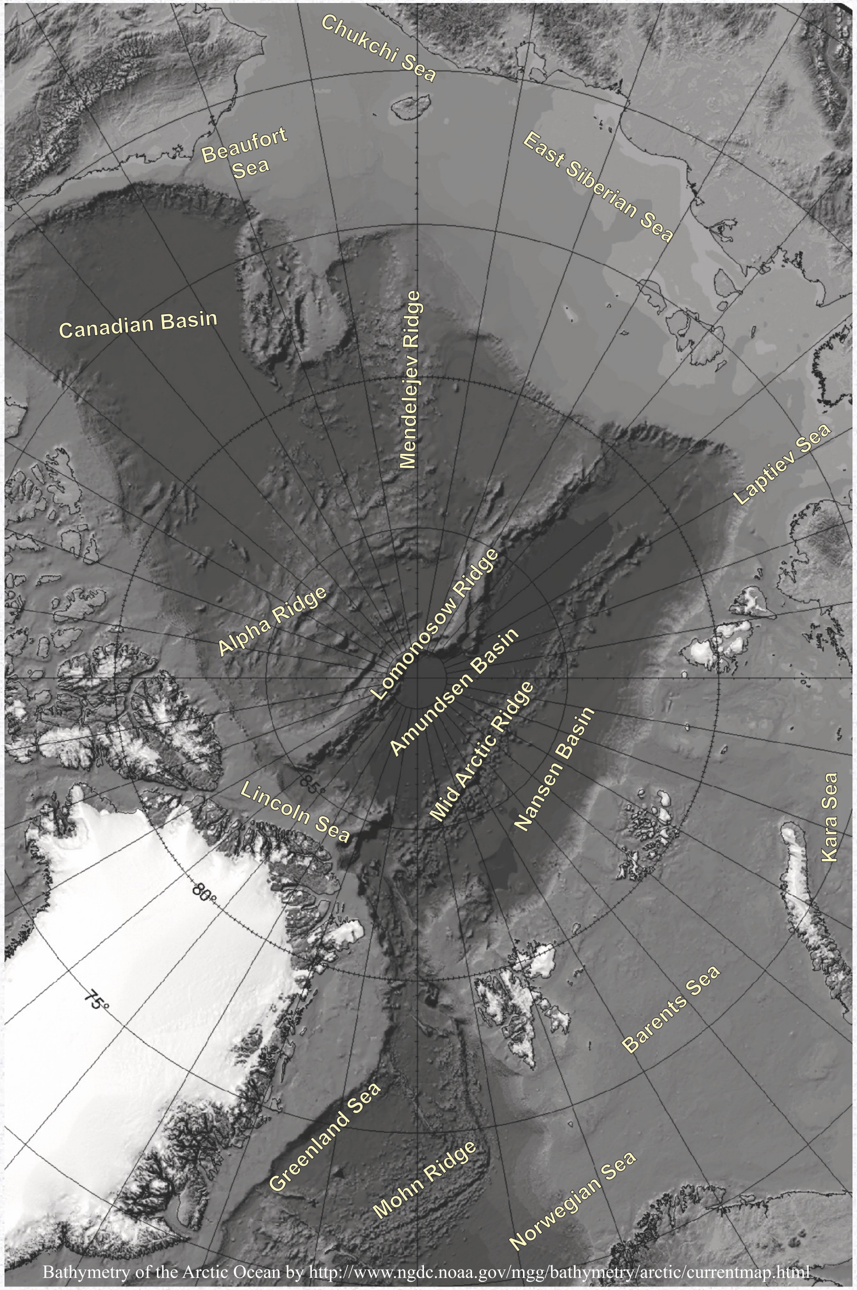
# EUROPEAN ARCTIC

## - sea users guide

Institute of Oceanology Polish Academy of Sciences, Sopot 2013



Bathymetry of the Arctic Ocean by http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/currentmap.html

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## Introduction

Jan Marcin Węsławski

The Institute of Oceanology PAN has conducted regular European Arctic oceanographic surveys from the r/v Oceania every summer since 1988. The Institute of Geophysics PAS maintains the year-round Stanislaw Siedlecki Polish Polar Station in Hornsund on Spitsbergen Island in the Svalbard Archipelago. A number of Polish universities and research institutes organize local Arctic expeditions annually. All this activity is coordinated and supported within the framework of international collaboration. Why do so many countries, Poland included, spend this much time and money on Arctic research? Countries like Russia, the USA, Canada, Denmark, Greenland, Norway, Sweden, Finland, and Iceland, which all have territories in the Arctic, do it for obvious reasons – they need to be knowledgeable about their own lands. Still, polar expeditions are organized by many non-Arctic countries, notably Germany, the UK, the Netherlands, Poland, and a number other countries from outside Europe. The international research station in Ny Alesund on Spitsbergen has Japanese, Korean, Indian, and Chinese facilities. The main reason for such massive interest in Arctic research is the Earth's changing climate, and the role of the Arctic in this process. Other reasons are the exploitation of oil, gas, coal, and gold mineral resources and living stocks of fishes and crustaceans. The most compelling reason for all of this scientific interest is the need to deepen our understanding of how planet Earth functions, and the vast, unpopulated, remote Arctic domain is still not well understood. Curiosity and the quest for knowledge are the drivers and imperatives of human civilization. Since all of the processes that influence the Arctic also directly impact us, e.g., global increases in sea levels stem from the mass melting of Arctic glaciers, and European temperatures depend on heat exchange between Atlantic and Arctic ocean interrelations, we must organize international efforts to continue observations and research. All of the knowledge acquired about the Arctic must be made available to the public, because only then we will all come to understand that the Earth is a single, connected system. Every one of us is a user of and a stakeholder in the Arctic, and this should encourage us to learn more about it and to develop an understanding of this nearby wilderness.

Polish Polar Station in Hornsund, Spitsbergen (photograph M. Szymocha, IGF PAN).

## The Northern Lights of the Aurora Borealis

Tomasz Petelski

The beautiful and mysterious phenomenon of northern lights has fascinated people for ages, and the myths of peoples inhabiting the far north attest to this. For example, the Eskimos used to perceive the lights as a path which enabled the souls of the dead to reach heaven. According to their beliefs, the lights were produced by the spirits playing ball with a walrus skull. The Nordic nations associated the phenomenon with the dance of spirits, while the Vikings believed it was the dance of dead virgins.

The first scientific reference to the northern lights is found in Meteorology by Aristotle, who thought the lights were the flames of burned gases. The same belief was still held by Galileo, who was one of the first scientist to use the term aurora borealis. In 1600, Wiliam Gilbert discovered that the Earth can be thought of as a huge magnet. His discovery, although not linked initially with the aurora borealis, was very important to the development of an understanding of the true nature of this phenomenon. The Norwegian Kristopher Hansteen (1784-1873) was the first to postulate that auroras comprised a continuous circle around the pole. At the end of the nineteenth, another Norwegian, Kristian Olaf Birkeland (1867-1917), achieved even more by conducting a number of experiments with a magnetized model of the Earth called Terella. He placed the model in a vacuum, bombarded it with streams of electrons, and produced an artificial aurora. This led him to draw the conclusion that the northern lights are the result of electrons from the Sun bombarding the Earth.

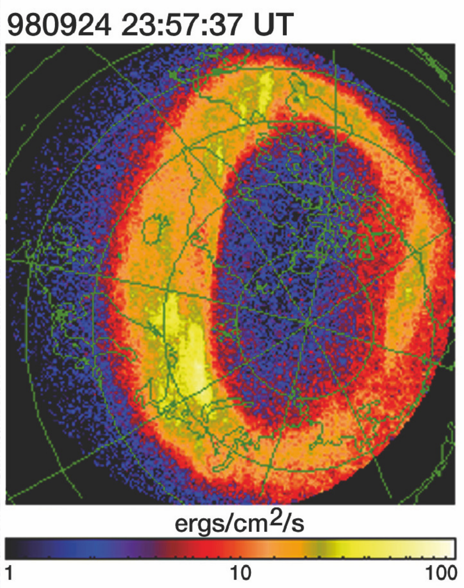
Molecules of gases are excited by the stream of high-energy electrons or protons. The brightest is the light emitted by oxygen, at a wave length of 557.7 nm, and it is green, hence the characteristic yellow-green color of the majority of northern lights. The shapes of them depend on the lines of the magnetic fields. Not all the aspects of shape variability are yet understood, and there are still no answers to questions such as the origin of the stimulating particles that light the atmospheric gases; not all of them come directly from the Sun. Most reside for some time in the Van Allen's radiation belts discovered in 1958 during one of the missions of the Explorer 1 Earth satellite.

Thanks to space research, images of Earth's magnetic field has changed dramatically. We now know that powerful explosions that cause coronal mass ejections (CME) occur in the Sun's atmosphere from time to time. These plasma clouds and their magnetic fields crash into Earth's magnetic field and induce powerful currents in the magnetosphere causing magnetic storms. CME are usually accompanied by flashes. The more sunspots there are, then the more flashes and CME there are; hence, there is a correlation between the aurora borealis phenomenon and the sunspot cycle. Solar wind, which pulls at Earth's magnetic field, causes some lines in the field to remain open. The area of open lines in the field constitute the interior of what is called the aurora oval on the surface of the Earth. Most of the auroras appear within this oval, the center of which is at the magnetic pole and the radius of which depends on magnetic activity and usually equals several degrees and has a width of about 10 degrees. Only two kinds of auroras appear outside the aurora oval, and these are known as low latitude auroras and bows connected with the Sun.

Low latitude auroras, which are usually red, can be observed during very strong magnetic storms. The bows connected with the Sun appear on the day side of the Earth and form the chord of the aurora oval. They cannot be seen from the Earth as they appear only on its day side. However, they have been discovered recently thanks to satellite observations.



The aurora borealis over the Polish polar station in Horsund, Spitsbergen (photograph T. Petelski).




The aurora oval during the solar storm in 1998 observed in ultraviolet from a satellite (source: NASA).

## Polar Day and Polar Night

Jacek Piskozub

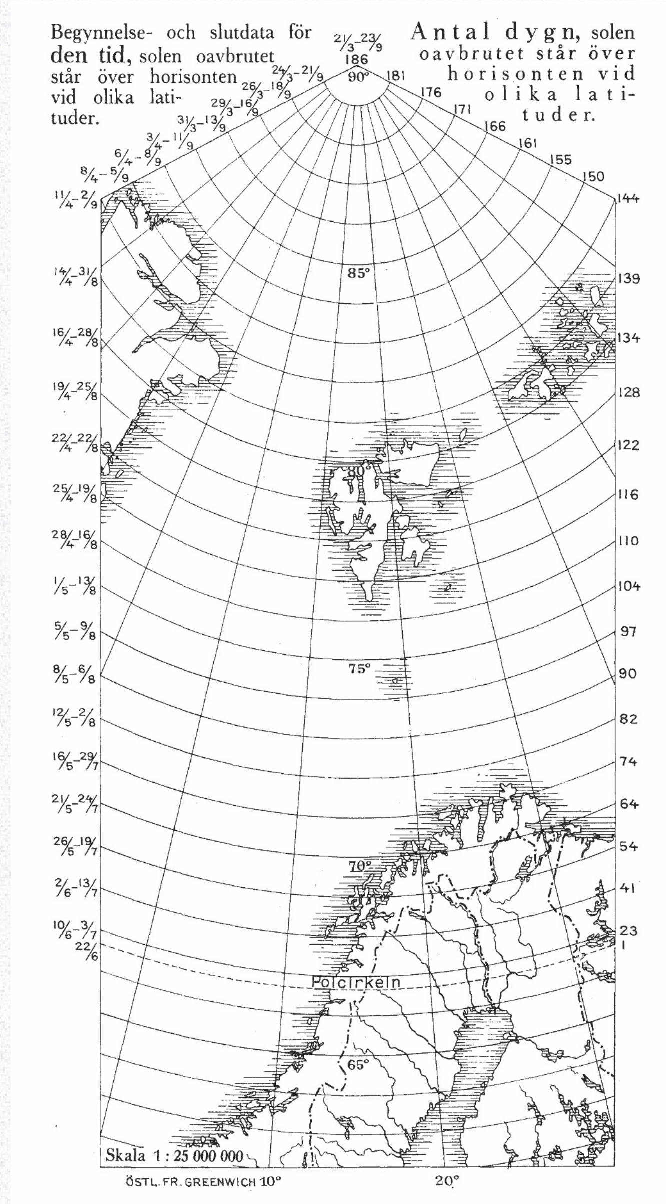
Everybody knows that the days in summer are longer than those in winter. However, few people realize that daylight length also varies with latitude. The time between sunrise and sunset in June is one hour longer in Sopot in the north of Poland than it is in Zakopane in the south, and the opposite happens in December.

Different daylight duration at different latitudes is caused by the same mechanism responsible for differences in daylight duration among the months of the year, namely the inclination of the Earth's equatorial plane towards the plane of its orbit around the Sun, which, at 23.5 degrees, is known as the ecliptic. For half of each year from March to September, the north end of the axis of our planet revolves around the north pole, so it is constantly illuminated by the Sun. During the other half of the year, the sun never rises above the horizon at the north pole. The farther away from the pole, the shorter the periods of constant daylight and constant darkness are. These are known respectively as the polar day, or the midnight sun, and the polar night. For example, the polar day at the Polish polar station in Hornsund, Spitsbergen lasts from April 21 to August 21 (121 calendar days), while the polar night is from October 29 to February 12 (106 days). To the south of the latitude of 66.5 degrees, the Sun rises and sets every day. This latitude, called the polar circle, is usually regarded as the outer border of the Arctic.

The famous low temperatures of the polar regions are not caused by the length of daylight, which, if averaged out over the whole year, is 12 hours daily, but rather by the low angle of the sun over the horizon. The dose of energy received per square meter of a flat horizontal surface, known as solar insolation, depends directly on this angle. For example, the region of Svalbard receives only 20 % of the insolation illuminating a comparable area of the tropics. However, the radical differences between illumination in summer and winter makes the polar regions different from other climatic zones. During the polar night, the Arctic receives no energy directly from the Sun. During the summer solstice in June, Svalbard receives irradiation comparable to that which Sopot, Poland receives during the spring and fall equinoxes in March and September, respectively. At mid day on Svalbard the amount of irradiation is 58 % of that which the tropics receive when the Sun is at its zenith.

The variability of seasonal insolation means that the polar regions host the only biosphere on Earth that must survive several months each year without solar energy. Photosynthesis is impossible during the polar night, so the biosphere depends on the biomass it accumulates during the polar day. The energy budget of the polar regions also differs from that in other parts of the world. During the winter, the heat the Arctic accumulates in summer and the energy transported northwards by winds and ocean currents is emitted into space. This means the heat flux during the polar night is always directed upwards away from the surface identically to the way it happens during normal night elsewhere. Thus, the use of the term polar day and polar night is justified.






Dates of the beginning and end of the polar day (left panel) and its duration (right panel), after Svensk världsatlas (1930), p. 140.

## Changes in insolation and ice ages

Jacek Piskozub

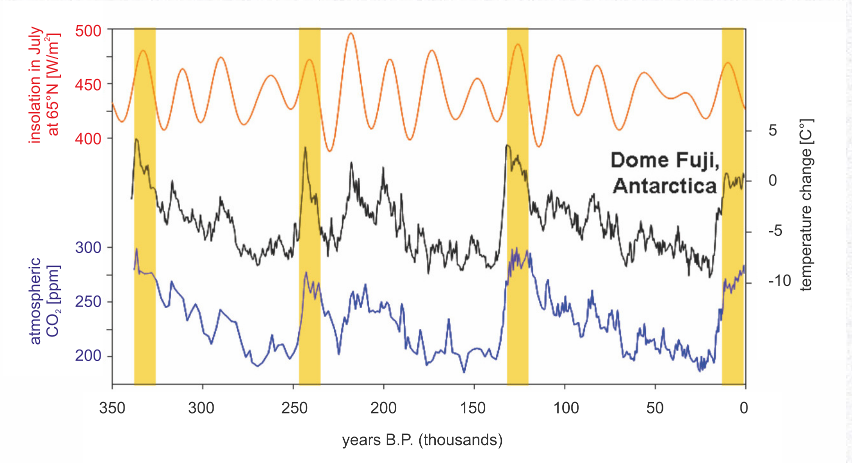
Insolation in the polar regions changes not only with the season, but also very slowly along with changes of the Earth's solar orbit parameters that are caused by the gravitational pull of the Moon and other planets in the Solar System. These orbital change cycles last tens of thousands of years, and they do not greatly alter solar insolation averaged over the whole Earth, but they can influence summer insolation levels in the polar regions that influence Earth's climate, and they control the duration of ice ages on Earth. This was hypothesized by the Serbian mathematician Milutin Milankovich during World War I, and it was confirmed a half a century later when scientists began to study the climate records written in ocean bottom sediments and ice cores from Greenland and Antarctic ice-sheets.

Earth's orbit is not a circle, but an ellipse, and because of this, the total amount of energy it receives varies throughout the year. The parameter ruling how elliptical the orbit is, or its eccentricity, changes slowly over a period of about 100,000 years. This alone does not change global insolation; however, the season when Earth is closest to the sun varies within a period of about 20,000 years, and insolation changes between the northern and southern hemispheres because of this orbital precession.

In the present era, Earth is closest to the sun during the winter in the northern hemisphere. This means the southern hemisphere receives slightly more solar energy during summer than does the north, but 10,000 years ago, the opposite was true because of the 20,000 year precession cycle. This is why the ice age ended around this time, and the present Holocene period began. This is also why the warmest the northern hemisphere was throughout the Holocene was 7,000 years ago after the last ice-sheets melted in Scandinavia and Canada. The last 6,000 years have been a period of northern hemisphere cooling that only ended at the beginning of the industrial era in the late nineteenth century.

The third orbital cycle influencing Earth's climate is the 41,000-year cycle of orbital inclination, which is the angle between Earth's equatorial and orbital planes. The present value of inclination is 23.5 degrees and lies close to the middle of its variability range of 22.1 to 24.5 degrees. When the Earth's axis is more tilted, the polar regions are better insolated. This is why ice ages always end when inclination is close to its maximum, and precession favors the northern hemisphere. For over two million years, glaciation periods ended every 41,000 years. Although it is not yet fully understood why the last eight ice ages were longer at 82,000 or 123,000 years, which is two or three inclination cycles, they did always end during times of high summer insolation in the Arctic. Data from sea bottom sediments and continental ice-sheets leave no doubt about the importance of this small region of Earth for the climate of the whole planet.






Summer insolation in the Arctic, average temperature, and carbon dioxide atmospheric concentration were calculated using isotope ratios from an ice core collected in the Antarctic. It is notable that the end of every ice age, or deglaciation, happens when there is high Arctic summer insolation. The results of climate modeling show that insolation changes alone are insufficient to end an ice age without increased carbon dioxide concentrations being the positive feedback of insolation-induced climate change caused by slow changes of the Earth orbit, or the so-called Milankovich cycles (Source: NOAA).

## Why is the Arctic warming so fast?

Jacek Piskozub

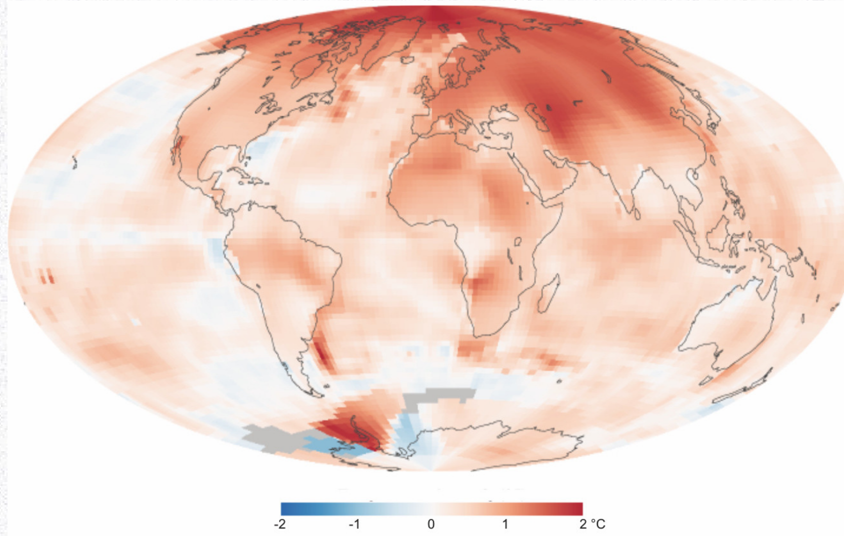
Throughout the industrial era that began in the late nineteenth century, Earth's average temperature has increased by 0.8 C. This has been caused almost certainly by increasing atmospheric concentrations of greenhouse gases, namely the carbon dioxide and methane emitted as a side effect of various human activities. At least science knows of no other process that could explain the temperature increase observed.

In some polar regions, including the Arctic, the temperature increase is three times faster than the average for the whole planet. It is interesting that this 3:1 ratio is typical not only for industrial-era global warming, but also for glacial cycles. During the Last Glacial Maximum, the Arctic was at least 15 degrees colder than it is presently, while the whole Earth was about 5 degrees cooler. This is known as Arctic amplification, and it has been explained by modern science, and was even predicted in the nineteenth century by Arrhenius, a Swedish scholar.

Polar regions are cold not only because the Sun is always low over horizon. Another cause of this the high reflectivity, or albedo, of snow and sea ice. Albedo is the ratio of radiation reflected from the surface to radiation incident upon it, and the lower it is, the more solar energy surfaces absorb that heats the ground or sea water. The average albedo of the Earth is only 15 % because both water and forests absorb visible light very efficiently; for example, the albedo of the ocean is less than 10 %, which makes it the darkest region on satellite photographs of the Earth. Deserts are much brighter, but the brightest parts of our planet are regions covered with snow or ice, because the albedo of fresh snow is higher than 90 %.

