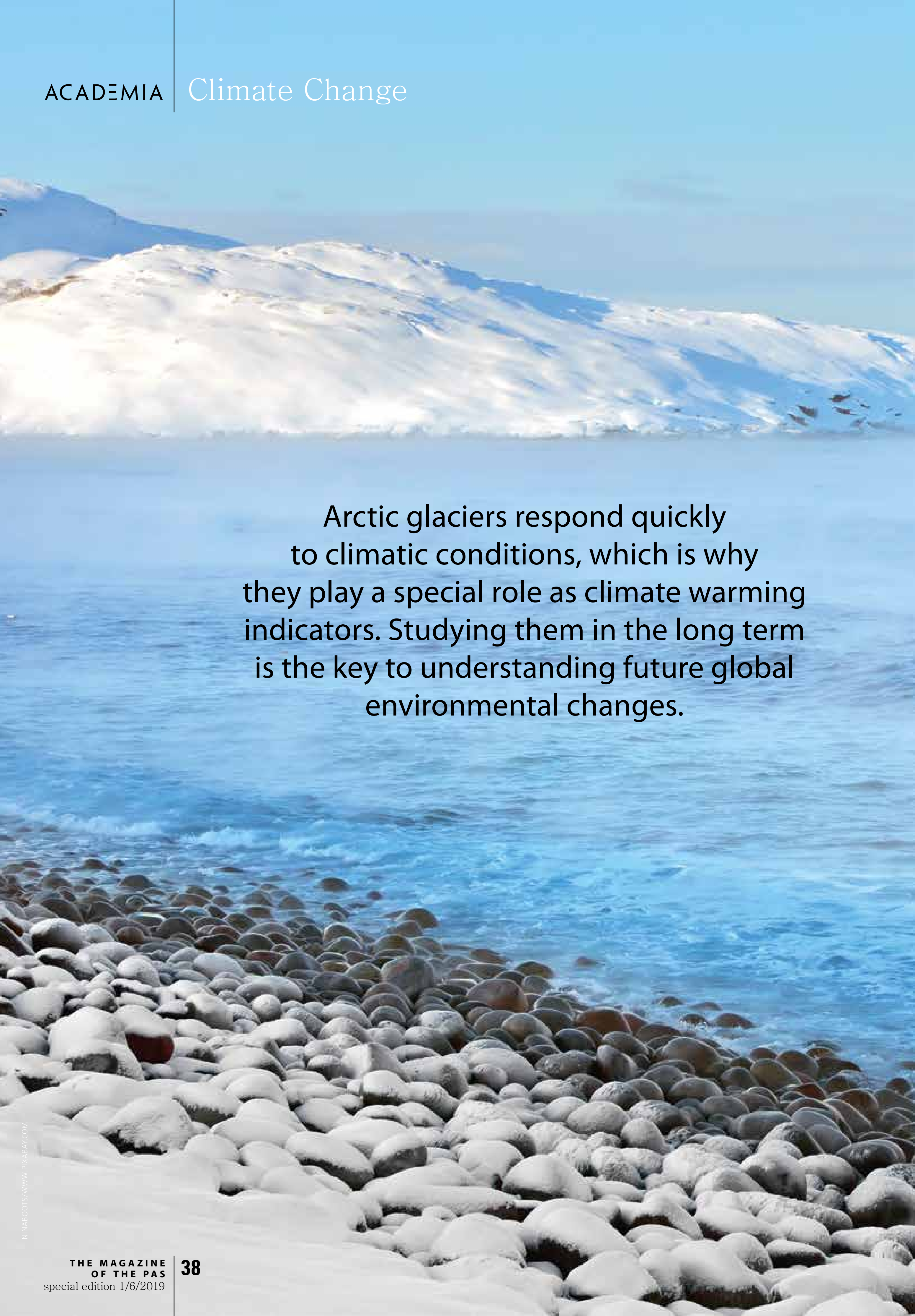

Arctic glaciers respond quickly to climatic conditions, which is why they play a special role as climate warming indicators. Studying them in the long term is the key to understanding future global environmental changes.

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Telling the Future from Ice

Prof. Jacek Jania

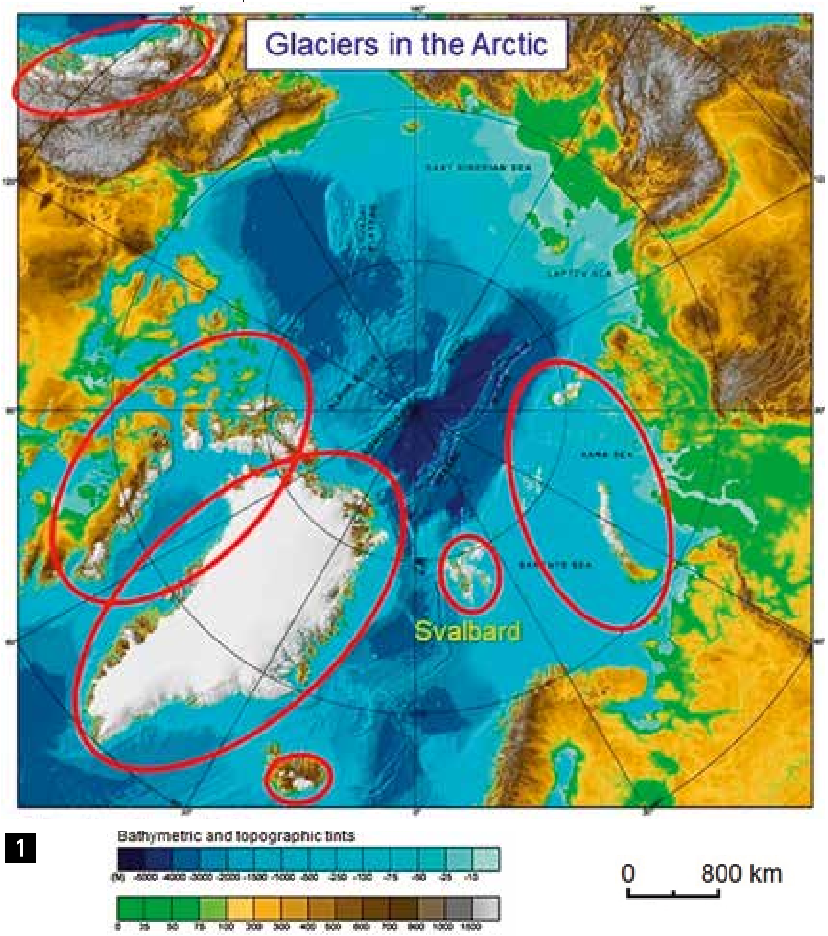
Centre for Polar Studies,
University of Silesia, Katowice
Committee on Polar Research,
Polish Academy of Sciences

Glaciers are masses of ice formed on land due to accumulating annual snowfalls. These include the major glaciers in Antarctica and Greenland, the ice caps in many Arctic regions, and smaller mountain and valley glaciers around the world. They are in constant, usually slow motion under the influence of gravity. They vary in terms of size, shape, thickness and thermal structure. A very important differentiating factor is the tip of their tongue. Most glaciers (usually the smaller ones) terminate on land, whereas ones that terminate in the ocean, known as tidewater glaciers, transport ice from the largest glaciated areas.

The climate influences glaciers by affecting the main factors contributing to the ice mass balance: the magnitude of winter snowfalls (the rate of accumulation) and the rate of melting (surface ablation). In the classic approach to the mass balance of glaciers, the loss of mass on the front of the glacier terminating in the sea is not taken into account. This frontal ablation is the combination of melting on contact with sea water and glacial calving (when icebergs break off the edge of a glacier). Global warming both increases the melting process as well as boosts the formation of icebergs, which can significantly affect the length and thickness of glaciers.