This means that if temperatures in the Arctic change for any reason, such as shifts in Earth's orbit, the solar energy flux, or atmospheric greenhouse gas concentrations, changes occur in Arctic land snow coverage and in the sea ice. Temperature increases cause snow and ice to melt a little earlier in the spring. The albedo change caused by this causes radical increases in the fraction of solar insolation absorbed by the ground or sea water from about 10% to 90%. Even if the albedo change happens only one day earlier, it changes the Arctic energy balance in a tangible way. Since the polar day is not much longer than 100 days, every additional day without snow or ice means the total solar energy dose absorbed in that year increases by about 1%. The effect is further amplified by the fact that a warmer Arctic means that sea ice freezing and snowfall on land will come later in the fall. This, in turn, means that thinner ice will thaw earlier in the subsequent spring. These processes are being observed at present in the Arctic, and they provide evidence in support of the theoretically predicted Arctic amplification of global warming.






Map of temperature anomalies in the 2000-2009 period in comparison with those of the 1951-1980 period. The Arctic and the Antarctic Peninsula regions are warming faster than any other part of the world (source: NASA).

## Atmospheric circulation

Jacek Piskozub

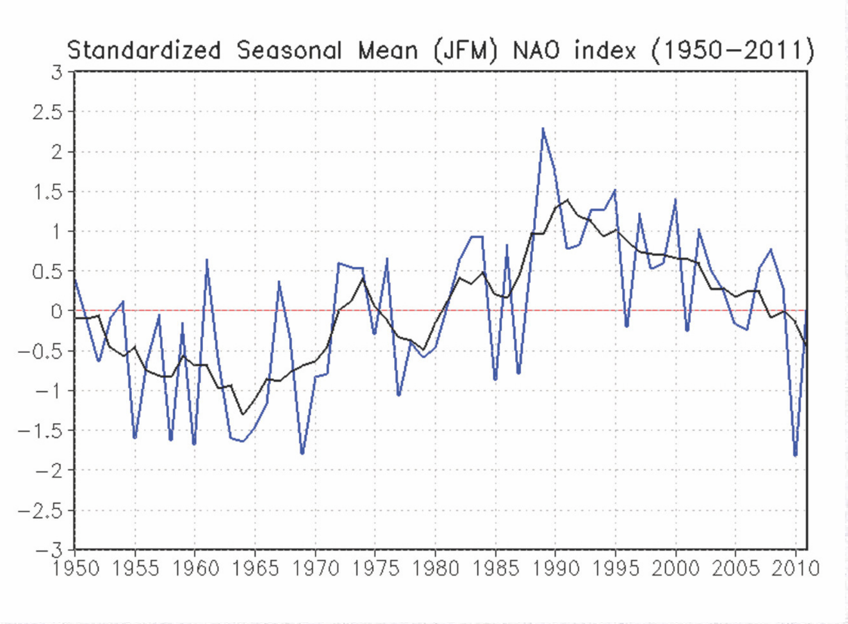
The distribution of temperatures in the Arctic as well as extent of sea ice in the Arctic Ocean are influenced by winds, or, in other words, atmospheric circulation. There is usually a weak high pressure system over the north pole, but this is usually surrounded by low pressure systems, including the polar lows known as Arctic hurricanes, which have yet to be studies thoroughly. The surface pressure differences between the north pole high and surrounding low pressure makes the winds blow towards the pole, which are called southerly winds in meteorology terminology. The Coriolis effect caused by the Earth spinning makes wind turn right and blow eastward, which makes them westerly winds. This is why the typical winds in the high latitudes are westerlies.

Meteorologists have been studying this circulation for over a hundred years. Its oldest index is the North Atlantic Oscillation (NAO), which, defined historically, is the difference in surface pressure between Lisbon, or sometimes the Azores, and Iceland. At present, the NAO is defined as a feature of the whole pressure field of the North Atlantic sector, or its first Empirical Orthogonal Function. However, its physical sense is simple: it is the index of westerly circulation in the region of the North Atlantic.

The NAO is the most important factor controlling winter temperatures and precipitation over a large area stretching from the Arctic to the Mediterranean. When the NAO is positive, western circulation brings northern Europe stormy, warm winters, while the Mediterranean is dry, and the Arctic is cold. Negative NAO causes the inverse situation: the winter in central and northern Europe is cold, the Mediterranean is wet, and the Arctic is warm. A more general index of western circulation is the Arctic Oscillation (AO) that is based on the pressure fields of the whole northern hemisphere. Both indexes are highly correlated and show similar patterns of multidecadal variability. Western winter circulation was generally weak between the 1950s and the 1970s, strong from the 1980s to 2009, and again weak in the recent winters of 2009-10 and 2010-11.

Atmospheric circulation also influences the sea ice coverage of the Arctic Ocean. A decreasing trend has been observed in recent decades especially in the extent of summer sea ice. This is caused by several factors, including increasing concentrations of greenhouse gases, atmospheric pollution from anthropogenic aerosols like smoke, variability in cloud coverage, and changing amounts of heat transported to the Arctic by winds and ocean currents. However, the sea ice mass balance does not only depend on the temperature, but also on the rate of its export from the Arctic through the Framm Strait between Greenland and Svalbard. This export rate is controlled by atmospheric circulation as wind is the main driving force of sea ice drift. Satellite observations inform us that export is faster when the AO/NAO indexes are positive. In recent years, other indexes of Arctic atmospheric circulation have been proposed to explain sea ice movement, such as the Arctic Dipole (AD), the surface pressure difference between the European and Canadian sectors of the Arctic, or the similar Central Arctic Index (CAI), the pressure difference along the 90 E and 270 E meridians, which is along the dominant sea ice drift direction towards the Framm Strait. Satellite observations confirmed that atmospheric circulation did contribute to record low sea ice coverage in the summers of 2007 and 2012. However, the Arctic sea ice volume has been decreasing during both positive and negative AO/NAO periods, which implies this is not the most important reason why Arctic ice keeps melting.






Winter NAO index values since 1950 (blue line) and the five year average (black). The index has mostly negative values from the 1950s to the 1970s, positive from the 1980s to 2009 and again negative values in recent winters (source: NOAA).

## What do the NAO/AO signs depend on?

Jacek Piskozub

Because the NAO and AO are so important for winter weather in Europe and the Arctic, much research effort is invested in trying to understand which climate parameters influence them. The research has revealed multiple factors that influence the NAO/AO. In fact, we know too many of them to be able to use them successfully for predicting long-term winter circulation patterns. None of them explains all, or even most, of NAO inter-annual variability, although each one has some statistically significant influence:

• The more solar activity that is measured from satellites as brightness changes from the Earth as the number of sun spots increases, the more positive the NAO/AO is. The correlation is not strong, but the predictability of the 11-year solar cycle makes it possible to make long term NAO/AO forecasts.

• The ENSO cycle of the tropical east Pacific sea surface temperature changes, oscillating between the warm El Niño and the cool La Niña, is the largest source of inter-annual temperature variability in the tropics, and it has some influence even at our latitudes. Positive ESNO values (El Niño) favor negative NAO/AO values in late winter making February and March cooler, while negative values (La Niña) favor positive NAO/AO.

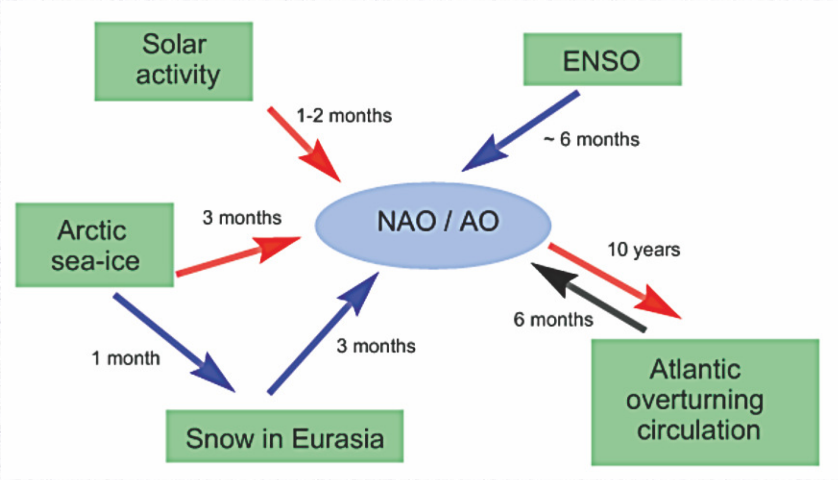
• Fall sea ice cover in the Arctic Ocean correlates with winter NAO/AO values, namely that less sea ice predicts a more negative NAO. This is a statistical relationship, and it is not certain if it will hold in the coming decades. But if it does, a future with no summer Arctic sea ice should see cold winters in Europe, even in a much warmer world.

• The amount of fall Siberian snow anti-correlates with winter AO/NAO, with more snow predicting a more negative NAO/AO. This seems to contradict the previous relationship with sea ice, but, in fact, less sea ice implies more evaporation and therefore more snow fall. This means the sea ice and Siberian snow correlations might describe the same climate process. In fact, snow correlation seems to be the best-known predictor of NAO with a three month time lag.

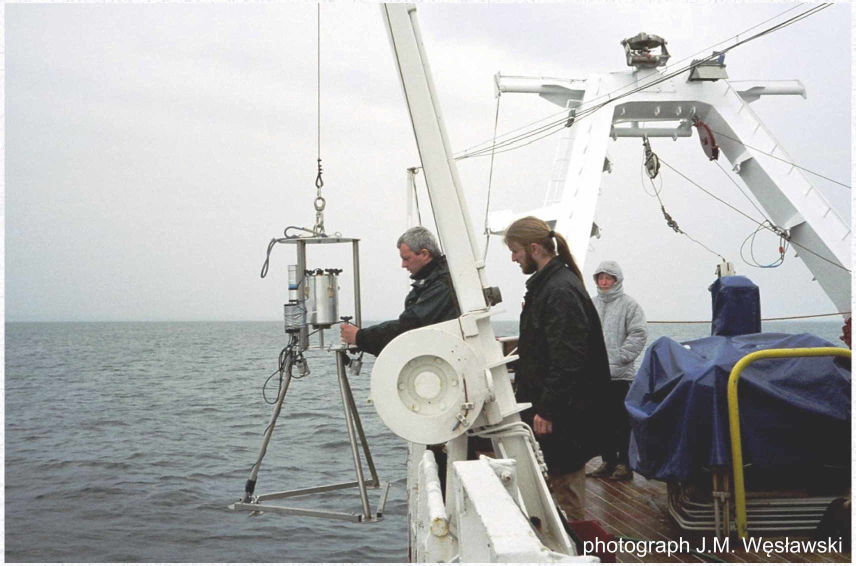
• The temperature of the North Atlantic Ocean outside of the Arctic also influences the NAO/AO almost six month in advance. Predictions made on this basis are of lesser quality than those made based on the amount of fall Siberian snow, and they allow predicting the correct NAO/AO sign only about two-thirds of the time.

There is additional evidence that ocean circulation does influence the NAO, and, thus, winter weather in Europe and the Arctic. Climate circulation models predict NAO better if their representation of the North Atlantic sea surface temperatures is closer to observed values. In addition, both the North Atlantic sea surface temperatures, which is confusingly referred to as the Atlantic Multidecadal Oscillation index (AMO), and the AO/NAO have similar 65-70 year oscillation patterns. The AMO seems to lag in atmospheric indexes by about 10-15 years. Therefore, since the NAO has been negative in recent years, the cooling of North Atlantic surface waters can be expected in the near future. This lag does not mean that ocean processes are controlled by the atmosphere. The atmosphere, unlike the ocean, does not have enough heat capacity to provide long term climate memory. Therefore, it seems logical that both the AMO and the NAO/AO are manifestations of the same long-term climate oscillation involving both the ocean and the atmosphere. We do not yet fully understand all the processes involved. So, does this mean we can correctly predict next winter's weather in the Arctic or Europe? Not yet, but we are making progress.






A chart explaining the state of knowledge about winter NAO/AO dependance on other climate parameters. The red arrows denotes positive correlations, while the blue – negative, or anticorrelations. The black arrow denotes the complicated relationship of the NAO with the surface temperatures of different parts of the North Atlantic. The numbers of the months or years are time delays (compiled and designed by Jacek Piskozub).



## Sea Aerosols

Tomasz Petelski

The non-gas components of the atmosphere are called aerosols. These are tiny crystals, droplets excluding those in clouds and fog, plant particles, dust, soot, etc. Aerosols are divided into two groups: primary and secondary. Primary aerosols are created outside of the atmosphere and are later emitted into it, for example by volcanoes and chimneys, or they are lifted from the soil by wind. Secondary aerosols are formed in the atmosphere as the result of the chemical reactions of gases. A different division criterion singles out another pair of aerosols: natural and anthropogenic, the latter which are produced by human activity.

The seas are one of the greatest sources of the primary and secondary natural aerosols emitted into the atmosphere. Primary aerosols come from sea salt, while the largest source of secondary aerosols are dimethyl sulfide organic compounds, or DMS, which comprise sulfides formed during plankton decomposition. It is estimated that aerosols of maritime origin constitute 40 % of all the aerosols in the atmosphere.

Cracking gas bubbles are the main source of aerosols emitted from the sea surface. Two kinds of droplets are ejected into the atmosphere when gas bubbles crack on water surfaces: film droplets that are born of the membranes of bubbles protruding above the surface and jet droplets that are ejected from the bottom of the membrane by the stream.

Another mechanism that is commonly considered to be a very important factor in the mass transfer between the sea and the atmosphere is the direct lifting of some droplets from wave crests by wind.

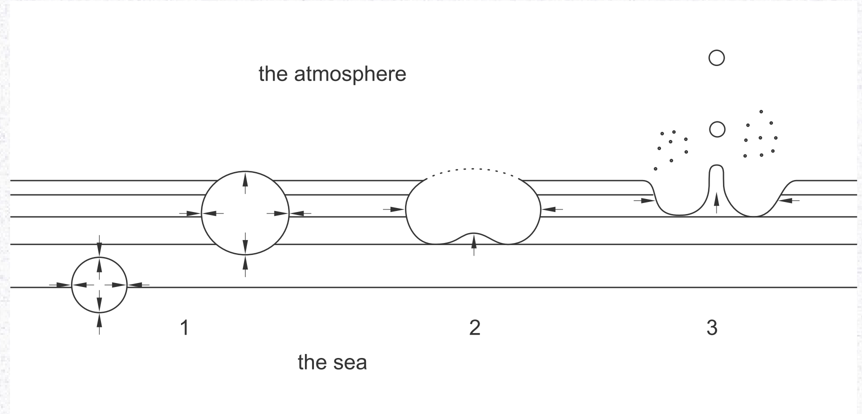
The third mechanism of aerosol production occurs when water drops hit the sea surface thus launching small droplets into the air.

All aerosol generating mechanisms are connected with the phenomenon of wind wave collapse. When waves collapse they push huge masses of air in the form of bubble clouds into deeper waters.

There are also other ways of generating bubbles in water depths, for example, biological and geological processes and temperature changes saturate waters with gases. Nevertheless, the effectiveness of these processes, with the exception of the wave collapse mechanism, is insignificant so they can be ignored as sources of gas bubbles.

It has been known since the 1950s that sea salt is an important aerosol, but quantifying sea aerosol emissions is extremely difficult. The challenge of separating some components of local aerosols from those originating from remote areas is the main cause of error. This is why the Arctic sea region is the appropriate areas to conduct studies of sea surface aerosol emission. The Institute of Oceanology of the Polish Academy of Sciences has been studying sea aerosols since the 1980s. Initially, impactors and microscope analysis were used to study the aerosols collected, but currently modern aerosol counters based on laser techniques are used. It is noteworthy that the IO PAS research vessel Oceania provides a unique aerosol measurement platform because of its low silhouette that only disturbs air movement slightly and its tall, 25-m masts that provide the means necessary to use the gradient method for measuring aerosol flux. When the gradient method came into use in the 1990s, the amount of aerosol emission flux was known to be within 7 orders of magnitude. One of the positive outcomes of research at IO PAS, among others, is the current acknowledgment that uncertainty about emission amounts is now no higher than 2 orders of magnitude. This demonstrates that this research should be continued especially in light of how vital aerosols are for the Arctic climate.






The sea-aerosol generation mechanism during air bubble cracking on the surface of water. Jet droplets and some smaller film droplets are visible (Garbalewski, C. ( 1999 ), The physics of aerosol activity of the sea, Monographic Thesis, PAN).

The r/v Oceania, a unique aerosol measurement platform, sailing into Port Anderness in the Lofoten during the MACRON experiment in 2007 (photograph J. Piskozub).

## Aerosols and clouds

Tomasz Petelski & Anna Rozwadowska

Atmospheric aerosols influence the climate significantly. They scatter and absorb solar radiation, which reduces the solar radiation reaching Earth's surface. This is known as the direct aerosol effect on climate. The indirect effect, through cloud microphysics, is even stronger.

Clouds consist of water droplets. Atmospheric water vapor needs condensation nuclei to turn into water droplets. Condensation nuclei are the tiny particles on which water vapor condensates. Sea salt is strongly hygroscopic; therefore, its crystals are excellent condensation nuclei. The more condensation nuclei there are in the atmosphere, the more droplets there are in the clouds. Under the same conditions, clouds contain more droplets when air is rich in condensation nuclei than they do in air in which nuclei are scarce. The same amount of water forms more droplets then. Clouds with more droplets are less transparent to solar radiation than those with larger droplets that contain the same amount of water. Such clouds also have a higher albedo, which means that they reflect more radiation than do clouds with larger droplets. Moreover, the formation of small droplets suppresses or delays precipitation, so clouds with smaller droplets live longer in the atmosphere.

All over the world, except in the polar regions, low-level clouds cool the Earth's surface by attenuating the solar radiation reaching its surface. The effect of high-level clouds depends on their optical thickness. Therefore, in Poland, it is colder on cloudy days than it is on sunny days except in winter. In the Arctic, however, clouds typically warm the surface. During most of the year, the sun is close to the horizon or below it, so there is little or no solar radiation on the Earth's surface then. However, clouds hinder the escape of thermal radiation emitted by the surface to space. During nine months, low-level clouds warm the surface by insulating it. In summer, the effect of solar radiation attenuation dominates and low-level clouds cool the surface then.

The impact of aerosols on cloud properties is called the indirect aerosol effect. Aerosols also influence the Arctic climate directly through the reflection and absorption of solar and thermal radiation. In winter, during the polar night, the aerosols warm the Arctic. This leads to the retention of more thermal radiation emitted by the Earth's surface. In summer, it mainly cools the surface by reducing the amount of solar energy reaching the surface. In spring, when the sun is close to the horizon, the "blanket" and "umbrella" effects balance each other. When this happens, then, from a climatic point of view, the most important factor is the acceleration of snow and ice melt by soot deposition. Absorbing aerosols, like soot, deposited on snow and ice surfaces reduce their albedo, or darken them, thus accelerating melting.

Relationships among aerosols, clouds, solar and thermal radiation, snow and ice cover, and processes of horizontal and vertical transport in the atmosphere are so complex that it is not clear yet whether an increase in the amount of pollution and pollution-related aerosols will ultimately warm or cool the Arctic.



For nine months, low-level clouds warm the Arctic by hindering the escape of thermal radiation emitted by the surface to space (photograph T. Petelski).

Aerosols affect clouds in the Arctic leading to modifications in the amount of energy received and emitted by surfaces. In the picture, scientists from IO PAS and Warsaw University admire clouds in the Norwegian Arctic at latitude 69° 17' N (photograph J. Piskozub).

## Atmospheric aerosol and long-range pollution transport Anna Rozwadowska

Compared to the lower latitudes, the air in the Arctic is very clear and transparent. Typical aerosols in the Arctic consist of sea salt particles, mineral dust, the oxidation products of dimethyl-sulphide emitted from the sea surface, and insoluble organic particles derived from the surface microlayer of the ocean from bubble bursting. The Arctic is characterized by a low aerosol load. However, under moderate to strong winds, the sea becomes an efficient source of sea-spray aerosol.

In the high Arctic, local pollution sources are small and limited to the vicinity of the Arctic Circle. They include non-ferrous metal smelters in northern Russia, marine and air transportation, mining industries, oil and gas activities, and urban sources such as car transportation and energy production plants. Since the disintegration of the Soviet Union, significant reductions have been observed in emissions from the metal-production industry, the main local source of pollution. However, the shrinking Arctic sea ice cover could result in increased pollution emissions from ships, and the quest for fuel will likely lead to increased pollution being emitted by developing oil and gas industries.

Pollution can be emitted into the atmosphere as particles or dust, which are primary aerosols, and as gases. Various chemical, photochemical, and physical processes in the atmosphere transform some gases into aerosols, which are secondary aerosols. Sulfur and nitrogen oxides are examples aerosol precursor gases of anthropogenic origin.