Monitoring the mass balance of glaciers enables us to identify more precisely how they react to climate change. Out of the nearly 200,000 glaciers in the world, only a few are being studied long-term, and a similar problem applies for the Arctic ice cover. Studying frontal ablation, as opposed to surface ablation, is very difficult. Only a handful of tidewater glaciers have their mass balance, including calving, regularly measured. For others, estimates are made using various kinds of satellite data. Researchers from the University of Silesia and the United States Geological Survey were among the first to study tidewater glaciers. Back in the late 1970s, research began on the Columbia glacier and other glaciers in Alaska, and a few years later on the Hans glacier in southern Svalbard near the Polish Polar Station on the Hornsund fjord.

In this article, we will illustrate how Arctic glaciers serve as indicators of global warming and examine the



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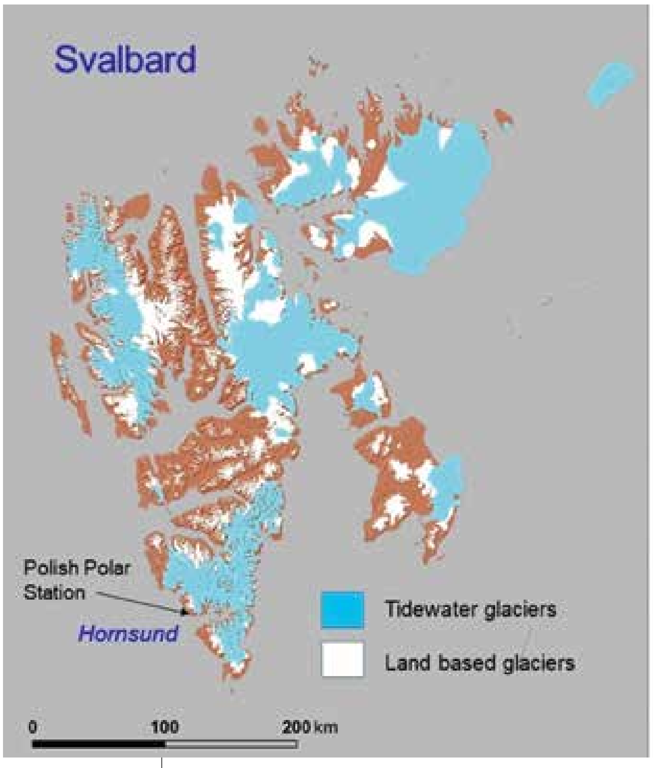
Glacierized regions of the Arctic (Fig. 1) and tidewater glaciers in the Svalbard archipelago. The location of the Polish Polar Station is marked on the northern shore of the Hornsund Fjord (Fig. 2).



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SOURCES: THE INTERNATIONAL BATHYMETRIC CHART OF THE ARCTIC OCEAN (IBCAO) HTTPS://WWW.NGDC.NOAA.GOV/MGG/BATHYMETRY/ARCTIC/ARCTIC.HTML MAP PREPARED BY M. BŁASZCZYK (DEPT. OF GEOMORPHOLOGY, UNIVERSITY OF SILESIA)

special role played by ice masses flowing into the sea. The latter are still poorly researched, which is why the Polish research initiatives are important for fostering a better understanding of global environmental changes.

On the move

In the Arctic part of the Northern Hemisphere, apart from the great Greenland Ice Sheet (about 1.71 million km^2) and its surroundings, glaciers are found in Svalbard, the archipelagos of the Russian Arctic, the Canadian Arctic, as well as in the Sub-Arctic in Iceland, Alaska and Scandinavia. With the exception of Iceland and Scandinavia, tidewater glaciers account for a majority of surface area. In Svalbard, the main area of Polish research, the total area of glaciers is about 33,800 km^2, of which 68% are tidewater glaciers.