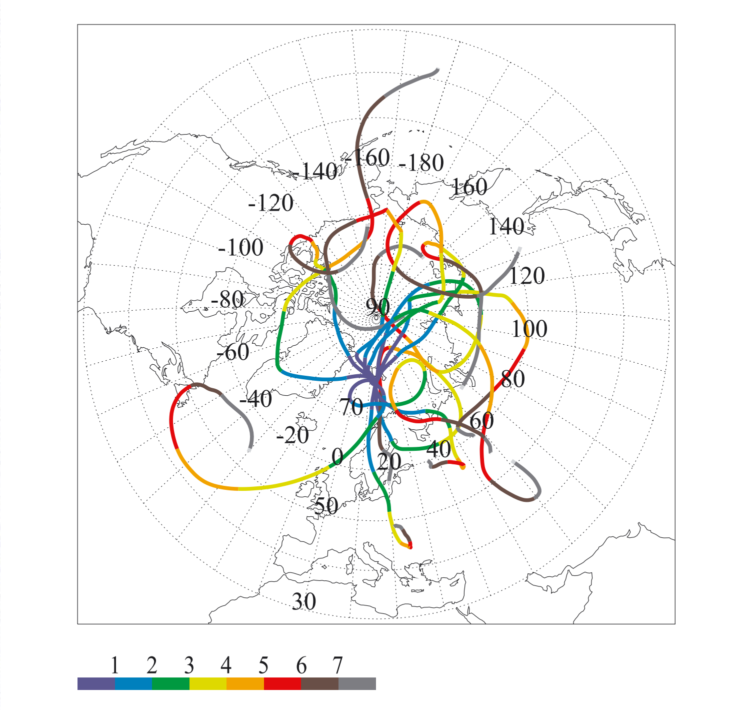
Nearly all pollution in the high Arctic originates from the more southern latitudes. Local Arctic sources introduce twenty times fewer sulfur oxides and nearly two hundred times less nitrogen oxide into the atmosphere than does long-range transport from the mid-latitudes. The largest source of anthropogenic pollution in the Arctic are Europe and the region of the former Soviet Union. The impact of the industrialized regions of North America is lesser, and near the surface it is observed mainly in Greenland. Scientists do not agree on the contribution of southern and eastern Asian to Arctic anthropogenic pollution.

Biomass burning in Eurasia and North America, especially boreal forest fires, is also an important source of pollution and related aerosols in the Arctic. In years when there are many fires, they are the main source of soot, or black carbon, over the high Arctic in summer. Volcanic activity and desert dust advection can occasionally play important roles in Arctic air pollution.

While the long-range transport of aerosol and its gas precursors from the southern latitudes is most prevalent in winter and spring, events of pollution advection can occur throughout the year. Pollution transport to the Arctic is stronger in years when the North Atlantic Oscillation is in a "positive" phase.



Ny Alesund and Kongsfjord, Spitsbergen, during a smoke advection event from biomass burning in eastern Europe (2.05.2006) and several days later (8.05.2006) (photograph A.C. Engvall Stjernberg, Stokholm University).

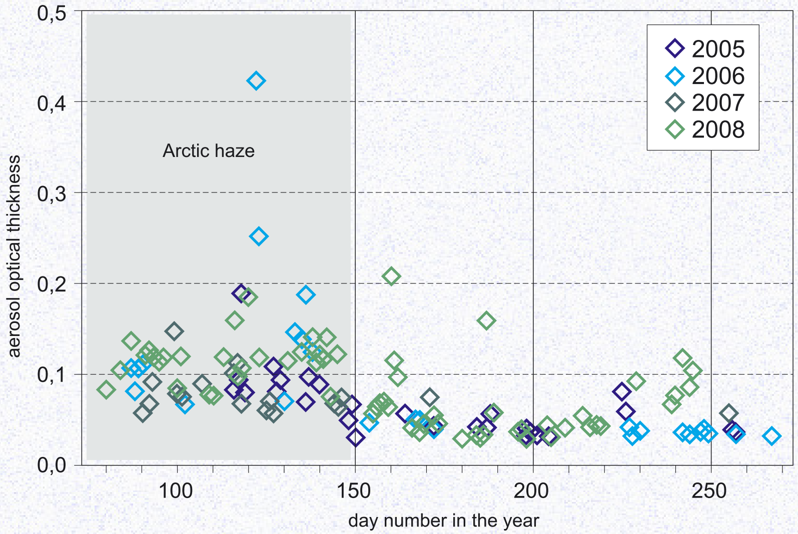



Examples of eight-day-long pathways of air arriving at the Polish polar station at Hornsund at an altitude of 5 km in spring 2005-2008 on days with high air aerosol loads. The colors denote the one-day path of the air parcel, e.g., the gray indicates the positions of the air on the 8th day before it reached Hornsund (A. Rozwadowska).

In the 1950s, pilots flying over Alaska and the Canadian Arctic observed a strong haze of unknown origin. Sometimes the haze was tinted. Initially, the haze was thought to consist of ice crystals or mineral dust. Only in the 1970s was the haze identified as pollution of anthropogenic origin, and it was also observed to occur regularly at the end of winter and in spring. The haze is often distinctly layered, and ranges in size from several hundred meters to 1 km thick and from 20 to 200 km wide. Now, it is obvious that Arctic haze is of anthropogenic origin. It is composed of aerosols generated from pollution transported to the Arctic from lower latitudes during winter and at the beginning of spring and trapped in the Arctic air mass. Sulfates comprise 90 % of the Arctic haze, with the remaining 10 % including particular organic matter, nitrogen compounds, mineral dust, black carbon that gives it its brownish tint, heavy metals, and other pollutants. Arctic haze is mainly made of aerosols generated from gaseous pollution in the atmosphere. Particles of Arctic haze are "aged", which means they have resided in the atmosphere for long periods. The regular occurrence of Arctic haze at the same times of the year is caused by several factors. The Arctic is covered with a cap of cold air, which makes the penetration of warm air from lower latitudes to the Arctic difficult. In winter and early spring, the Arctic front that divides cold Arctic air and warmer polar air weakens and shifts southward to about 50o N. This facilitates the advection of polluted air from the mid-latitudes, mainly from Europe and Asia. Additionally, the dominant direction of atmospheric circulation changes in winter. The typical pathway in summer leads from the North Atlantic Ocean across the high Arctic towards the North Pacific Ocean, but in winter the mean circulation is characterized by low-level transport from industrialized northern Eurasia across the Arctic to North America. Moreover, air flow in winter is faster so it facilitates the long-range transport of air pollution. Therefore, the main source region for Arctic haze is northern Eurasia. The stable, extremely dry atmosphere, relatively infrequent precipitation, and the relatively low cloud amount in winter and spring also support very long lifetimes for gases and aerosols. Moreover, the darkness of the polar night delays the oxidation of sulfur oxides and leads to enhanced concentrations of them, thus further increasing residence times in the atmosphere. Sulfur oxides are precursors of sulfate aerosols.

Particles of Arctic haze scatter light strongly and also absorb it weakly because of the black carbon. Arctic haze can enhance aerosol optical thickness, which is a measure of aerosol content in the atmosphere, to values close to those typical of the mid-latitudes. Moreover, it can reduce the horizontal visibility range to several kilometers and more. Arctic haze aerosol influences the radiative balance of the Arctic. Light absorbing particles like soot, that deposit on the snow and ice surfaces accelerate snow and ice melting, and sulfate aerosols also lead to the acidification of the Arctic environment.






An example of annual variability of aerosol optical thickness at the Polish polar station at Hornsund (A. Rozwadowska, based on AERONET data).

Locations of the Arctic front in winter (blue line) and summer (red line) (A. Rozwadowska, based on various sources).

## Light in the Arctic Ocean

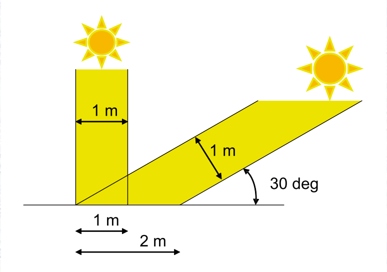
Mirosław Darecki

The North Pole stays in sunlight all day long throughout the most of the summer season (April to August) and opposite, most of the winter season (mid-October to March ) the Sun is hidden below the horizon. But despite the fact that in the areas located north of the Arctic Circle (63°N) for some period of the year the Sun is shining twenty four hours per day, the total amount of sunlight energy delivered per year is less than in the areas closer to the equator. The fact that solar radiation reaching the surface of the Arctic Ocean at a smaller angles makes it less "effective". In addition, in such a case, there is also relatively longer path of the solar radiation in the atmosphere, so this radiation is more reflected and scattered on its way to the surface, what gives us even less solar energy reaching the Arctic Ocean. For comparison, the amount of solar energy reaching the Earth's surface during the whole year at the latitude 75°N is about 1100 kWh/m$^2$ , at Latitude 52°N (e.g. the location of Warsaw) is about 1700 kWh/m$^2$ and at the equator is about 2700 kWh/m$^2$ . In fact, mainly because of clouds, these values can be much lower, e.g. the annual amount of solar energy near Warsaw location, may be about 1000 kWh/m$^2$. On the figure presents modeled daily doses of solar energy for cloudless sky, for the each mentioned Latitude.

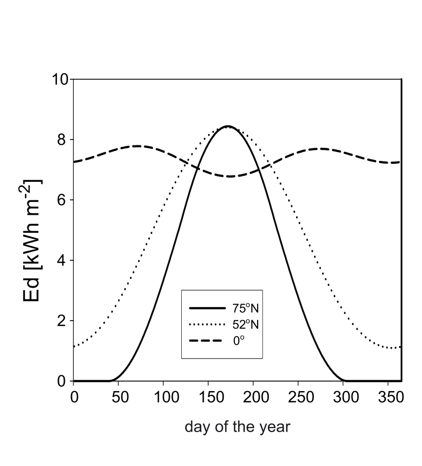
In spring, when most of the Arctic Ocean is covered with ice, the real amount of energy reaching the water column is further decreased. Snow is an additional barrier to the light, but much more effective than the ice. Through a thick (over one meter) layer of the ice passes almost 50% of the visible solar radiation needed for photosynthesis of marine plants, but when only 10cm layer of snow is placed on this ice, that number has dropped to 1%. As a result of all mentioned processes, the amount of light reaching the Arctic seas is relatively small compared to the other seas. Also, a propagation of the light within the water column can be much more variable in the Arctic Sea. In the coastal areas, where the surface water contains large amount of suspended matter, discharged from melted ice, the light is very strong scattered and absorbed by these particles. In the summer, a large area of the Siberian Sea, is characterized by relative low transparency, so only objects immersed in the water to depth of 1m can be seen there. Nearby glaciers, this transparency can be even lower and visibility can be reduced here to only 10 cm. Often, strong absorbed and scattered suspended matter is mainly located only in a thin, surface layer of melted water and below such a layer the water is very clear. The water transparency and underwater visibility is of great importance for predators, searching their prey visually (birds and marine mammals).

The study of light in the sea, and the water optical properties, typically consist of many various measurements. Among them, most often are measured: amount of light reaching the water surface and reflected on it, vertical distribution of light in the water column and optical properties (scattering and absorption) of the water components, like: organic and inorganic particles, dissolved organic matter. These properties determines the amount of light passing through the water column and its spectral characteristics (color of light). Usually the red and blue, together with ultraviolet, radiation is absorbed more intensively by water. Strong absorption of the UV radiation in the water provides safe environment, free from this lethal to micro-organisms radiation, which level in the atmosphere over the poles is higher compare to the other regions.






The solar energy in the hypothetical light beam wide on 1 m and reaching the surface at angle of 30deg, is spread over four times larger area compared to the similar but vertical light beam ( the Sun at zenith) (prepared by M. Darecki).




Modeled daily doses of solar energy for cloudless sky, for various Latitudes.

Radiometers measuring the spectral characteristics of the light reflected from the sea surface and emerged from the water column as well spectral characteristic of the downward light reaching the water surface (photograph M. Darecki).

## The ocean as a major factor shaping Earth's climate

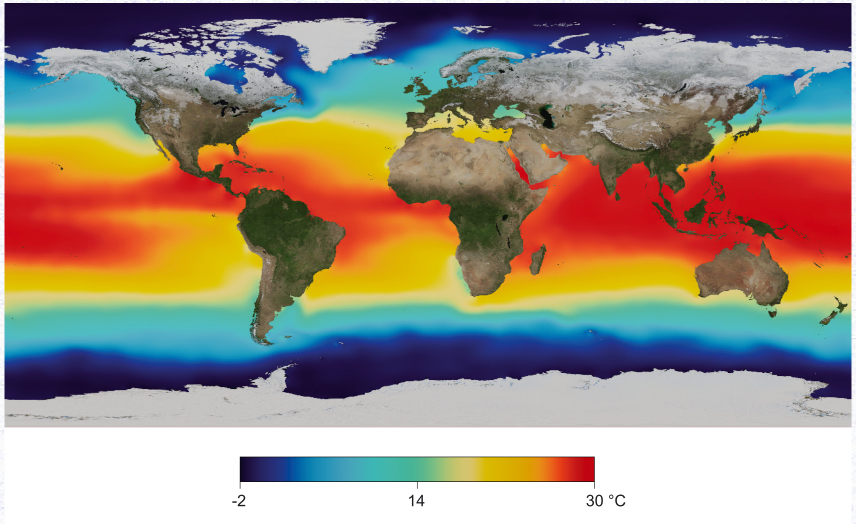
W. Walczowski

Everyone who lives by the sea knows it affects the weather and climate. Seaside winters are not usually as cold as they are inland, while summers are cooler and more humid. In a word, the sea moderates the climate, at least in the northern European zone in which we live. This is because of the great amount of heat that water is able to accumulate. Both fresh water and seawater are substances with the greatest specific heat. To warm a kilogram of water by 1°C we need 4200 J; this is nine times the energy required to heat a kilogram of iron, and four times more than for air. Considering that the 1 $m^3$ of air weighs just over 1 kg and 1 $m^3$ of water weighs 1,000 kg, it is easy to understand that a three-meter-thick layer of water can hold as much heat as the entire column of the atmosphere above it. And yet, almost 71% of our planet is covered by the ocean. It is no wonder that the upper layer of the ocean accumulates as much heat as Earth's entire atmosphere. Since the average depth of the oceans is almost 4 km, it is a great reservoir of heat. During the summer, the ocean warms by absorbing solar radiation, and it cools in winter by transferring heat to the atmosphere. However, only the upper 100 to 150 m layer of the ocean warms up, and since warm water is lighter than cold water, it floats on the surface. Vertical mixing is necessary to heat the deeper layers of the ocean. In recent years, increases in the average ocean temperature, particularly in the polar regions, have been noted. The ocean absorbs the heat surplus created by the greenhouse effect.

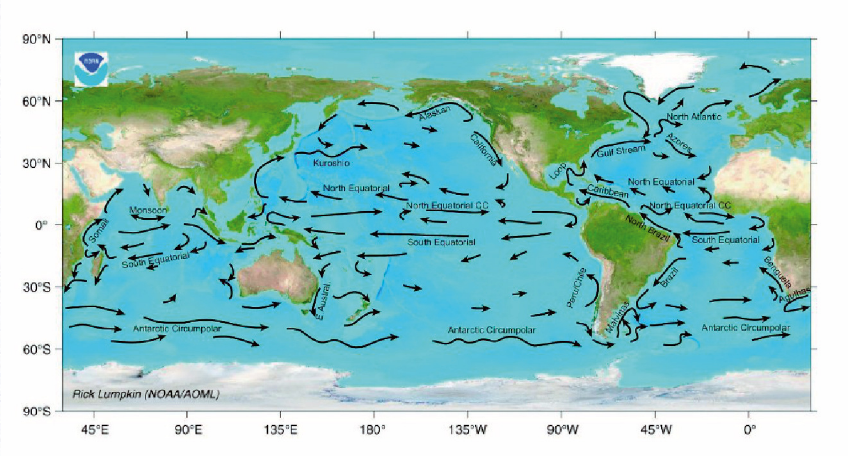
The role of the ocean as a heat reservoir with a seasonal cycle was recognized by climate researchers long ago. However, the ocean heats up unevenly; in the tropics it is warmer, but towards the poles it cools down. Additionally, the ocean is dynamic with its waters in endless motion. The processes happening in the ocean are definitely much slower than those in the atmosphere, and oceanic currents do not flow with the speeds at which winds blow, but oceanic circulation is an important process influencing the climate. Surface currents move the heat excess accumulated in tropics towards the poles, and the energy that is transported is in the order of magnitude of petawatts, which is 1015 watts. This is up to 20,000 times more than the amount of electricity production in Poland. Along the way, the water transfers heat to the atmosphere. The cycle of evaporation-condensation plays an important role in this process. Large amounts of energy are required, about 2257 J for each gram of water, to convert water into water vapor, and this is the latent heat of the phase change. In the atmosphere, the water vapor can move latent heat over long distances, and when the vapor condenses it releases it and warms the air.

A beneficial effect of the Gulf Stream, or rather its extension – the North Atlantic Current, on the climate in Europe has been known for a long time. Just look at the 54°N parallel; Gdańsk and Dublin lie at this latitude, where both corn and potatoes are grown in Europe. On the other side of the Atlantic Ocean, the icy tundra of Labrador is located at this same latitude where not even trees grow. The Gulf Stream has been described by sailors, and Benjamin Franklin explored it. Even today, we admire the maps drawn by him. However, there was no coherent theory to describe global ocean circulation or to link the ocean with the climate until 1987 when the theory of Conveyor Belt Circulation was proposed. This system of currents, also called Thermohaline Circulation, is driven by ocean water density gradients resulting from the differences in the temperature and salinity of water masses at high and low latitudes.






Average sea surface temperature (SST) (http://svs.gsfc.nasa.gov/vis/a000000/a003600/a003652/).




General oceanic surface circulation (http://oceanmotion.org/html/background/wind-driven-surface.htm).

## Thermohaline Circulation

Waldemar Walczowski

When, in 1751, Captain Henry Ellis stated that at the latitude of 25°N water taken from a great depth was ice cold, he did not realize that this was the first description of a symptom of a process that we refer to today as Thermohaline Circulation (THC). Captain Ellis was conducting experiments on behalf of an English scientist and did not appreciatethe importance of the discovery. In his notes, Captain Ellis wrote that such cold water in the tropics could be useful for cooling wine and bathing. A correct explanation of this phenomenon was published in 1797 by the inventor and physicist Benjamin Thompson, who wrote "It appears to be extremely difficult, if not quite impossible, to account for this degree of cold at the bottom of the sea in the torrid zone, on any supposition than that of cold currents from the poles; and the utility of these currents in tempering the excessive heats of these climates is too evident to require any illustration".

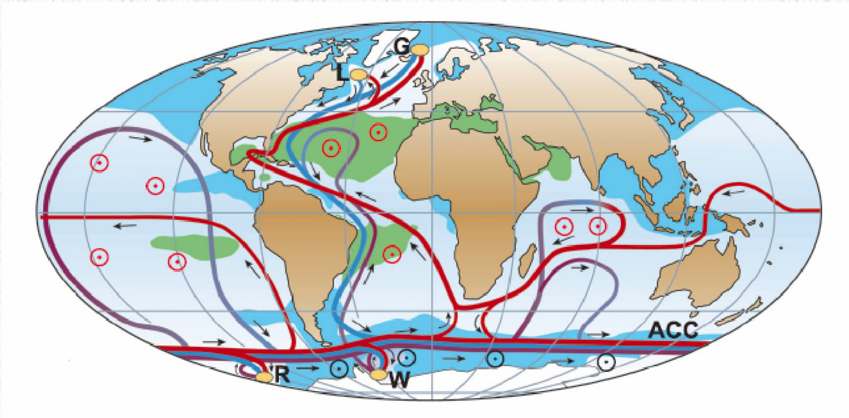
However, it was not until 1987, almost 200 years after Thompson's work, that the theory of the oceanic Conveyor Belt Circulation was formulated. The American Wallace Broecker presented the concept of surface and deep currents that connect all the oceans and transport salt and heat among them. Broecker also postulated that changes in the Atlantic thermohaline circulation led to rapid and extensive changes in climate that occurred in the North Atlantic region during the last glaciations.

Today's views of the Conveyor Belt differ from those presented by Broecker. The global ocean circulation is now referred to as the Thermohaline Circulation, and the names Meridional Overturning Circulation (MOC) or Atlantic Meridional Overturning Circulation (AMOC) are used to describe north-south transport in the Atlantic Ocean. The role of the Atlantic Ocean, and particularly the processes occurring in the northern regions of the Nordic Seas and the Arctic Ocean, are especially important to the maintenance of the THC.

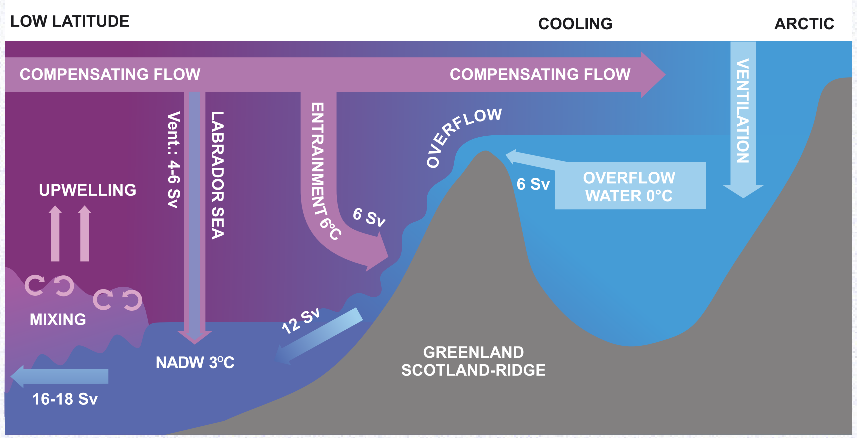
Thermohaline Circulation is the principal mechanism driving large-scale ocean currents. Water cooling and the formation of sea ice in the high latitudes increases the density of surface waters sufficiently to initiate deep convection together with another process known as thermohaline ventilation. In the northern hemisphere, deep water formation occurs mainly in the northern parts of the Atlantic Ocean, in the Greenland and Labrador seas, and in the Arctic Ocean.

Dense water formed in the Arctic Ocean and the Greenland Sea flows over the Greenland-Scotland Ridge as overflow water that mixes with waters from the Labrador Sea and creates the North Atlantic Deep Water (NADW), one of the most important deep-ocean water masses. Vertical mixing processes in the tropical zones cause deep water temperatures to increase thus reducing density, and this leads to upwelling to the surface. The cooling and ventilation in high latitudes and the heating and vertical mixing in low latitudes results in the creation of a horizontal water density gradient. The differences in water density force the surface flow of warm, salty waters towards the pole and the flow of deep-sea waters towards the equator. The transformation of surface waters taking place during its advection towards the Arctic means that the global climate system receives the excess heat accumulated by the ocean in the tropics.






Contemporary scheme of Global Thermohaline Circulation. Surface currents are marked by the red line, and deep-water currents by the blue line. The main areas of deep water formation in the Greenland (G), Labrador (L), Ross (R), and Weddell (W) seas are labeled with yellow circles. The areas of mixing and deep-water upwelling are marked with circles (by http://www.eoearth.org/article/Atlantic/article/Atlantic_meridional_overturning_circulation).




The deep convection process in the Arctic (ventilation) and the formation of cold North Atlantic Deep Water (NADW). The surface flow of warm water from the tropics (compensating flow) compensates the abyssal flow towards the low latitudes (by Hansen at al. 2004 ).

## Circulation in the Nordic Seas and Arctic Ocean A. Beszczyńska-Möller

The Arctic Ocean is the smallest of all oceans with more than a half of its area occupied by wide, shallow shelf seas. Most of the inflow to the Arctic Ocean originates in the North Atlantic. Warm, salty Atlantic waters are carried northwards by a complex system of sea currents in the Nordic Seas. On the way from Norway towards Svalbard, the Norwegian-Atlantic Current splits into two branches. The first one, the West Spitsbergen Current, supplies Atlantic water into the Arctic Ocean through the deep, wide Fram Strait. The second branch crosses the shallow Barents Sea, where water of Atlantic origin loses most of its heat to the atmosphere before reaching the Arctic. Both branches of Atlantic water join again on the shelf slope of the Nansen Basin and continue eastward around the deep basins of the Arctic Ocean as the Arctic Circumpolar Boundary Current.

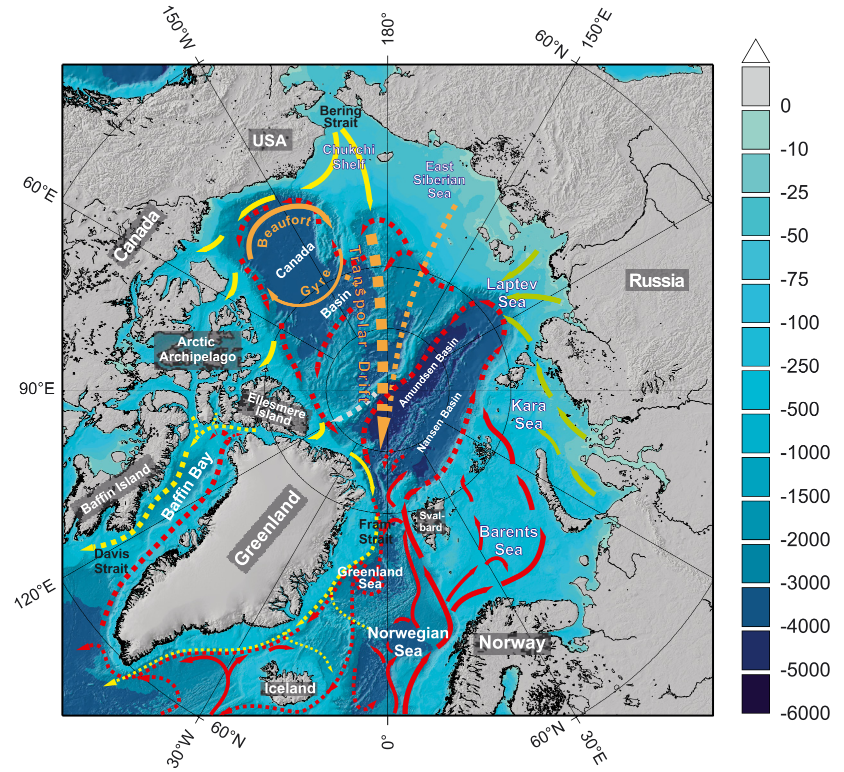
When circumventing the Nansen Basin, the upper part of warm Atlantic waters is mixed with cold fresh water originating from sea ice melting and precipitation. Passing by the Laptev Sea shelf, the surface layer of the Arctic Circumpolar Boundary Current is further diluted by a high volume of fresh water discharged by large Siberian rivers. Consequently, a layer with a strong increase in salinity and near-freezing temperature, the cold halocline, is formed between the surface and the warm Atlantic waters. The existence of cold halocline prevents the heat contained below in the Atlantic layer from melting the sea ice on the surface. Farther along to the east, part of the water of Atlantic origin splits from the boundary current and recirculates along several loops following the system of underwater ridges that separate the deep basin of the Arctic Ocean.

In the Canadian Basin, the boundary current is supplied by relatively warm, low saline water of Pacific origin that enters through the shallow, narrow Bering Strait. The Pacific inflow to the Arctic Ocean is significantly smaller than that from the Atlantic Ocean. Moreover, the waters of Pacific origin are less saline, and thus lighter, than Atlantic waters, which means they remain on the surface mixing with freshwater from rivers and sea ice melting. As a result, the freshwater layer in the Canadian Basin is thicker than that in the Eurasian Basin, and the halocline is stronger.

Surface circulation and sea ice drift in the Arctic Ocean is largely driven by the prevailing winds. The clockwise circulation of the Beaufort Gyre in the Canadian Basin results from the atmospheric high-pressure system over the region. In periods when the circulation of the gyre strengthens, large amounts of fresh water, both liquid and solid, accumulate in the Beaufort Sea. Surface waters and sea ice leaving the northern boundaries of the Beaufort Gyre join the Transpolar Drift Stream, a surface current crossing the interior of the Arctic Ocean towards the Fram Strait.

Most drifting sea ice leaves the Arctic Ocean through the western Fram Strait and is carried by the East Greenland Current. Part of the fresh, cold Arctic surface waters also contributes to this current on its way towards the North Atlantic, while a remaining part of the Arctic water is transported southward through the narrow, shallow straits and passages of the Canadian Arctic Archipelago. The modified cooled, diluted waters of Atlantic origin return to the Atlantic Ocean through the western Fram Strait after circumventing the Arctic Ocean along different loops






Schematic illustration of the circulation in the Nordic Seas and Arctic Ocean. The red arrows represent the Atlantic inflow, the yellow arrows show the Pacific inflow, and the green arrows indicate the inflow of fresh water from Siberian rivers. The solid orange lines depict the Beaufort Gyre, while the orange dashed line shows the Transpolar Drift. The circulation of the modified Atlantic water in the Arctic Ocean and its southward flow towards the North Atlantic is shown by red dashed lines. The surface southward outflow of fresh Arctic water, which is a mixture of Pacific, river, and melted fresh water, is depicted by yellow dashed lines (prepared by A. Beszczyńska-Möller).

# Water masses and their transformation in the Nordic Seas and the Arctic Ocean

Ilona Goszczko

The definition of a water mass is used in oceanography to define a significant volume of water of uniform physical and chemical properties and a common origin. Temperature, salinity and other properties enable defining the place of water mass forming and trace both its route and transformation processes it undergoes.

A series of water masses can be distinguished in the North Atlantic, the Nordic Seas and the Arctic Ocean. Warm and highly saline Atlantic Water which forms as a result of warming and intense evaporation in tropical areas is the most significant. While being transported northward, it gradually releases heat to atmosphere and decreases salinity as a result of mixing. By cooling down, the water gets more dense and progressively lowers in the water column, thus forming intermediate water. The process of the Atlantic Water transformation is extremely important as regards climate – heat fluxes released to atmosphere in winter warm up and modify the circulation.

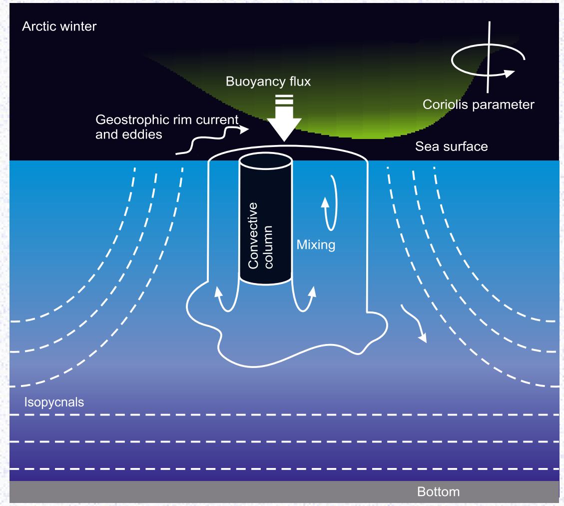
The Atlantic-origin water masses can be observed along the West Spitsbergen coast and farther in the Arctic Ocean. However, a portion of the Atlantic Water recirculates in the Greenland Sea where a uniform and unstable layer is formed as a result of mixing and cooling on the surface. During winter cooling the waters sink during the process of deep convection. The so-formed Greenland Deep Water passes across the Greenland-Scotland Ridge and feeds the North Atlantic Deep Water. That is how the most dense water of the World Ocean is formed, and the forming conditions the intensity of thermohaline circulation as well as the global climate.

The surface waters also play an important role. The Arctic Ocean drains great Siberian and Canadians rivers. Their freshwater, along with the precipitation water and water generated by ice melting creates a layer which separates the warmer Atlantic Water from the atmosphere. The ice cover which forms in winter additionally isolates the sea surface, thus hindering further heat loss. The salinity gradient layer between the surface water and the intermediate layer of the Arctic Ocean is called the cold halocline and contributes to maintenance of thick layer of sea ice in the Arctic, even in winter.

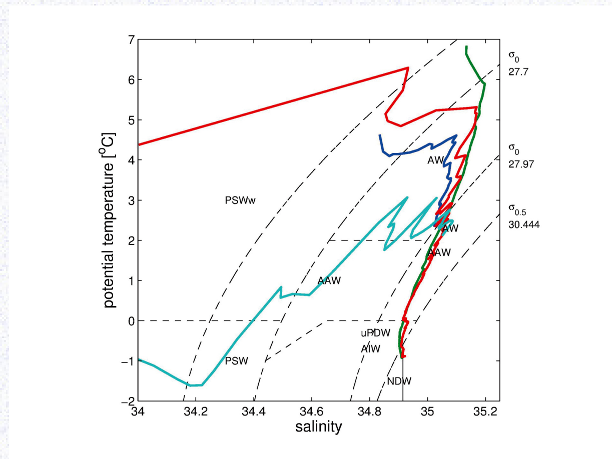
An exemplary division of water masses includes: the Polar Surface Water (PSW) - originating from the polar mixed layer and warmer PSWw - a layer formed as a result of ice melting, the Atlantic Water (AW) - transported by the West Spitsbergen Current, the Arctic-Atlantic Water (AAW) and the Arctic Intermediate Water (AIW) - the Greenland Sea water, the Polar Deep Water (PDW) - water from the Arctic Ocean, and the Nordic Deep Water (NDW.)[1]

[1] Rudels B., Bjørk G., Nilsson J., Winsor P., Lake I., Nohr C., The interaction between waters from the Arctic Ocean and the Nordic Seas north of Fram Strait and along the East Greenland Current: results from the Arctic Ocean-02 Oden expedition, Journal of Marine Systems 55 (2005) 1–30






Forming of convective columns in the Greenland Sea Gyre. A heavily mixed water layer forms in the centre of the geostrophic circulation area (the state of equilibrium between the pressure gradient and the Coriolis force). The hydrostatic buoyancy flux (directed towards the bottom, as a result of cooling) causes heavier elements of fluid to sink from the surface to a deeper level of equilibrium. The isopycnals denote equal density lines. Deep water is the most dense




Vertical profiles taken in the Greenland Sea in summer 2011 (colour lines). A single profile reflects potential temperature and water salinity. It is equal to potential density σ (density which the adiabatically risen water would have at a density level denoted with a number: 0 - at the surface, 0.5 - at 500 dbar, 1000 kg m-3 is subtracted to facilitate the format, the striped lines denote the selected density levels) .

## Fronts – water mass separation and mesoscale phenomena

I. Goszczko

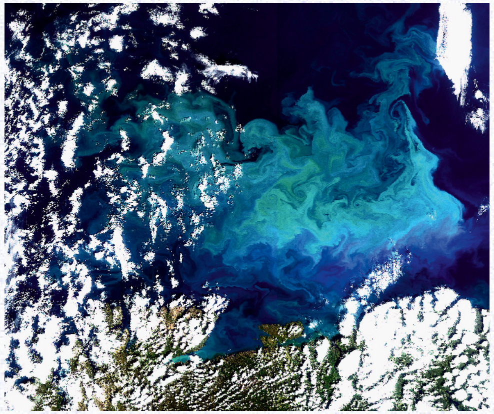
Ocean fronts are phenomena that occur in areas where sea currents converge and various water masses come into contact and interact. Fronts are long boundaries and, more frequently, wide areas featuring significant horizontal differences in physical water properties. In fact, frontal zones are not perfectly vertical structures; the contacting water masses overlap to form a slightly inclined wedge.

Depending on the conditions in which fronts form, several types are distinguished: large-scale ocean fronts dividing large circulation systems; shelf break fronts; fronts located near river mouths or other fresh water run-offs such as fjord mouths; fronts connected with upwelling or vertical water mass movements; and others. All fronts are areas of particular dynamics, and the processes occurring there are fast and intense. The margins between water masses are in continuous movement; they meander and the meanders close and detach to form eddies. This is an important mechanism of water exchange that occurs across front lines. Exchange can also manifest as intrusions or the stratification of water masses. Thin tongues of Arctic water can penetrate several kilometers into the Atlantic water domain. The dynamic upwelling of water masses along front lines provide living organisms with vital oxygen and other diluted chemical substances, which makes fronts favorable areas for intense primal production. Shoals of feeding fish, flocks of birds, and sea mammals frequently gather there.

Eddies are areas of rotating water that occur from disturbances in stable movements that are often due to changing bottom topography. Mesoscale eddies that are 10-500 km in diameter and last for a period ranging from days to months occur above underwater ridges, in the mouths of underwater canyons, or they detach from meandering currents that lose stability. In the northern hemisphere, they separate in the frontal zones of warm currents to form structures with warm centers and rotate clockwise, thus, anticylonically. Eddies that separate from cold currents rotate counterclockwise, thus, cyclonically. Cold-core eddies can generate vertical movements of water masses and raise the thermocline, which is a layer that separates the colder deeper waters from the warmer surface layer. The mechanism also transports upwards nutrients that are necessary for living organisms. On the other hand, warm-core eddies lower the thermocline and do not increase nutrient supplies. Eddy structures frequently transport water masses with properties that differ from those of surrounding waters over long distances.

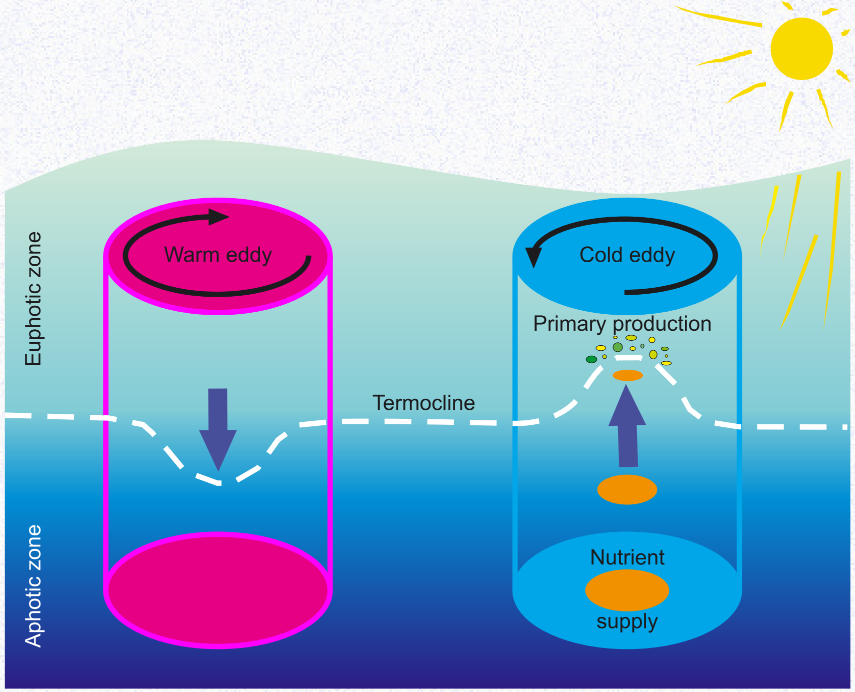
Frontal zones and other mesoscale phenomena such as eddies and meanders can be observed from planes and satellites because of their sizes. Such observations, combined with direct research, help us to understand the essential role of mesoscale phenomena in the redistribution of heat and salt in the oceans. As the processing capacity of computerized climate modeling such as the coupled ocean-atmosphere-sea ice model increases, it is becoming more and more possible to consider such significant components of oceanic circulation.





The ENVISAT MERIS spectrometer satellite image showing a phytoplankton bloom over an area the size of Greece, stretching north of the Scandinavian Peninsula in the Barents Sea on 19 August 2009. The color differences show frontal zones between warm Atlantic water and Arctic water, and eddies that formed alongside it.
The greener the structure, the more phytoplankton it contains. Navy blue and blue denotes waters that contain less pigment that reflects radiation, thus fewer plant organisms.

satellite image ASA – http://www.esa.int/esaCP/index.html




The effect imposed by eddies on the vertical water structure in the northern hemisphere. An anticylonic warm-core eddy (on the left) lowers the thermocline and the sea surface rises while the eddy moves; this phenomenon is seen from a satellite. A cold-core cyclonic eddy (on the right) raises the thermocline and supplies nutrients for biological production (preparet by Ilona Goszczko).

## Fjords – where ocean, glacier, and land meet

Agnieszka Promińska

Fjords are created when glacial valleys flood. They are common formations in the Arctic landscape with many branches reaching far inland. The lengths of fjords are highly variable; they can range from a few to several hundred kilometers, and they appear to be increasing in length continually. Dramatic retreats of Arctic glaciers and increased supplies of freshwater into fjords have been observed in recent decades, and these factors could significantly influence climate change.

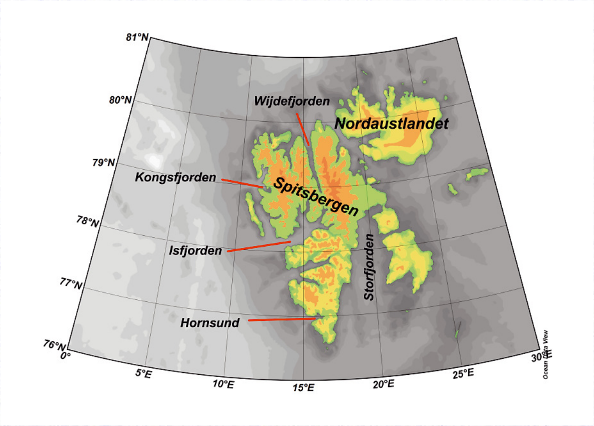
The fjords along the west coast of Spitsbergen are among the most extensively investigated. Their proximity to the West Spitsbergen Current (WSC) makes them especially interesting subjects for study. The warm, saline waters of this current flow northward along the continental slope of Spitsbergen and interact with the Arctic fjord environments. Polish scientists working from the Polish polar station in Hornsund Fjord have an opportunity to investigate the unique phenomena occurring in this area.

Three categories of external factors drive water circulation in the fjords, namely the atmospheric factors of precipitation, wind, air temperature, and solar radiation; terrestrial river runoff and melting water from glaciers; and oceanic water inflow from outside of the fjords. Moreover, topography can also significantly impact water circulation and exchange. Depending on the intensity of these forces, they can cause dynamic changes in water properties, especially with regard to temperature and salinity distributions, and water column stratification can also be modified.

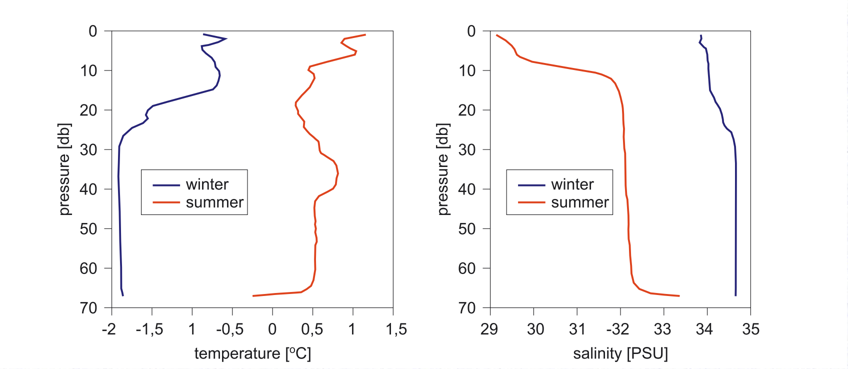
Fjord water stratification changes annually. In winter during the polar night when solar radiation fluxes are limited and large parts of fjords are covered with sea ice the water column is fully mixed. In spring, increased heat flux from the atmosphere causes ice to melt and the surface layer to warm. Moreover, progressing glacial ablation increases inputs of fresh water into fjords, and the intensity of these processes render the water column highly stratified in summer, when there are generally three distinct layers. The surface layer comprises warm, fresh water, while beneath is the intermediate layer of slightly colder, more saline, and denser water that forms when local fjord waters mix with advected oceanic waters. The threshold that limits water circulation in deeper basin areas is the third layer, which is known as the Winter Cooled Water. As is indicated by its name, this water mass is formed in winter and it can persist throughout the year. In the fall, when air temperatures decrease, surface layers cool and become denser, which causes them to sink and mix with the water masses beneath thus leading to mixing throughout the water column in winter. With this, the annual cycle comes full circle.