The Arctic is warming up faster than the climate in middle latitudes and the rest of the globe, a phenomenon known as Arctic amplification. For example, over the last three decades, the average annual air temperature in the Polish city of Katowice increased at the rate of 0.4°C/10 years, whereas on Svalbard, during the same period it increased by 1.1°C/10 years in Hornsund (77°N) and 1.4°C/10 years in Longyearbyen (the capital, 78°N). This means the Arctic is warming up about three times faster.

This increases the melting of glaciers, affecting the mass balance on their surface. The resulting meltwaters penetrate deep into the glaciers through crevasses and caves in the ice, reaching the floor. The increase in the amount of the sub-glacial waters, and therefore their higher pressure, reduces friction on the substrate and facilitates the sliding of glaciers along the floor, which makes them flow faster. This is glacers' dynamic reaction to global warming. The fronts of the tidewater glaciers experience a lifting force due to the hydrostatic displacement of seawater, in accordance with Archimedes' law. This further reduces friction and accelerates the advancement of glaciers.

The lower part of the ice tongue becomes stretched out, which results in the formation of numerous slits parallel to the ice cliff. These slits loosen the frontal structures, which leads to the formation of icebergs. This process, called "calving," is influenced by a combination of many factors. Although no general "calving law" has yet been determined, it is obvious that the key factors controlling the intensity of calving include: the depth of seawater in relation to the thickness of the ice, the speed of the flowing glaciers and the temperature of the seawater washing the ice cliff (it affects the intensity of underwater melting, and thus the stability of the glacial front). With the exception of the first factor, which mainly

JAKUB OSTAŁOWSKI

Prof. Jacek Jania, PhD, DSc

is a geographer studying glaciers and the polar environment and their response to climate change since 1972. Internationally known for his research on Arctic tidewater glaciers, he is a member of the European Polar Board (EPB), Chairman of the Committee on Polar Research of the Polish Academy of Sciences, and Head of the Centre for Polar Studies – a Leading National Research Centre in Poland. He is a full professor at the Faculty of Earth Sciences, University of Silesia, where he lectures on geodesy, cartography, glaciology and climate change problems. The author of numerous papers and three books.

depends on the topography of glacial substrates, the remaining ones are related to the changing climate. Put simply, the warmer the climate, the more intensive the calving, especially in deep water at the front of the glacier.

Tidewater glaciers are spatially dominant in the Arctic, and at the same time are more sensitive to global warming.

Retreat

Longer-term observations of the mass balance of Arctic glaciers are rare and focus on Svalbard. They include land glaciers, which are easier to be measured directly. Polish research on the Hans glacier (since 1989) is one of the few long-term studies involving tidewater glaciers. The surface mass balance of this glacier is slightly negative. Measuring mass loss due to calving requires hard-to-obtain data: the cross-sectional area through the ice tongue at the front, the average annual speed of the glacier at the front, and changes in the location of the glacier front (the amount of recession or possibly advancement).

It is necessary to measure the topography of the front and the thickness of the ice (very difficult at the ice cliff due to the crevices), as well as the depth of the sea at the front, the average speed of the glacier, and to track changes in cliff position during the year. The results for the period 2009–2014 showed that calving is responsible on average for 38% of the overall mass loss of the Hans glacier (the rest is due to surface melting). At the same time, significant inter-annual variability of the impact of frontal ablation is observed (25–54%). Subtracting the icebergs from the glacier mass balance, the cumulative sum is dramatically negative, more than 4 times more negative than for land glaciers. This means that calving is an extremely important process in the current accelerated Arctic deglaciation. This points to a persistent long-term global warming of the region.

An example of accelerated Arctic deglaciation is the Hornsund fjord in the south of Svalbard, studied by M. Błaszczyk's a team from the University of Silesia. Using historical maps, aerial photographs and satellite images, they tracked the recession of glaciers since the beginning of the 20th century. In the first four decades, glacial surface decreased at a rate of 0.8 ± 0.2 km^2/year. In the period 1936–1976, the rate of surface recession increased to about 1.6 km^2/year, and then to 2.6 km^2/year after 2000, to 3.5 km^2/year in recent years. This points to the dramatic acceleration of deglaciation in the twenty-first century.