Location of the main fjords along coastal Spitsbergen, the largest island of the Svalbard Archipelago.




The Hans Glacier outlet into Hornsund Fjord (photograph A. Promińska).




Typical vertical profiles of temperature and salinity in winter (blue line) and summer (red line).

## Water freezing and sea ice

Ilona Goszczko

*Some thin ice now appeared, and from the crow's-nest we could see, when the fog cleared off a little for a few moments, several large channels running in a southerly direction both east and west of our position. Besides, we noticed an increase in the number of birds and small seals, and we also saw an occasional bearded seal - all evidences that we could not be very far from the open water.*

*Between 3 and 4 p.m. we were released from the floes which had held us enclosed, and at 5.30 p.m. we steamed off in a S.E. direction through steadily improving ice. The ice now became noticeably thin and brittle, so that we were able to force the smaller floes. From 5.30 p.m. till midnight we advanced about 16 miles; the engine was used as compound during the last watch.*

*After midnight on August 13th we steered S.W., then S. and S.E., the ice continuing to grow slacker. At 3 o'clock we sighted a dark expanse of water to the S.S.E., and at 3.45 we steered through the last ice-floes out into open water.*[1]

This is how the three-year-long drift of the Fram through the Arctic Ocean's ice fields ended in the summer of 1896 near North Spitsbergen. The Nansen experiment was repeated as part of the DAMOCELS Project when the yacht Tara drifted for nearly two years in 2006-2008. The significantly shorter time confirmed the increased intensity of Arctic ice dynamics, and its accelerated transport towards the Greenland Sea. The minimal extent and the thinning of the Arctic Ocean sea ice cover was observed during the experiment.

The sea ice formation process differs from fresh water freezing. The chemical substances dissolved in sea water lower the freezing temperature to nearly -1.8 °C. The higher the salinity in water, the lower its freezing temperature. Unlike icebergs calving from glaciers, sea ice is initially a saline, porous substance composed of a crystal structure, brine, and the air bubbles trapped in it. As it grows older sea ice gradually loses the brine, and after a few years it contains only a few percent of the initial salt content.

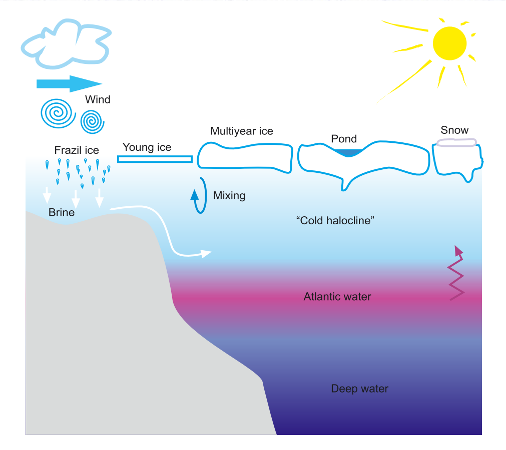
Sea ice formation is complex and occurs in several stages, and the properties of the types of forming sea ice vary considerably. Originally, as the sea surface cools, single, lengthwise, randomly located crystals called frazil ice form. If the weather is windless, the sea ice grows downwardly; if, on the other hand, there is strong wind and waves, the ice forms as flat pancakes. Falling snow causes newly-formed sea ice to sink making its structure more granular. In the final freezing stage, compact one-year ice followed by multi-year ice is formed that features both lower salinity and density.

The sea ice dynamic depends on the extent and plasticity of ice cover. Underwater sections form ice overhangs and hummocks form on the surface acting like sails in the wind. Open leads may stretch for miles, and there are also greater areas free of ice called "polynias". These regions feature intensive ocean-atmosphere heat exchange and sea ice formation. Ponds filled with melt water, which considerably change ice-cover albedo, form on the surface of the sea ice.

[1] Nansen, F., Sverdrup, O. N., Farthest North; Being the Record of a Voyage of Exploration of the Ship Fram 1893-96, and of a Fifteen Months' Sleigh Journey by Dr. Nansen and Lieut. Johansen, (1897), Volume 2.



Drifting sea ice south of Spitsbergen in June 2011. It is transported from the northwestern Barents Sea and is presumably one-year old (photograph I. Goszczko).




Sea ice forming in the Arctic Ocean. Under winter conditions, low temperature and wind cool the exposed, mixed water layer where ice forming begins, firstly as frazil ice and then as thin ice cover. The precipitating brine increases the subsurface water density. It flows from the shelf into deeper basins and feeds the cold halocline which protects thick multi-year ice against the heat released by Atlantic water (illustration by I. Goszczko).

## Sound in the Sea

Joanna Szczucka

Light and sound are the primary tools of human and animal communication. Sound is more useful in water than light is, because electromagnetic waves are much more attenuated than acoustic waves and can travel maximum distances of tens of meters. Very long sound waves, however, can propagate over distances of thousands of kilometers.

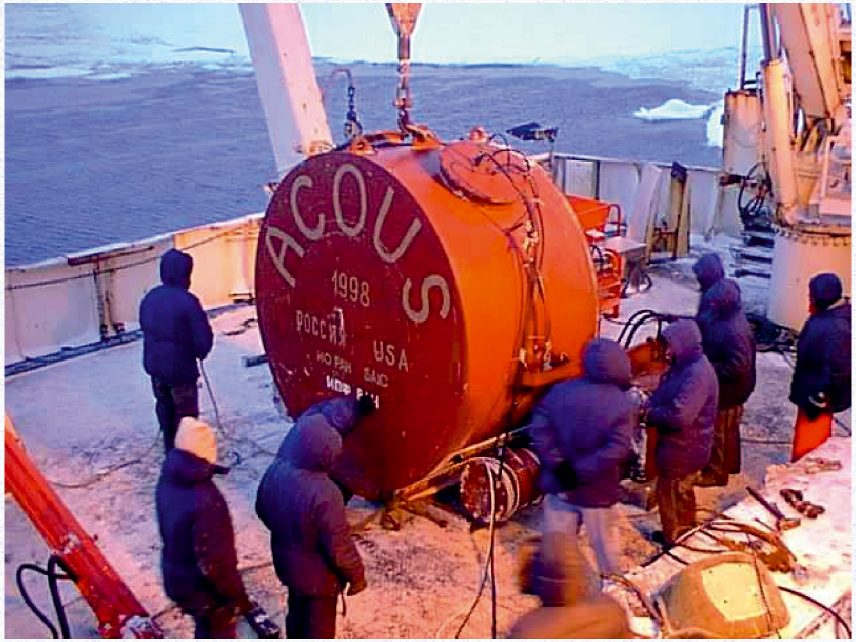
The average speed of sound in the sea is 1500 m/s, which is almost five times faster than in the air. This is not a constant value, so acoustic waves do not propagate in a straight line, but they bend, or are refracted. The speed of sound increases with temperature, salinity, and pressure. In the ocean, the minimum value is usually recorded at a depth of a few hundred meters in the coldest underwater layer. This local minimum makes acoustic waves bend in the direction of this minimum axes so they propagate in this layer like the waveguide without touching the sea bed or the water surface. This lack of reflections means they propagate with a minimal loss of energy and cover vast distances. This phenomenon is called the deep sound channel.

The idea of acoustic ocean thermometry is based on the fact that the speed of sound in water depends mainly on temperature. This is based on the simple idea that if the sea is becoming warmer, then the time it takes acoustic pulses to travel along a specified route is becoming shorter, because they travel faster in warmer water than they do in colder water. Implementation of this idea is not simple, because it requires expensive equipment and highly complex algorithms for signal processing and analysis.

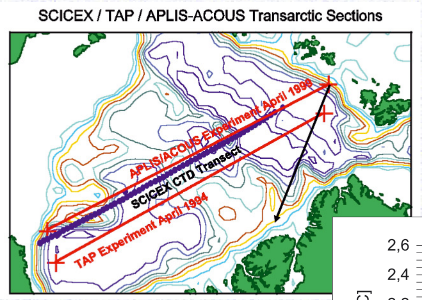
The first acoustic measurements of Arctic Ocean water temperature were conducted in 1994 as part of the Transarctic Acoustic Propagation (TAP) experiment, which concluded that these waters had warmed by 0.4 ºC since the 1980s. In 1998-1999, the Russian-American Arctic Climate Observations using Underwater Sound (ACOUS) research program was conducted. A huge acoustic transmitter was placed 60 m below the sea surface about 200 km north of Franz Josef Land. It emitted specially coded signals at a very low frequency of 20.5 Hz every four days for 14 months. Of the total of 107 signals emitted, all were received in the Lincoln Sea at a distance of 1,250 km from the transmitter, and two reached a measurement point in the Chukchi Sea, which was 2,720 km from the signal source (NB: this is not depicted in the figure because of a lack of space). The results were surprising: within five years of TAP, the average water temperature of the upper layer of the Arctic Ocean had increased by another half a degree. Simultaneously to the ACOUS program, the five-year Scientific Ice Exercise (SCICEX) research program was conducted using American nuclear submarines. The unlimited mobility of submarines operating in the ice-covered ocean permitted collecting data from areas never before visited by humans. Among many measurements, data on vertical temperature and salinity profiles were collected. They directly confirmed the increasing trend of water temperature, and indirectly permitted determining acoustic wave propagation paths and the areas of water bodies penetrated by them.

In addition to actively using sound waves to perform physical studies of the marine environment, passive methods are used that entail listening to the sounds made by animals. The development of acoustic communication between cetaceans and other marine mammals was a consequence of the evolutionary reduction of their sense of sight because of high light absorption in water. These animals use different frequency sounds for navigation, communication, hunting, and even courtship. Whale songs play an important role in their development and well-being, and we can use them to track their social behavior and migration routes.

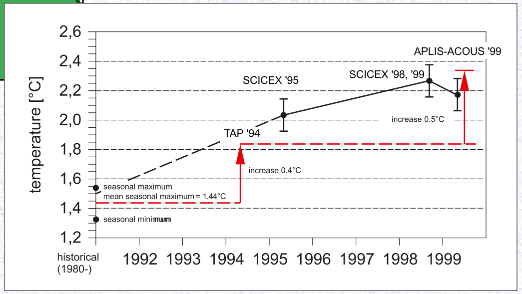





Hydroacoustic transducer used in the ACOUS experiment.




Location of temperature measurements of Arctic Ocean waters.




Increases in average Arctic Ocean water temperature determined by the TAP, ACOUS, and SCICEX research programs.

Illustration by: P.Mikhalevsky, Acoustic Termometry in the Arctic Ocean, http://acoustics.mit.edu/dyerparty/Arctic%20Thermometry%20Dyer%20June%202007%20final.pdf

## Modern technologies in polar observations

A. Beszczyńska-Möller

The Arctic Ocean is one of the least studied regions on Earth because of its limited access, harsh weather and ice conditions, and remoteness from permanently inhabited areas. Even as late as the nineteenth century, controversy persisted as to whether the North Pole was entirely covered by sea ice or surrounded by open water. Not until the trans-Arctic drift of the Fram in 1893-1896, when the ship was purposely frozen into the ice to drift with surface currents, was the existence of sea ice cover in the interior of the Arctic Ocean finally proven. This expedition, led by the Norwegian scientist Fridjof Nansen, was also the first ever which provided observational data from the deep Arctic basins.

Currently, most oceanographic observations in the polar regions are conducted from research vessels equipped with modern instrumentation and advanced sampling devices. Sea water temperature, salinity, and dissolved oxygen and sea currents are measured in situ, which means directly in the water column, by probes lowered on cables into the water column. Water samples collected from different depths are analyzed for biogeochemical parameters aboard vessels or later in laboratories. Modern sampling nets can collect biological samples from different water layers separately during a single cast. Because of permanent or seasonal ice cover, research icebreakers such as the Polarstern, Oden or Akademik Fedorov are employed in the high Arctic, while in the Nordic Seas measurements are conducted by research vessels including the Lance, Oceania, and the Haakon Mosby operating in open waters or along the ice edge.

Bottom-anchored oceanographic moorings deliver continuous, long-term time series from instruments distributed at different depths in the water column. The autonomous, self-contained moored instruments are equipped with internal memory cards and battery packs and can remain in the water for up to a few years. However, the sea ice cover in the Arctic regions prevents using surface buoys for satellite data telemetry; therefore, the data collected are available only after the moorings are recovered. Systems for acoustic data transmission between instruments moored in the water column and receivers located on ice floes, or carried by autonomous underwater vehicles, are currently under development.

Since the International Polar Year of 2007-2008, multidisciplinary observation systems located on drifting ice floes, called ice-tethered platforms (ITPs), have been used widely to collect atmospheric, sea ice, and oceanographic data in the ice-covered part of the Arctic Ocean. Sensors fixed to ice surfaces and frozen into ice usually provide meteorological observations and sea ice property data, while below the floe profiling instruments measure temperature, salinity, and sea currents to depths of a few hundred meters. The positions of drifting ITPs and the collected data are sent to land stations by satellite telemetry. In the ice free areas of the Nordic Seas, profiling Argo floats carried passively by sea currents are used to measure the oceanographic properties of the water column and to trace current pathways.

The newest generation of autonomous vehicles has recently been deployed for in situ observations in Arctic and sub-Arctic areas. Underwater gliders are the most promising technology. Different from vehicles with thruster propulsion, gliders ascend and descend in the water column by changing buoyancy, while their wings ensure forward movement. Their very low power consumption permits long missions up to several months. Equipped with a wide suite of oceanographic sensors, gliders travel along seesaw trajectories and collect data to maximum depths of 1000 m. At each surfacing gliders transmit the collected data to the base station and receive new commands via satellite link.

For the past several decades, satellite observations have provided the majority of data from the ocean's surface. Sea ice concentration has been continuously monitored by satellites since the early 1980s, and this has allowed observations of the most dramatic climatic change of the last century – the unprecedented rapid shrinking of the Arctic Ocean summer ice cover. The newest satellite dedicated to sea ice observations, Cryosat-2, has been operating since April 2010 and has provided not only information on sea ice concentration, or area, but also on ice thickness, and, thus, ice volume, surface currents, and sea wave heights.



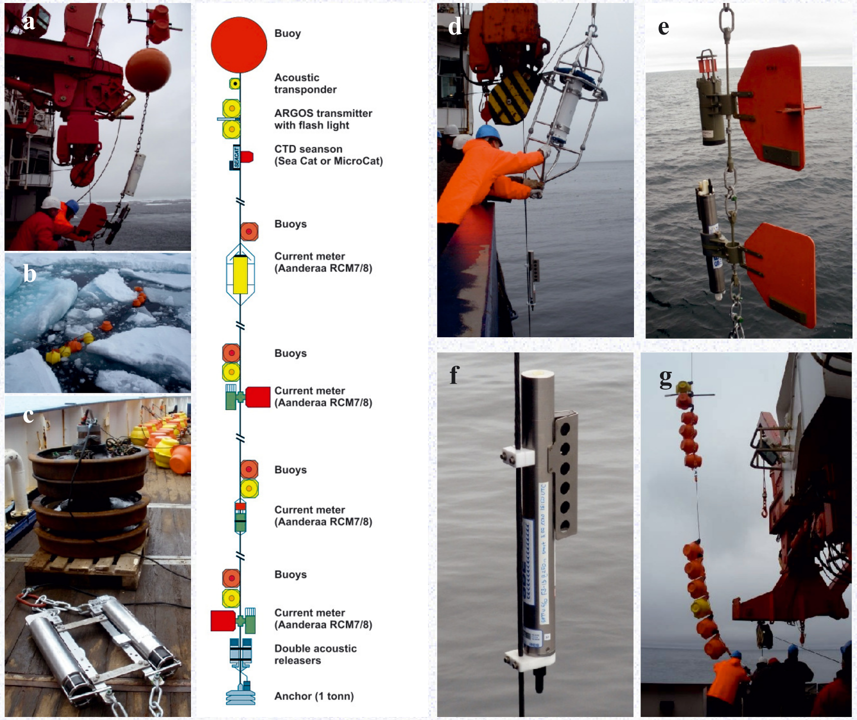



Illustration of moored instrumentation. The photographs depict (a) top flotation with acoustic pinger, (b) buoyancy floats in ice, (c) a bottom anchor with double releasers, (d) Acoustic Doppler Current Profiler, (e) Recording Current Meter with CTD (conductivity, temperature, depth) sensor, (f) Microcat CTD sensor, (g) deployment of mooring with float packages attached to the mooring cable (photographs Agnieszka Beszczynska-Möller).


(a) Deployment of autonomous glider, (b) surfacing glider with the research icebreaker Polarstern in the background, (c) deployment of AUV (autonomous underwater vehicle) equipped with thruster propulsion (photographs Agnieszka Beszczyńska-Möller).

## Ocean-atmosphere-ice interaction and Nordic Seas W. Walczowski

The Earth's climate is a complex system of various media interacting with each other. These spheres, as we call them, accumulate, move, transform, or reflect the Sun's heat that warms us. The spheres include the water or hydrosphere, the air or atmosphere, the sea and land ice or cryosphere, land or lithosphere, and, finally, living nature or the biosphere. The first three spheres are the most important in the Arctic, and their interactions, which comprise a complex feedback system, are especially significant to Earth's climate.

Thermohaline Circulation, which is the global oceanic current system, delivers a vast amount of oceanic heat transported by Atlantic waters to the Arctic. During the winter at high latitudes, heat is radiated into the atmosphere and then into space. In the ice-free areas of the Greenland Sea heat fluxes to the atmosphere reach 350 W / $m^2$, which is comparable to the average flux of solar radiation reaching the upper atmosphere. Therefore, the Arctic is a huge cooler of the Earth's thermodynamic machinery.

However, even the Arctic heats up in summer from the Sun that shines around the clock. Both the air and land warm, glaciers melt, the temperature of the ocean surface increases, and some of the sea ice melts. The role of sea ice is extremely important in summer, because it reflects sunlight; scientists refer to this by saying the ice has a high albedo. In contrast, the ocean absorbs more than 90 % of the solar radiation that reaches its surface. So, by reflecting the Sun's radiation, ice prevents the ocean beneath it from warming, and it deflects the Sun's energy directly back into space. This means that even in summer the Arctic cools the Earth's climate system.

In an age facing the problem of excess energy retention in the atmosphere because of an increasing greenhouse effect, the fragile balance of the machinery is becoming unstable. Although the excess retained energy is actually quite small at about 1 W/$m^2$, it could result in disastrous consequences in the long term. The ice covering the Arctic Ocean is already disappearing at a rapid rate in summers. The decreased areas of ice, which are surface mirrors that reflect radiation, lead to the ocean absorbing more heat. Although new ice is formed during the winter, it is "one-year ice", which is thin and fragile and melts more quickly in the warmer ocean. This causes one of the climate feedback systems to shut down: thin ice disappears quickly in subsequent summers, the ocean heats up even more, and the effect intensifies.

While it is true that the main causes of disappearing sea ice in the Arctic are changes in wind and ocean current patterns that drive the faster drift of sea ice into the Greenland Sea, these changes are also related to increased ocean temperatures. And this is the next feedback system involved in this complicated machinery.

Of course, we do not yet fully understand all of the mechanisms governing Earth's climate. But in an age with a penchant for disasters, the "thermohaline catastrophe" scenario is proclaimed far and wide. According to it, the increased supply of freshwater released from melting glaciers could cover the ocean with a thin layer of freshwater. This layer could reduce the exchange of heat between the ocean and the atmosphere to such an extent, that it will limit the production of deep water, as described in a previous chapter. Without this production, which is one of the "driving wheels" of ocean circulation, surface currents will weaken, oceanic heat transport to the north will decrease, and a new ice age will begin.

However, it does appear that this scenario is unlikely to occur in the twenty-first century.



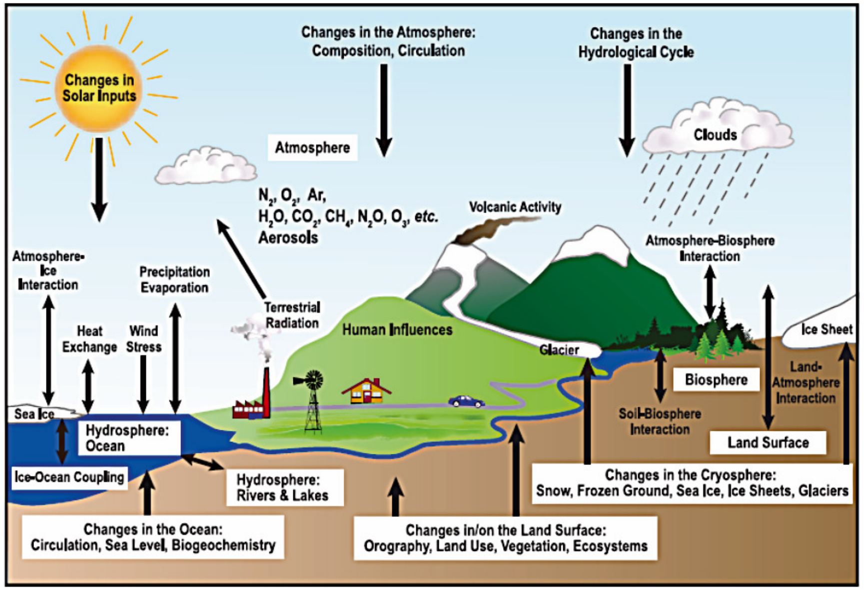
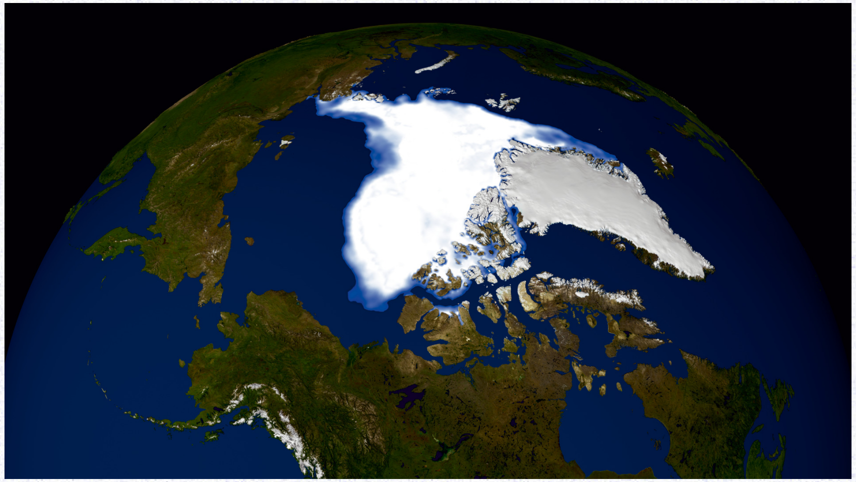



Diagram of the components of the Earth's climate system, its processes, and interactions (IPCC 2007, http://www.ipcc.ch/publications_and_data/ar4/wg1/en/faq-1-2.html).



Minimum extent of Arctic sea ice observed in summer 2007 (NASA/Goddard Space Flight Center Scientific Visualization Studio).

## Climate change vs. seawater chemistry

Janusz Pempkowiak

Climate warming, which is best manifested by increases in atmospheric and surface seawater temperatures, has no direct influence on seawater chemistry in the Arctic. However, substantial indirect changes are predicted. Changes in equilibrium regarding biocenosis, land-sea interactions, seawater-marine bottom sediment material fluxes, and seawater-cryosphere can and will cause changes in the chemical composition of seawater.

Without thorough, dedicated investigations, it is difficult to predict the probability and range of changes in Arctic seawater chemistry that will result from climate warming. Seawater acidification, modifications in the trophic pyramid, and increased concentrations of organic matter in seawater are likely to be the first symptoms of change that will be possible to quantify. Some of the changes are described in the following chapters of this booklet. It is well worth mentioning that, apart from climate warming, there are a few other processes, known collectively as global changes, that affect chemical equilibrium. These are listed in the chart on the facing page.

**Land-sea interactions**. Increases in both dissolved and particulate chemical substances delivered to the coastal zone of the Arctic seas with the river run-off are expected. Increased nutrients will have an effect on the primary production of organic matter. This will cause increases in both dissolved and particulate organic matter, and the intensification of processes that organic matter impact including the optical properties of seawater, trace organic and trace metal complexation, and the absorption of chemical contaminants by biota.

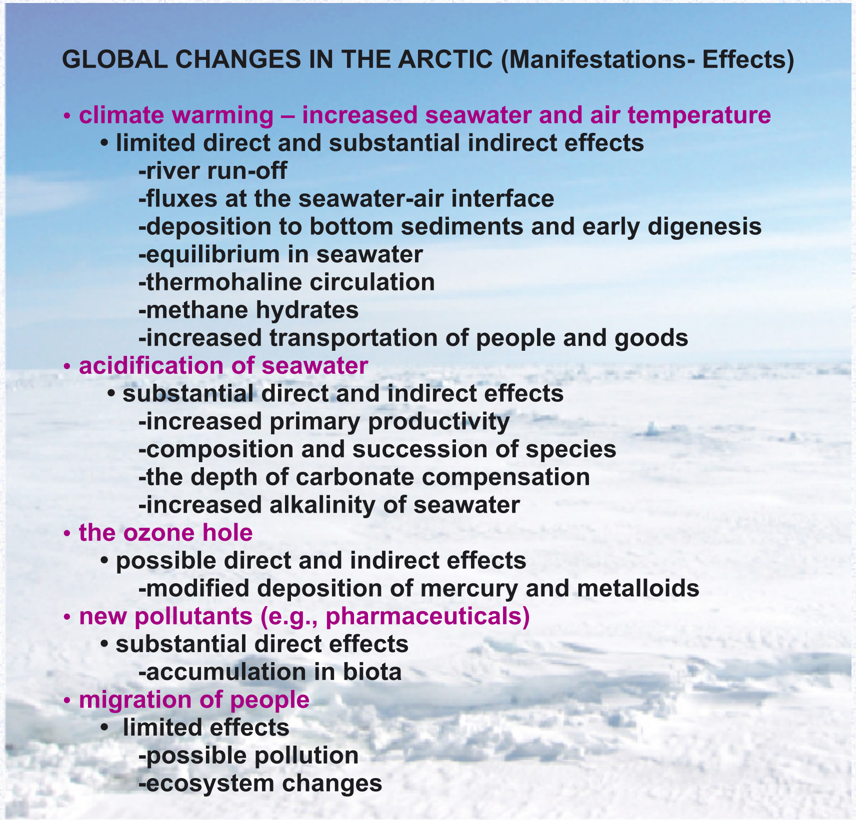
**Seawater-atmosphere interactions**. The expected increase of carbon dioxide in the atmosphere will result in an intensified physical-chemical pump that delivers carbon dioxide to seawater. This will lead to decreased seawater pH. The process often referred to as acidification will have a profound effect on biota, and both changes in the composition and succession of species are expected. Benthic organisms are likely to suffer the most.

**Seawater**. Increased temperature, nutrient concentrations, and acidification will cause shifts in the composition of phytoplankton and the succession of species. Increased primary production and biomass of higher trophic layers is to be expected. This will cause increases in dissolved and particulate organic matter in seawater, and the deposition of organic matter to the bottom sediments. In the extreme, anoxic conditions could develop at the sediment-seawater interface.

**Cryosphere**. Fresh water originating from melting glaciers could lower surface seawater salinity and disrupt thermohaline circulation, and this could prompt local negative feedback to climate warming. Depending on intensity, the changing boundaries of and shifts in sea ice-pack will result in processes such as the influx of substances from multiyear-old ice, the flux of organic matter from phytoplankton, and the transport of minerals and suspended matter with sea ice.

**Marine bottom sediments**. There will be increased fluxes of organic matter to the sediments, and, on the one hand, the sedimentation rate of minerals will shift geographically as less material is delivered to the sea with migrating sea ice, while on the other hand, more suspension will be delivered to the sea with river run-off. Increased fluxes of organic matter could cause local anoxic or even reducing conditions. The mineralization of fresh organic matter in bottom sediments will result in an increased diffusion of carbon dioxide from the sediments to the overlying water, causing further acidification of seawater above the bottom sediments, and methane-hydrate deposits could possibly be released. The destabilization of deposits will cause emissions of methane from the sediments to the overlying water and, eventually, into the atmosphere. Increased bacterial production will lead to increased carbon dioxide from methane oxidation, and, in the extreme, there could be methane explosions in the atmosphere from mechanical and thermal energy release.






Scheme of the global change influence on the Arctic Environment (photography background A. Zaborska).

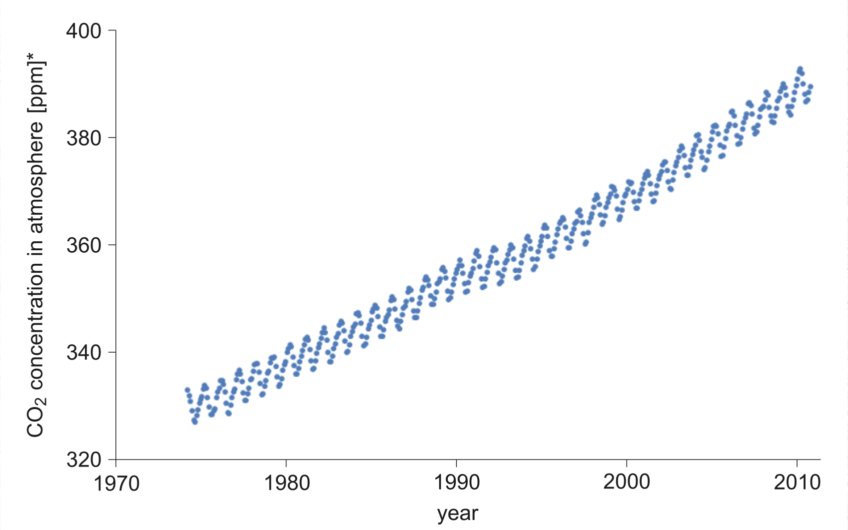
## Carbon dioxide and sea water acidification

Karol Kuliński

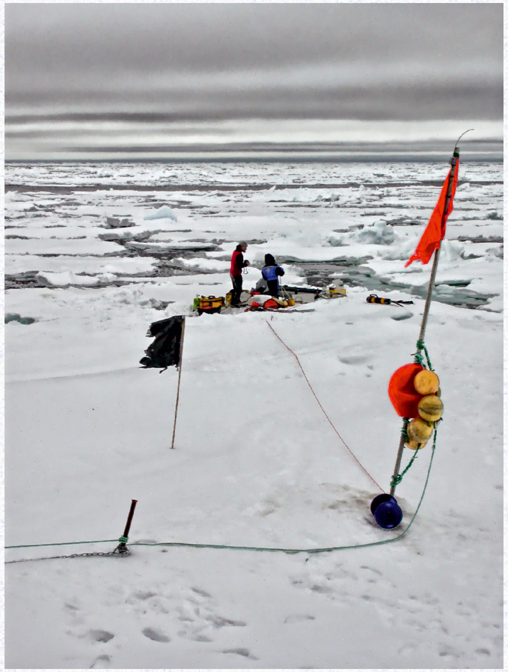
Carbon dioxide ($CO_2$) is a natural component of the Earth's atmosphere. The physico-chemical properties of $CO_2$ molecules enable them to absorb the infrared radiation. Thus, $CO_2$ contributes to the heat accumulation in the atmosphere and is considered as one of the green house gases. The green house effect is believed to be indispensable to provide the temperature conditions on Earth appropriate for the growth of organisms. The concentration of $CO_2$ in the atmosphere is related mostly to photosynthesis and respiration processes. However, the age of industry started about 150 years ago and since that time a great progress of world economy is observed. It was possible due to establishment of new methods for energy production on a large scale. They are based mostly on the fossil fuels combustion with $CO_2$ as a by-product. Additionally, $CO_2$ is produced during cement production from carbonate rocks as well. In this way people emit to the atmosphere $CO_2$, that was in the form of fossil fuels or carbonate rocks excluded from the natural carbon cycle several million years ago. Accordingly people contribute to the rise of atmospheric $CO_2$ concentration and to the global temperature increase and climate change.

The global temperature increase is not the only consequence of rising $CO_2$ concentration in the atmosphere. The another is so called ocean acidification. Seawater has relatively stable, slightly basic pH of little over 8. Carbon dioxide dissolved in seawater forms a carbonic acid ($H_2CO_3$) that contributes to the pH decrease of a seawater. The amount of $CO_2$ and carbonic acid in a seawater is directly related, similar as for the atmosphere, to the balance between photosynthesis and respiration. However, the surface waters of the ocean are under very high influence of the atmosphere. Thus, the higher $CO_2$ concentration is observed in the atmosphere the more $CO_2$ is absorbed by the oceans from the atmosphere globally. It is believed that most of the Arctic basins absorb $CO_2$ from the atmosphere. This process is amplified by the low seawater's temperature since solubility of $CO_2$ in water, similar as most other gases, increases with the temperature decrease. Additionally, the uptake of atmospheric $CO_2$ by a seawater is strengthened by the deep water formation processes occurring in the North Atlantic Ocean. The warm surface waters coming from the equatorial zone cool down in high latitudes and sink. They transport simultaneously $CO_2$ from a surface ocean to the deeper water layers. This process acts as "a pump" enhancing atmospheric $CO_2$ uptake by the ocean. The increase of $CO_2$ concentration in a seawater results in pH decrease, what may be dangerous for the marine organisms, especially those building their exoskeletons from carbonates (e.g. cocolithophores and/or corals). This is due to the fact, that carbonates dissolve in low pH. Until now the pH changes of seawater are small. However, the increasing anthropogenic $CO_2$ emissions and resulting from this an ocean acidification may be in the future the real threat for the marine organisms. One of the most exposed regions to these threats is the Arctic.






$CO_2$ concentration in the atmosphere measured at the Mauna Loa Laboratory (Hawaii); *ppm – parts per million



Surface seawater sampling for chemical analyses directly from sea ice (photograph A. Zaborska).

## Carbon cycle in the Arctic

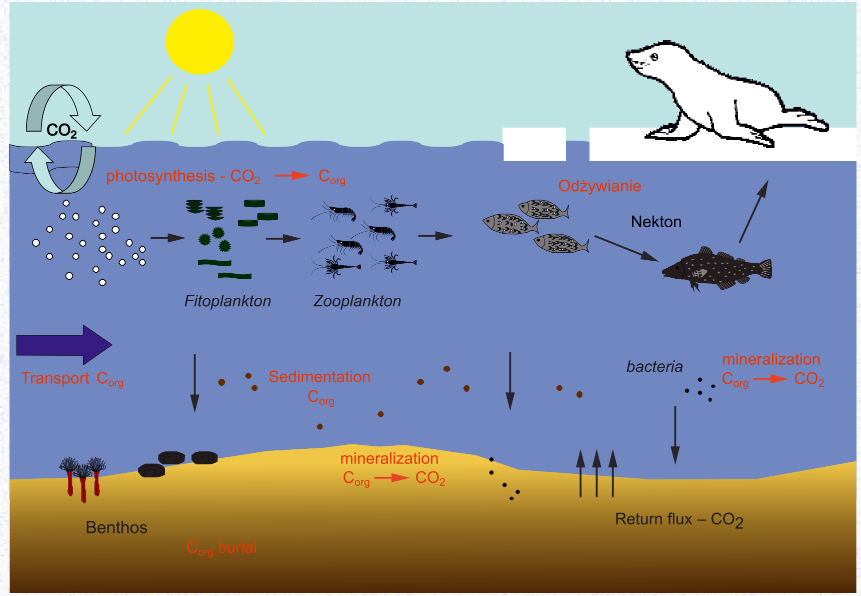
Karol Kuliński, Agata Zaborska

Carbon is a key chemical element of the Earth's crust even though its concentrations are relatively low. The importance of carbon stems mostly from the fact that it is a fundamental component of organic compounds, and, thus, one of the basic chemical components of life on Earth. This portion of carbon is called organic carbon ($C_{org}$). Apart from $C_{org}$, carbon also exists in inorganic forms. The dominant species are here carbon dioxide ($CO_2$) and carbonates ($CO_3^{2-}$) and bicarbonates ($HCO_3^-$) that are crystallized in rocks or dissolved in water. The carbon cycle links all three of the Earth's compartments: the land, the ocean, and the atmosphere. The major carrier of matter in this cycle is $CO_2$. Photosynthesis consumes $CO_2$, while respiration produces it. Thus, the $CO_2$ concentration in the environment is controlled mostly by the growth of organisms. Carbon dioxide absorbs heat radiation in the atmosphere, so it is designated as one of the greenhouse gases. People have been emitting large amounts of $CO_2$ into the atmosphere through intensified cement production and fossil fuel combustion since the mid nineteenth century. This is how human activities lead to climate warming and all of its consequences, including melting glaciers.

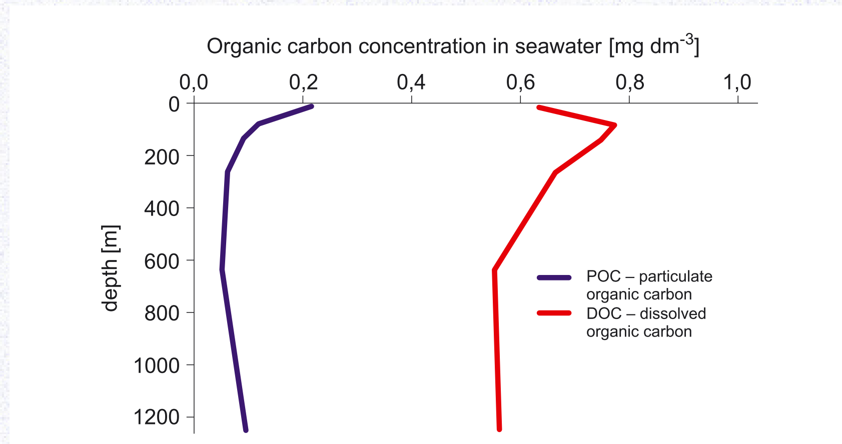
One of Earth's regions that is most vulnerable to the threats of climate change is the Arctic. This is why much scientific effort is focused currently on Arctic research in general, and on the Arctic carbon cycle specifically. Scientific studies indicate that a significant part of the marine areas in the Arctic absorbs atmospheric $CO_2$ very effectively, thus reducing its influence on the climate. The key role here is played by the so-called "biological pump" that is additionally strengthened by low seawater temperatures that enhance the uptake of $CO_2$ and other gases. The biological pump is driven mostly by the activity of small vegetative organisms known as phytoplankton that inhabit water. During photosynthesis, phytoplankton consume the $CO_2$ dissolved in seawater and transform it into the organic matter ($C_{org}$), which allows it to be transported between different compartments of the food web. Part of the $C_{org}$ is mineralized during the growth of organisms and just after their death during sedimentation. As a consequence, $CO_2$ is released back into the water column. However, a portion of the organic matter reaches the sediments, where it is buried, and excluded from the present carbon cycle.

The Arctic regions are also believed to be a great repository of organic carbon that is accumulated in the permafrost, which is the upper layer of soil that is permanently frozen. Global warming causes the partial thawing of permafrost that releases organic compounds into streams and rivers. This organic matter ultimately enters the Arctic Ocean, where a great portion of it is mineralized and $CO_2$ is produced.






Scheme of the carbon cycle in the Arctic. $CO_2$ dissolved in seawater is consumed by phytoplankton during photosynthesis. Organic carbon ($C_{org}$) originates from primary production. Other sources of carbon are: water currents, rivers, and melting ice. Organic matter is mineralized in the water column and on sediment surfaces and inorganic carbon, as $CO_2$, is released back into the water column (A. Zaborska, own materials).




Plots of dissolved (DOC) and particulate (POC) organic carbon concentrations in the water column. Samples were collected from the Greenland Sea in summer 2010. The highest concentrations of organic carbon were noted in the upper water layer (0-80 m), because of the intensive primary production observed in surface waters (results of A. Zaborska).

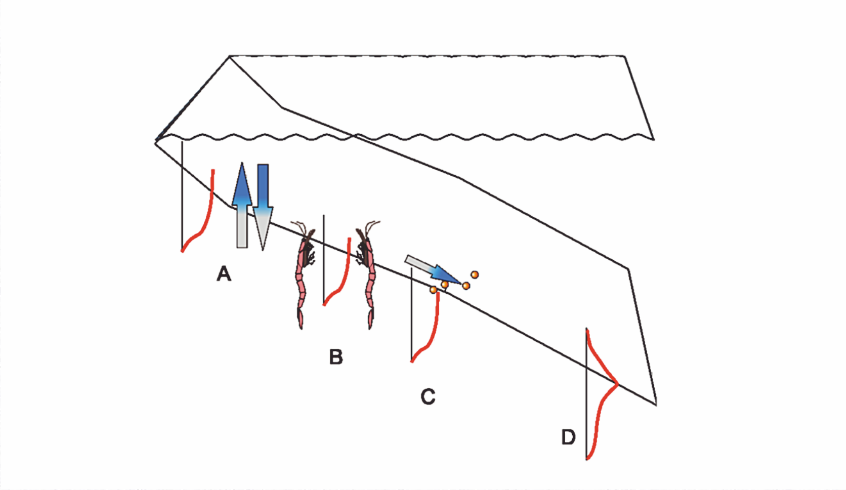
# Chemical exchange between sediments and water

Jacek Bełdowski

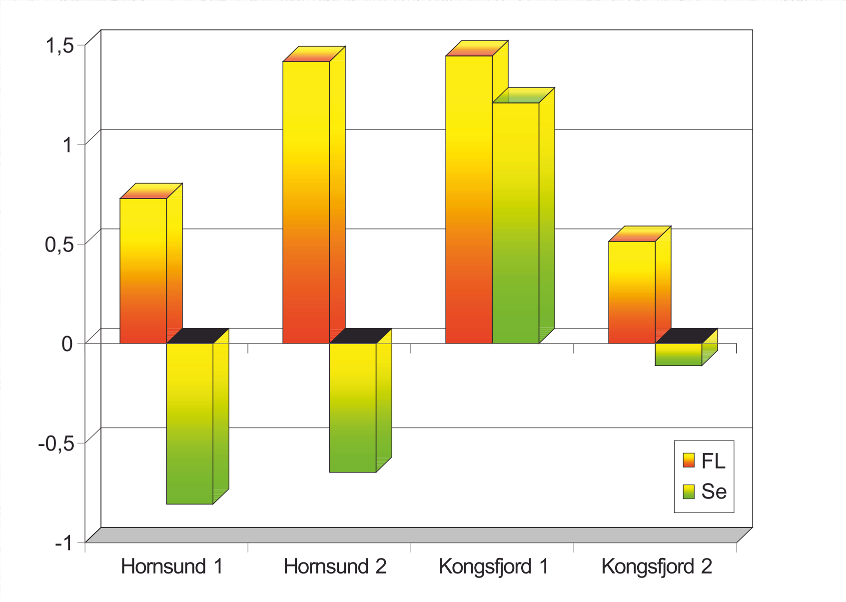
The migration process of chemical substances such as nutrients, pollutants, and some gases, for example methane, from the sediments to overlying waters is extremely difficult to quantify. Substances contained in the sediments can enter the water column as a consequence of several processes. The most important, especially in deeper areas, is molecular diffusion when chemical and biochemical processes release chemicals into porewaters, which are the waters contained between sediment grains. The laws of diffusion mean that concentrations of substances in water approach equilibrium, and this results in a slow, steady upward flux into areas where concentrations are lower . The three substantially faster processes of dispersion, resuspension, and bioturbation occur in shallow sea areas. Dispersion occurs because of wave action that literally disperses dissolved substances. When porewaters travel continuously up and down as a result of pressure shifts, the concentration of chemical constituents in the uppermost sediments and in overlying waters become nearly identical; that which would take years for diffusion to accomplish is possible for dispersion to do within weeks or even hours. Wind waves, of course, affect only very shallow areas, but there are also waves generated by tides in the Arctic. The daily tidal cycle causes pressure shifts in even deeper bottom areas, which significantly increases areas affected by dispersion. Resuspension differs from diffusion and dispersion in that it affects particles, not fluids. In other words, it is the erosion of sediments when single grains or even layers of sediments are lifted into the overlying water, and the substances contained in the porewaters are immediately released. This process can be induced by waves, but also by bottom currents, which can be quite rapid in tidal areas. The third processes is bioturbation, which occurs through the activities of biota. This process can lead to both porewater migration and the movement of sediment grains into the water column.