Glacial thickness studies conducted by the same team from the University of Silesia (M. Grabiec et al.) using radar has shown that the Horn glacier substrate, which closes off the fjord from the east, lies 40 m below sea level. This means that its further recession will lead to the opening up of a sea link between the Greenland Sea and the Barents Sea in the future. The Hornsund Fjord will become a strait, probably around the middle of the twenty-first century. So the southern part of Spitsbergen – Sørkapp Land – will become a new island in the Svalbard archipelago.

Studies in the Atlantic part of the Arctic (JR Carr et al.) showed that the average rate of recession of tidewater glaciers has increased by 3.5 times between 1992–2000 and 2000–2010 (from 30.5m/year to almost 106m/year, respectively), albeit with differences between the regions studied. These results confirm observations from Svalbard that deglaciation is occurring swiftly and has been significantly accelerating in recent decades.

Changes

Glacier recession affects the surroundings. The land becomes exposed, but above all the water surface of the fjords increases. In both cases, because land and sea surfaces reflect less solar radiation than glaciers (from 50% for glaciers to approx. 30% for land and 10% for water), the average albedo of the region decreases. Higher absorption of solar radiation causes local and regional acceleration of global warming and melting of ice. This positive feedback increases the warming

The front of Hansbreen, a tidewater glacier flowing into the Hornsund Fjord.

M. MICHALSKI

of the Arctic's glaciated regions. Although the dominant positive feedback involves the disappearance of the sea ice cover across vast areas of the Arctic Ocean, the disappearance of glaciers is also of considerable regional significance.

Work by various authors, including studies conducted by the Dutch-Polish team on the Hans glacier (J. Oerlemans, J. Jania and L. Kolondra), shows that the accelerated deglaciation of tidewater glaciers is irreversible over the course of many centuries. It appears that depending on climate change scenarios, due to the deepening of the bottom of the glacial valley to 60–100m below sea level, by the end of this century the glacier will decrease to 10–12 km in length, and by 45–65% in volume.

Even if the emission of anthropogenic greenhouse gases is significantly reduced or stopped, the recession will not be halted, due to the calving of the glacier into deep water. In addition, even if the climate cools down and snowfall increases significantly (resulting in a positive mass balance of the glacier), the tongue will not flow into deep sea water. The frontal ablation in the deeper water will counterbalance the increased inflow of ice. Only a considerable shallowing of the fjord as a result of sedimentation of minerals from the surrounding land will allow the tongue to advance and stabilize itself on the piled-up bottom sediments. This is shown by the results of C^{14} dating of peat, which melted into the surface of the Hans glacier. They prove that there were no glaciers in the Hansbreen valley approx. 7,200–5,200 years ago BP (warm period during the Holocene era with temperatures 2°C higher than present). The marine sedimentation observed on Svalbard at a rate of 1cm per year is high. Despite that, the shallowing of about 50 m, which must have lasted about 5,000 years, enabled the glacier to advance during the Little Ice Age.

Considering the aforementioned fact that a large part of the Arctic glaciers flow into the recessed fjord valleys, we should expect further accelerated deglaciation. For glaciers to potentially return to their current state will take millennia, so we need to understand that the impact global warming will not stop within decades or even centuries after the end of the anthropogenic emissions of greenhouse gases into the atmosphere.

Increased melting of glaciers and formation of icebergs causes a global increase in sea levels. It is estimated at approx. 3.0–3.5 ± 0.5 mm/year (according to different authors). According to the latest work by

J. Box et al., Arctic glaciers are responsible for over 1/3 of this increase, constituting its largest regional source. Greenland's share in this is about 50 percent. The thermal expansion of seawater is the source of about 1/3 of the increase in ocean levels, and Antarctica along with other glaciers on Earth and reduced land water retention is responsible for the rest (less than 30%).