Scientists not observe only the effects of the three processes mentioned above, but by observing concentrations of chemical substances in sediments and waters they also try to estimate the magnitude of sediment-water fluxes. In the Arctic, one of the substances observed is mercury, which is transported in gaseous form from industrialized areas of the northern hemisphere. One of the ways to assess the rate of mercury sediment-water exchange is to measure its partitioning between particulate and dissolved phases. Of course, the more intense the sediment water exchange is, the more partitioning shifts towards dissolved forms. Last figure illustrates this in the two Spitsbergen fjords of Kongsfjord and Hornsund. Negative values represent the domination of particulate forms, while positive values represent dissolved forms taking the lead. The letters FL mark the fluffy layer of suspended matter covering the bottom surface, while SED indicates the sediment proper. This figure indicates that dissolved forms dominate in the fluffy layer, while in the sediments, where the opposite is expected, the situation is ambiguous. The reason for this phenomenon is sediment-water exchange, which is lively enough to cause mercury, which enters Arctic sediments during springtime, to stay dissolved for a relatively long time. In both areas bioturbation, diffusion, dispersion, and resuspension mean that the thin layer of mercury-rich uppermost sediments remain a source of mercury for the environment until it is covered by subsequent layers of sediments from nearby glaciers.






Sediment-water exchange processes. A) Dispersion, B) Bioturbation, C) Resuspension, D) Diffusion (prepared by J. Bełdowski).




Mercury partitioning between dissolved (positive values) and particulate (negative values) forms in the fluffy layer of suspended matter (FL) and sediments (SED) in Hornsund and Kongsfjord (prepared by J. Bełdowski).

## Nutrients in the Arctic

Beata Szymczycha

Nutrients, inorganic nitrogen, phosphorus, and silica compounds, are substances organisms take from the environment for metabolism, and they are essential for plants to live and grow. In the oceans, including the Arctic Ocean, phytoplankton must have these to survive and reproduce, because they are required to make proteins, nucleic acids, and other cell components. Moreover, phytoplankton need these nutrients in well-defined ratios. For example, phytoplankton need 16 atoms of nitrogen and 1 atom of phosphorous for every 106 atoms of carbon made into organic matter.

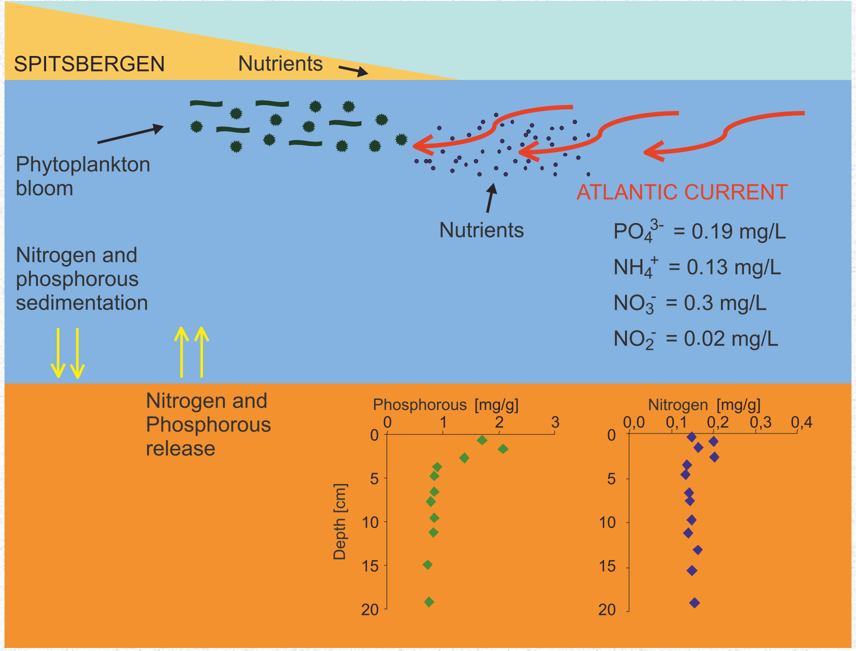
The main sources of nutrients in the Arctic Ocean are fluxes from the Atlantic and Pacific oceans, rivers, and mixing process, but the most important factor determining nutrient concentrations in the water column and sediments around Spitsbergen is the Atlantic Current.

Figure presents the main nutrient sources for the Spitsbergen region, and levels of nutrients in the water column and sediments. The surface sediment layers are characterized by enriched nitrogen and phosphorous levels; thus, nitrogen and phosphorous can also be released from organic matter mineralization and can then be trapped in the sediments. The process is called sedimentation. On the other hand, mainly phosphorous, but also nitrogen, can be released from sediments to the water column under specific conditions in a process called resuspension. The other process impacting concentration levels in waters and sediments is surface input. Rivers, streams, and other sources of surface runoff are rich in nutrients from bird guano, which is washed from land surface sediments and finally reaches coastal oceans. The coastal areas located near bird nesting sites are particularly rich in nutrients. The other process influencing nutrient concentrations in the water column is mixing. Sometimes bottom water reaches the surface water layer enriching it in nutrients especially in coastal areas.

Nutrient levels usually do not decrease below that essential for plants to live and grow, because the vegetation period is short and it mostly occurs in the surface layer where all primary production takes place. Primary production is limited by light in the polar regions with multi-year or seasonal ice cover. In the ice edge zone, which is the region of seasonal melting, the uppermost water column is stabilized.

Nutrient concentrations in sediments are determined by two processes – sedimentation and resuspension. Figure presents exemplary nitrogen and phosphorous depth profiles. The surface sediment layers are enriched in nutrients, and are also a source of nutrients for bottom waters. Below the surface, concentrations of both nitrogen and phosphorous decrease in the sediment layers as depth increases.






Nitrogen fluxes to Spitsbergen via external sources. The nitrogen and phosphorous concentrations in the Atlantic Current (the concentrations were measured in summer, 2010). The profiles present nitrogen and phosphorous concentrations in sediments (prepared B. Szymczycha).

Birds' guano represent significant source of nutrients for Spitsbergen (photograph A. Zaborska).

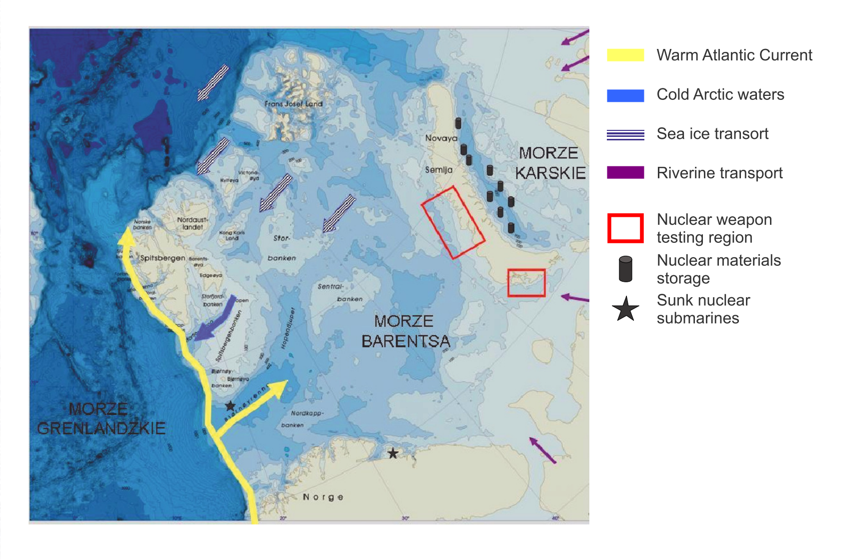
## Sources of cotaminants in the Arctic

Agata Zaborska

The Arctic is less urbanized in comparison to other regions on Earth, so it is expected to be a pristine environment. However, Arctic air, sea ice, oceanic waters, and sediments contain measurable levels of anthropogenic contaminants. The most widespread contaminants are radionuclides (e.g., caesium, strontium, plutonium, technetium), heavy metals (e.g., mercury, cadmium, lead), and organic contaminants (e.g., PCBs, PAHs). These contaminants originate primarily from industry, the burning of fossil fuels, and agriculture in Asia, Europe, and Northern America. Long-range contaminant transport occurs via the atmosphere, sea currents, sea ice drift, and rivers. Mercury and organic compounds evaporate into the atmosphere in the warm regions of Earth, and then they are moved north by winds, condensate at lower temperatures, and fall into the sea or onto land surfaces. This phenomena is called the "grasshopper effect". Anthropogenic radionuclides, also known as global fallout, originating from nuclear weapons testing in the 1960s are also transported by the atmosphere. Although they were emitted into the atmosphere fifty years ago, radionuclides are still present due to their long radioactive decay time. Some water-soluble contaminants continue to enter the Arctic environment through sea current transport. One example of this are discharges of radioactive technetium from the Sellalfield nuclear reprocessing facility in the UK. Radionuclides and other contaminants are also transported by large Siberia rivers such as the Ob and the Yenisey, which both flow through highly urbanized regions of Russia. The former underwater nuclear test site on Novaya Zemlya is another source of significant contamination in the Barents Sea. The sea bottom there is a storage site for barrels containing nuclear fuel, nuclear heads, and nuclear waste. Other local contaminant sources of regional significance are the coal mines on Svalbard. Contaminants can also be transported by sea ice since sediment particles containing contaminants are incorporated in the ice as it forms. This "dirty ice" is transported by polar drift to the Greenland and Barents seas where it melts during the summer.

Some contaminants are toxic to the animals and humans inhabiting the Arctic, which is why monitoring polar region contamination has become very important.






Main contaminants transport pathways (currents, sea ice, rivers) are shown on the map. At the Novaya Zemlya nuclear weapon material is stored (prepared by A. Zaborska).

"Dirty ice" containing particles with contaminants at the Barents Sea, Sea ice is formed at the Siberian coast and then it is transported by Polar Drift to the Arctic Ocean (photograph A. Zaborska).

## Sediments – sinks for contaminants

Agata Zaborska

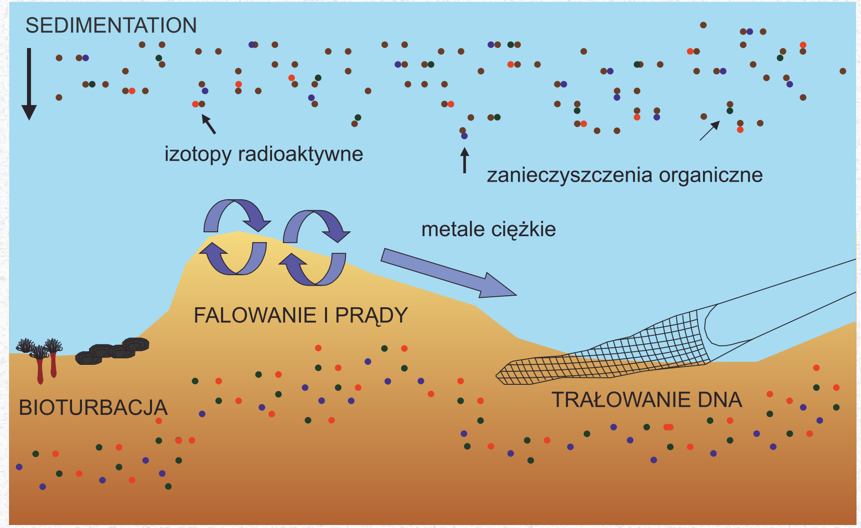
Marine sediments are often referred to as sinks for anthropogenic contaminants. As was described in the previous chapter, the Arctic receives contaminants from numerous sources the world over. Because of their affinity with organic matter and fine mineral fractions, most contaminants are absorbed on sinking particles in the sea. Particles with absorbed contaminants sediment to the sea bottom. The deposited particles are then covered by newly deposited particles, and so on. Subsequent layers of deposited particles form marine sediments. Even though particle sedimentation is a slow process, it does help to purify the water column of contaminants.

Numerous nuclear weapons tests were performed during the Cold War in the 1950s and 1960s, and radioactive isotopes of anthropogenic origin were introduced into the environment. Arctic marine sediments were contaminated by radionuclides since most of the tests were conducted in the northern hemisphere, among other areas on Novaya Zemlya. The highly contaminated sediment layers from that period have been covered by newly deposited sediments that are less contaminated; thus, the contamination has been buried in the deeper sediments. This phenomena is clearly visible in vertical depth profiles of plutonium and caesium activity concentrations in the sediments. A peak in radionuclide activity concentration is observed several centimeters below the sediment surface.

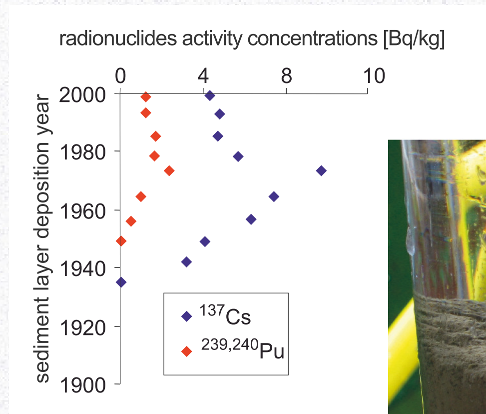
Thus, if lesser amounts of contaminants are discharged into the marine environment currently, we can expect that the seas will be cleaner, and the contaminants will remain stored in the deeper sediment layers.

Unfortunately, some processes can mix sediments and reintroduce contaminants into the water column. This results in contaminants becoming available again to marine organisms. Sediment mixing can be caused by natural processes such as marine currents, waves, or the activities of benthic animals in a phenomenon known as bioturbation. However, mixing can also result from human activities. Bottom trawling, such as that done during shrimp fishing, disturbs surface sediment layers, and the construction of oil platforms and other projects disturbs large areas of marine deposits. All of these natural and anthropogenic processes that disturb the sea bottom can also be unfavorable for the marine environment.






The sedimentation of contaminants absorbed onto particles sinking to the sea bottom. Contaminants may be re-introduced to the water column due to sediment mixing processes by natural or anthropogenic factors (prepared by A. Zaborska).




The profile of $^{137}$Cs and $^{239,240}$Pu activity concentration in the function of sediment layer deposition year. Peak of radionuclides activity concentrations is visible at layer deposited in early 70ties.

The picture of sediment core with benthic organisms (soft corals) that may actively mix bottom sediments (photograph A. Zaborska).

## Contaminants in Arctic organisms

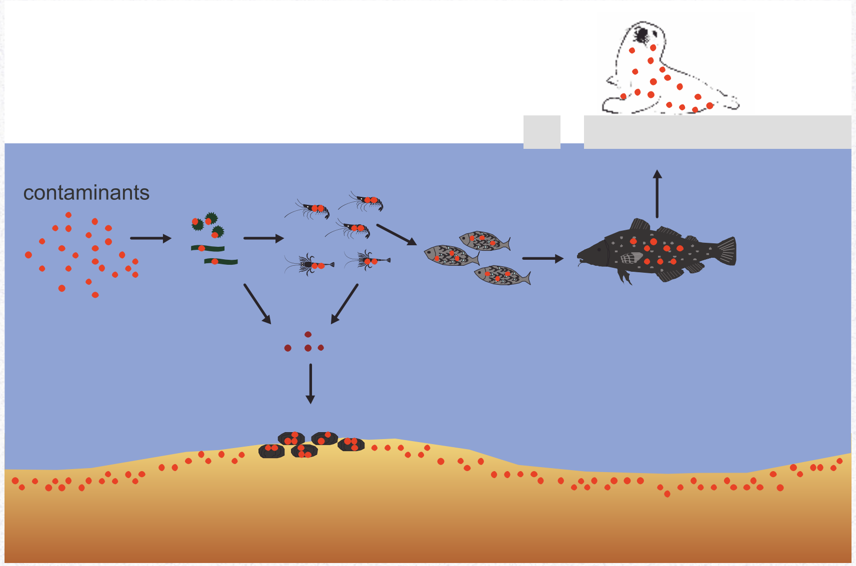
Agata Zaborska

Some contaminants, which are substances discharged into the environment through human activity, are toxic to marine organisms. The most dangerous of these in the Arctic include some heavy metals (mercury and cadmium), organic contaminants (PCBs, DDT, PAHs), and radionuclides (caesium and plutonium). Some of these contaminants exist in the marine environment in forms that are available for uptake by organisms. Contaminants can be transferred to organisms when skin comes into contact with contaminated waters or through ingestion. Most contaminants are persistent, fat-soluble substances, which means that marine organisms are unable to decompose or eliminate them from their bodies. Thus, contaminants can bio-accumulate in the tissues of organisms, and these toxic substances can be carcinogenic and can cause irreversible damage to the hormonal and/or nervous systems.

While contaminates accumulate in particular organisms, they can also bio-magnify through the trophic chain. Bio-magnification occurs when toxic substances accumulate in organisms at lower trophic levels and then are transferred to organisms at higher trophic levels. Increased concentrations of toxic substance (e.g., mercury, PCBs) in higher trophic level organisms can be substantial, and the longer the trophic chain is, the greater bio-magnification is. The bio-magnification factor is expressed as the ratio of contaminant concentration in predator organisms to that in their food. For example, mercury is a toxic substance that tends to accumulate in organisms, and the mercury bio-magnification factor for the predator-prey pairs of seal/fish is 163, while for whale/fish it is as high as 305.

While contaminants in the marine environment can be dangerous for marine organisms, the bio-magnification of these same contaminants can threaten humans. This problem is well documented among the indigenous peoples of the Arctic such as the Inuit. Since they eat mainly fish, seals, and whales, they are exposed to the bio-accumulated and bio-magnified contaminants in these organisms. Systematic studies of Inuit tissues show significant contamination of organs with mercury and PCBs. The consequences of this contamination include cancers, immune, hormone and nervous system diseases, liver damage, and infertility.






Bio-accumulation and bio-magnification processes are illustrated using the example of the Arctic food chain.

Seals are known to accumulate organic contaminants such as PCBs and heavy metals such as mercury in their tissues.

## Oil and gas in the Arctic

Aleksandra Szczepańska

One consequence of global warming and the melting ice cap in the Arctic is that the strategic importance of natural energy resources and transport routes in this area are increasing. Preliminary studies conducted by Norwegian and American geologists indicate that 25 % of the world's energy resources, including up to 10% of its petroleum, are located in the Arctic. This represents approximately 90 billion barrels of oil and 50 trillion cubic meters of natural gas. Petroleum deposits were discovered in the Arctic Ocean region in the 1960s, and drilling began in 1971. Although the precise quantities of these valuable resources remain unknown, new deposits of petroleum are being found continually. Recent reports indicate huge quantities of petroleum in the Barents Sea estimated at about 200-300 million barrels; these are resources of the twin Norwegian Skrugard and Havis deposits.

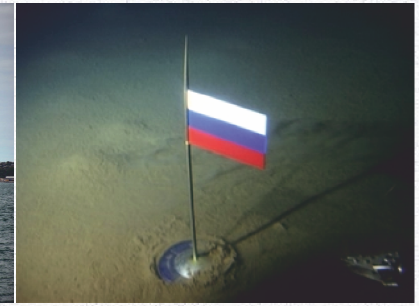
The petroleum-rich bottom of the Arctic Ocean has become a subject of great interest, and as such has sparked the beginning of the so-called "Cold War for the Arctic" that involves five countries with access to this region: the United States, Russia, Canada, Denmark, and Norway. The lack of legal status in the Arctic is the reason for this problem, but there are two theories. The first is that of the open sea, which dictates freedom of navigation, fishing, and scientific research as is observed in the open seas. The second is the sector theory, according to which states claim the areas of the Arctic that are adjacent to their territories. The boundaries of the individual sectors are determined by drawing lines from the north pole to the end point of the eastern and western land territory of the various states.