Between the years 1986–2005 and 2006–2015, the contribution of Arctic glaciers to raising global ocean levels increased threefold. Thus, Arctic glaciers play an important role in global environmental changes. The accelerated recession of Greenland outlet glaciers could threaten to bring about an accelerated rise in the global ocean level, which over a decade ago was estimated to be as much as 2 m through the end of the twenty-first century. W.T. Pfeffer et al. have shown that this number is not very realistic, because this glacier is surrounded on all sides by mountains, and the glaciers carrying the ice into the ocean squeeze through the narrow gates of the fjords.

We should remember, however, that increased ocean levels and sea water temperatures around West Antarctica are contributing to the slow disintegration of ice shelves and the acceleration of glaciers moving out of the West Antarctic Ice Sheet. Unlike Greenland, the largest of these glaciers (Pine Island Glacier and Thwaites Glacier, as well as the ice streams supplying the Ronne Shelf Iceberg) have wide gates with floors well below sea level. Many models show that with the significant instability of the Western Antarctic Ice Sheet, global ocean levels may rise by up to 3.3 m in a relatively short time, even over decades. Thus, the clear but limited impact of the Arctic glaciers on global ocean levels could contribute to a catastrophic sea level rise caused by glaciers on the other side of the Earth, in Antarctica, as suggested by the relatively numerous scenarios of global warming consequences.

A slow rise in sea level is also being observed on the Polish coast, caused by storm surges. The frequency of autumn and winter storm surges (>70 cm) has increased threefold in the last 60 years. This is also the result of global warming causing more intensive atmospheric circulation from the west. The destruction of beaches, erosion of cliff and dune coasts, and damage to coastal infrastructure are its consequences.

Responsibilities

- Arctic glaciers are exhibiting accelerated recession, confirming that global warming has been occurring for a long period of time.
- Increased melting accelerates the movement of tidewater glaciers, and consequently increases calving, which dramatically increases the negative mass balance of glaciers.
- This causes a positive feedback for further climate warming.
- Due to the fact that most tidewater glaciers are clearly below sea level, their recession will remain irreversible for several centuries, even if the warming stops and snowfall increases.
- The increased melting and calving of the Arctic glaciers plays a significant role in increasing global ocean levels. Their rise will not cease even if anthropogenic emissions of greenhouse gases are reduced.

We should therefore swiftly reduce greenhouse gas emissions in an effort to mitigate global warming. However, we should bear in mind that the glacier response will be delayed, even for millennia. Therefore, we should focus on adapting to life with a clearly warmer climate and rising sea levels.

Overall, work on tidewater glaciers highlights the complexity of climate research. It is particularly important to intensify international research efforts on studying the relationship between the atmosphere and the oceans and cryosphere.

Jacek Jania

Further reading:

D.I. Benn, D.J.A. Evans (2010): *Glaciers and Glaciation*. 2nd edition, Hodder Education, London, 802 pp.

M. Błaszczyk, J.A. Jania, L. Kolondra (2013): Fluctuations of tidewater glaciers in Hornsund Fiord (Southern Svalbard) since the beginning of the 20th century. *Polish Polar Research* 34(4), 327–352.

J. R. Carr, C. R. Stokes, A. Vieli (2017): Threefold increase in marine-terminating outlet glacier retreat rates across the Atlantic Arctic: 1992–2010. *Annals of Glaciology* 58(74) 2017 doi: 10.1017/aog.2017.3

J. Oerlemans, J. Jania, and L. Kolondra (2011): Application of a minimal glacier model to Hansbreen, Svalbard. *The Cryosphere*, 5, 1–11.

W. T. Pfeffer, J. T. Harper,2 S. O'Neel (2008): Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise. *Science* 321, 1340. DOI: 10.1126/science.1159099.