Competition for control of Arctic areas increased following the Russian "Arctic 2007" expedition, during which a Russian flag was deployed on the sea bottom, and the Russians announced that they have evidence to support their claim that a substantial part of the Arctic belongs to the Russian Federation. This referred to the Lomonosov Ridge, which, according to Russian studies, is an extension of the Siberian continental shelf. In response, Copenhagen announced that the Lomonosov Ridge is an extension of the Danish territory of Greenland. Meanwhile, Canada has made public plans to create new naval port at the northern end of Baffin Island. Negotiations among the states over these disputes have been on-going since 2007, and, according to some sources, a breakdown in them could lead to armed conflict.

Petroleum extraction in the Arctic has alarmed nature conservationists and scientists alike. The climate conditions in the Arctic render it impossible to stem any leakage using current technologies. In cold waters petroleum interacts with ice by penetrating into its structure, so it can be transported over vast distances from any leak. Additionally, cleaning up oil spills from ice-cold water is very difficult, which increases the likelihood of environmental disaster. One example of extreme environmental damage is the accident involving the Exxon Valdez oil tanker off the coast of Alaska in 1989, the consequences of which are still seen today.



Drilling platform in the northern Norway (photograph B. Szymczycha).



In 2007, the Russians placed a flag on the bottom of the Arctic Ocean, determining that the Lomonosov Ridge is a part of Russian territory (photograph Association of Russian Polar Explorers).


The five countries: the United States, Russia, Canada, Denmark and Norway are conducting "Cold War for the Arctic." The map shows the sectors, conventionally "belonging", to these countries and disputed territories (circled area) - the Lomonosov Ridge (illustration S. Węsławski).

## Methane clathrate in the Arctic

Jacek Piskozub

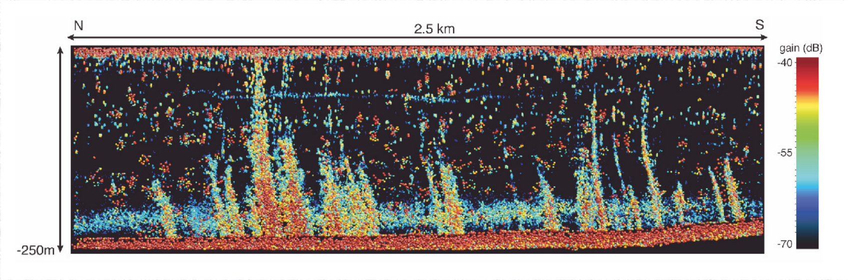
Methane ($CH_4$) is the second most important anthropogenic greenhouse gas. It is emitted naturally from wetlands, while anthropogenic sources include rice fields, biomass burning, and waste dumps. Its atmospheric concentration is at present about twice as high as in pre-industrial times. Increases in it seemed to halt around 2000, but recently it has started to rise again. This has sparked renewed interest in studying the role of methane in the global carbon cycle, especially in the Arctic. The rate of warming in the Arctic is much faster than the global average, and this could lead to the destabilization of the two large reservoirs of organic carbon: the permafrost on land and the methane clathrate beds under the sea bottom.

Large areas of the Arctic, mainly in Siberia, northern Canada, and Alaska are covered with permafrost deposits containing frozen organic matter. This organic matter can become a source of methane if consumed by methanogen bacteria in anoxic conditions. It has been estimated that the first three meters of permafrost alone contain about 1000 Pg of carbon, which could be transformed into 300 times the amount of methane presently in the Earth's atmosphere. This amount is a hundred times greater than present combined anthropogenic emissions of both carbon dioxide and methane. The warming of the permafrost could lead to irreversible thawing and carbon loss, which would act as positive feedback for global warming. Recent research has estimated that the permafrost could become a net source of methane by 2020, and the area of it could decrease within the next two centuries by 29 to 59 %.

Another possible source of methane in the Arctic is the clathrate beds under the sea bottom. Methane produced by microorganisms in the sediments is captured by the water ice crystal lattice and becomes methane hydrate. Under the cold Arctic Ocean, methane clathrate is stable at depths greater than 300 m. Recently, plumes of methane bubbles have been observed close to the western Svalbard shelf border and in waters off of east Siberia. In the Siberian waters, the area of the methane emission had a diameter of 1000 m. It is not yet clear if the methane fluxes in these areas were the result of recent warming or long-term processes that started at the end of the last glaciation. It is not even certain if the source of methane off Svalbard is clathrate deposits, since no isotope study of the methane from the bubble plumes has yet been performed.

Therefore, it remains impossible to say whether the recent discoveries of methane outgassing from the Arctic sea bed and the increased atmospheric concentration of $CH_4$ are because of improved research methods or if they are the result of the continual warming of the region that has caused the release of the gas from permafrost and clathrate beds. The renewed increasing trend of global atmospheric methane concentrations that was noted recently has been attributed mostly to tropical sources. Many processes controlling methane fluxes are still poorly understood.






Plumes of methane bubbles emitted from the sea bottom west of Svalbard observed using sonar from aboard the RSS James Clark in 2008. One of the plumes almost reached the sea surface (top of the figure). Reproduced with permission from Westbrook, G. K., et al. (2009), Geophys. Res. Lett., 36, L15608.

Blooming tundra hides permafrost, which is a massive reservoir of organic carbon (photograph A. Rozwadowska).

When writing about the geological history of the Arctic, or even just its European part, one cannot fail to address two basic issues that are universal to our planet.

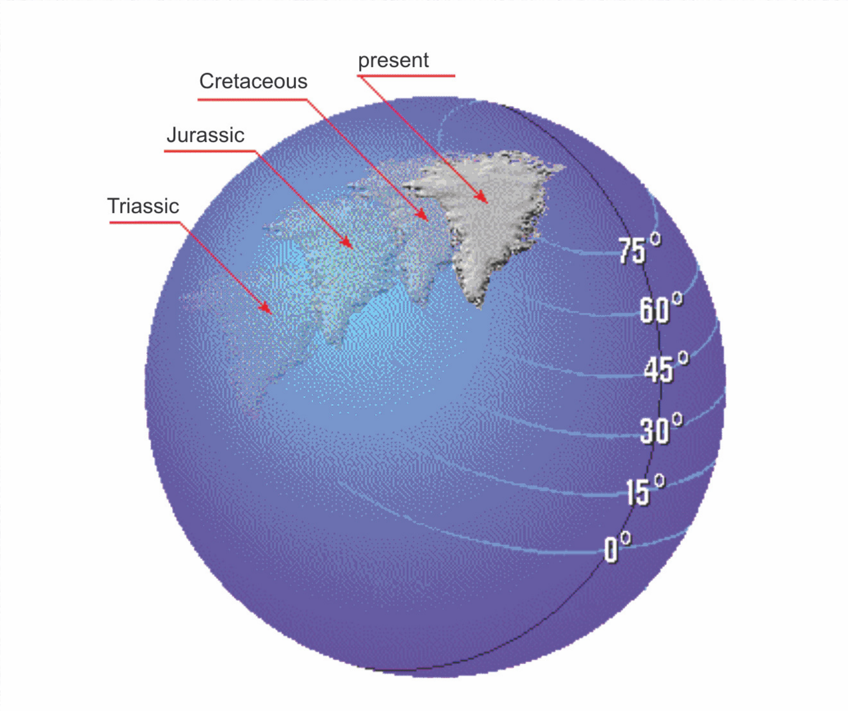
There are no stable points on the Earth, and its surface is in constant motion, which is an effect of the geological phenomenon known as "plate tectonics". The speed at which the plates move ranges from several millimeters to even as much as 10 centimeters annually.

The second basic issue is that the continental plates are formed from different materials than are oceanic plates. The continental part of the Earth's crust is thick and light, which allows it to rise significantly above sea level, while the oceanic plates are thin but heavy, so they remain at the bottom of the oceans. Continental plates are old, permanent elements of the Earth's crust. Oceanic plates are young and temporary elements that occur near oceanic ridges, or rift zones, and which spread before finally sinking into the Earth's crust in subduction zones where there is contact with continental plates. This process causes the continental plates to be in constant motion, and sometimes even collide.

The processes discussed above also occur in the Arctic Ocean. This region is divided into the Eurasian and Amerasian (and Canada) basins, but the authors of the latest studies of this area have recently identified the Norwegian-Greenland basin as a separate entity. The dormant Lomonosov Ridge divides the first two basins. Actually, in the Cenozoic period, the Earth's crust in the central Arctic ruptured along the Gakkel Ridge (Nansen) pushing apart the Lomonosov Ridge and the Barents Sea. While this process is on-going today, it is very slow at only approximately 2.6 mm annually. The Norwegian-Greenland basin lies between Greenland and the northwestern European shelf. The bottom in this area has a typically oceanic structure with a central ridge zone, the northern extension of which is the Gakkel Ridge. A vast hot spot and several transform faults in the southern ridge area near Iceland mean that tectonic processes in this area are highly dynamic.

The tectonic processes that formed the region of the north Atlantic and the Arctic began in the late Cretaceous period about 90 million years ago. Initially, the north Atlantic ridge ran to the west of Greenland pushing it away from the north American plate along the Labrador Sea. At this time Greenland was a separate continent, and not until the end of the Paleocene and the beginning of the Eocene periods about 55 million years age did the ridge to the northeast of Greenland become active and form, among other things, the Gakkel Ridge. Over the subsequent 20 million years tectonic processes in the east prevented Greenland from shifting away from North America and began creating the European Arctic by increasing the distance between the northwest European shelf slope and eastern Greenland. Finally, the Greenland plate shifted towards America and today these plates are considered to be one continental entity.






Changes of Greenland position towards the North Pole (compilation from different sources S. Węsławski).

## Formation of the ocean floor

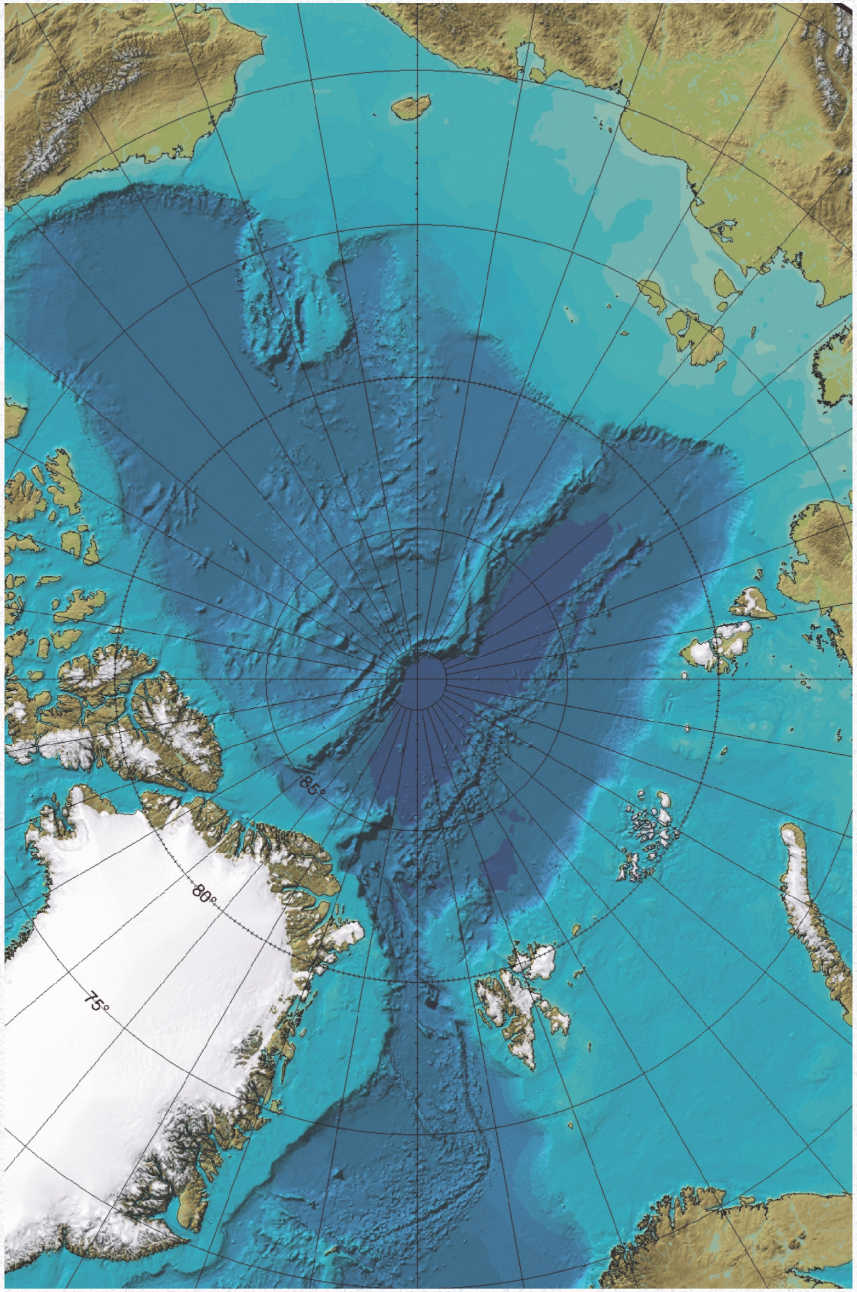
Marek Zajączkowski

The Arctic Ocean is surrounded by the continents of Europe, Asia, and America. Its surface area is approximately 1,4056,000 $km^2$, and its highly-developed coastline is 45,389 km long.

The Lomonosov Ridge, which extends from Ellesmere Island to the New Siberian Islands, divides the Arctic ocean into two basins with depths ranging from 4,000 to 4,500 m. The deepest area of 5,450 m is located in the Eurasian basin, while to the west of the Lomonosov Ridge the maximum depth is 4,683 m in the Beaufort Sea.

The Alpha Ridge in the Amerasian Basin connects with the Mendeleev Ridge, which extends from Ellesmere Island to Wrangel Island, and divides this area into the two smaller Makarov and Canada basins. The Fram Basin is situated between the Lomonosov and Gakkel ridges, but further to the south it is known as the Nansen Basin. This region's unusual system of oceanic ridges has been formed by intense tectonic activity, which, in turn, caused frequent environmental shifts here in the past. Events such as the tectonic opening of the Fram Strait increased the inflow of Atlantic waters into the Arctic Ocean. Eustatic changes in sea level affected the Bering Strait and regulated water exchange with the Pacific Ocean, and also permitted intermittent migrations of people across it from Asia to America. Many islands are located in the Arctic Ocean and these occupy a surface area of 3.8 million $km^2$. The largest of these include Greenland, Baffin Island, Novaya Zemlya, Spitsbergen, Ellesmere Island, Banks Island, Victoria Island, and Prince of Wales Island.

Today's Arctic Ocean is divided into eleven seas: Baffin, Barents, Beaufort, White, Chukchi, Greenland, Kara, Lincoln, Laptev, Pechora, and East Siberian. Most of these are shelf seas of relatively shallow depths, which means that parts of these seas were coastal plains when global ocean levels were lower. Currently, the Arctic Ocean is surrounded by the Earth's largest shelf region. The Russian part of the continental shelf is divided into three parts – the Barents, Siberian, and Chukchi. Shelf regions are particularly susceptible to changes in oceanic water levels and riverine inflows of terrestrial fresh waters carrying sediments. They act as filters that retain most of the eroded terrestrial minerals and other terrestrial and marine organic matter. This is also why many Arctic seas are rich in crude oil, natural gas, and various mineral ore deposits.




Arctic Ocean bathymetry (http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/currentmap.html)

## Arctic glaciers and ice

Marek Zajączkowski

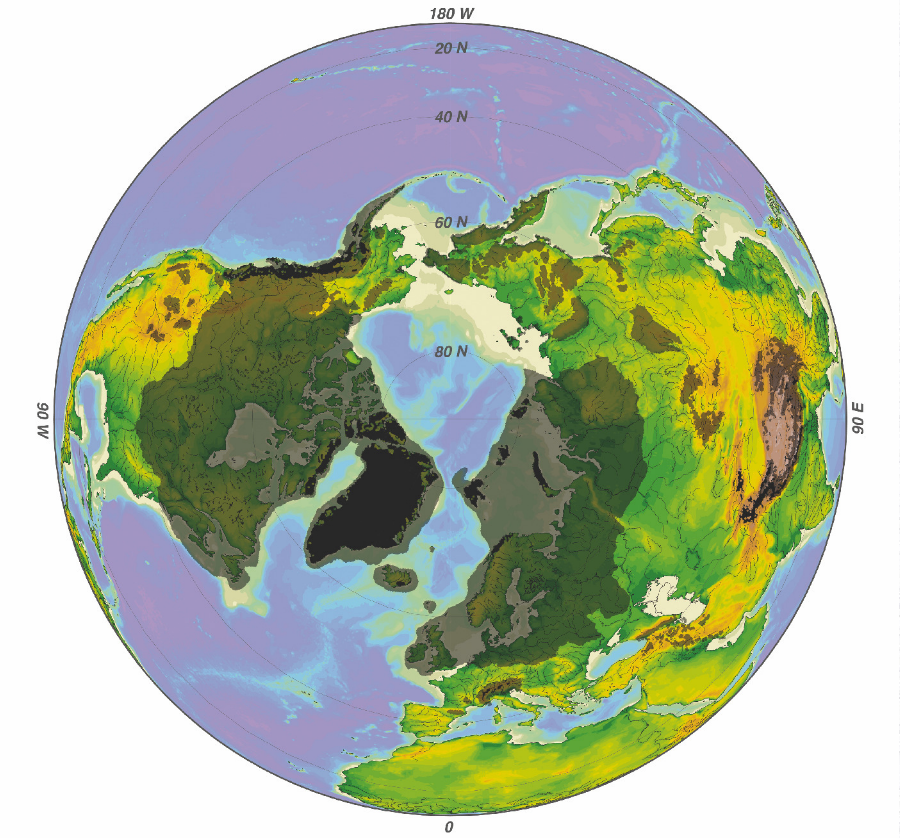
The Arctic ice cover, or the cryosphere, comprises glaciers, sea ice, and permafrost. The terrestrial portion of this is 3.1 million $km^3$ of ice, which is the equivalent of 8 m of water in the World Ocean at its current level. The distribution of Arctic ice is very uneven, and portions of it are found in highly varied climate regimes. The largest mass is the present-day Greenland ice sheet, which is more than four times larger than the glaciers in Alaska, Canada, Siberia, and Scandinavia combined.

During the glacial period in the Pleistocene epoch of the last ice age, the region covered with ice sheets was much larger than that of today. But larger does not necessarily mean that the entire Arctic was covered by ice sheets since they only form on land. In many instances, for example currently in the Antarctic, ice sheets push into the shelf regions thus creating floating ice barriers, but when ice sheets were at their maximum during the Pleistocene epoch the central region of the Arctic Basin was covered by sea ice, and not by ice sheets. In this period the ice sheets shifted significantly to the southern reaches of the Eurasian and North American continents. Many smaller ice caps joined in the shallow shelf seas and formed a uniform ice sheet cover, for example those in Canada or in the Barents and Kara seas. These ice sheets left a range of traces in the Earth, which, very briefly, can be categorized as follows:

- Geological – glacial striation, or scratches and gouges in rocks, u-shaped post-glacial valleys, moraines, drumlins, eskers, and kames;
- Chemical – stable isotope record in animal shells and carapaces and in air bubbles trapped in old, glacial ice formations;
- Paleontological – changes in the zoogeographic distribution of fossilized organisms.

The Pleistocene glacial period began approximately 2.58 million years ago at the end of the Pliocene Epoch. Since we are unsure if this period has ended, it is often referred to in the scientific literature as the modern glacial age. The record the Northern Hemisphere ice sheets left on the continent indicate four glacial and four interglacial periods, which, including the present Holocene Epoch, have lasted approximately 11,000 years. The deglaciation of the Arctic following the last glacial period has been very uneven. In the European arctic this has been linked to the intensified inflow of warm, highly saline Atlantic waters in the regions of the ice sheet edges meet the shelf line of the continent along Norway, the Barents Sea, and Svalbard. The ice sheet in the Barents Sea region rested on the bottom of this shallow basin in many locations. Approximately 13,000 years ago the warm Atlantic waters dissolved part of the ice cap joining Northern Scandinavia and Svalbard and then flowed to the east into the Barents and Kara seas. Records of this inflow were discovered by Prof. Lubinski of the University of Colorado in 2001. He reported that over 40% of the foraminifera identified in marine sediments dating from 13,000 to 10,000 years ago as the typically Atlantic species *Cassidulina teretis*. This discovery was also confirmed by the stable isotope record from the same period. After a rapid deglaciation period, there was a fast warming of the European Arctic during the Holocene Climate Optimum about 8,000 years ago. The Arctic climate has changed many times during the Holocene Epoch. We know that during the warmest period that the sea ice must have virtually disappeared in the Svalbard region, and that during this time the coastal rocks were covered with the thermophilic mussel *Mytilus edulis*, which occurs commonly today, for example, in the Baltic Sea. During the coldest Holocene period, which is known as the Little Ice Age, the glaciers of the Svalbard Archipelago and even northern Scandinavia advanced significantly, and the ice pack wiped out the mussel *M. edulis* from the Svalbard region






Maximal glaciation extent (http://en.wikipedia.org/wiki/ice_age).

Blue shell - thermophilic species of bivalve, indicator of the Arctic warming (photograph J.M. Węsławski)

The foundation of marine geology and paleoceanography rests firmly upon fossil records regardless of whether these are from marine sediment cores, glacier ice cores, or terrestrial rock layers. In order to retrace the history of a region under study, we have to know the age of the different layers. Age in glacier cores is read by counting the individual micro-layers, each of which represents the annual snow accumulation. Establishing the chronology of sediments is more complicated.

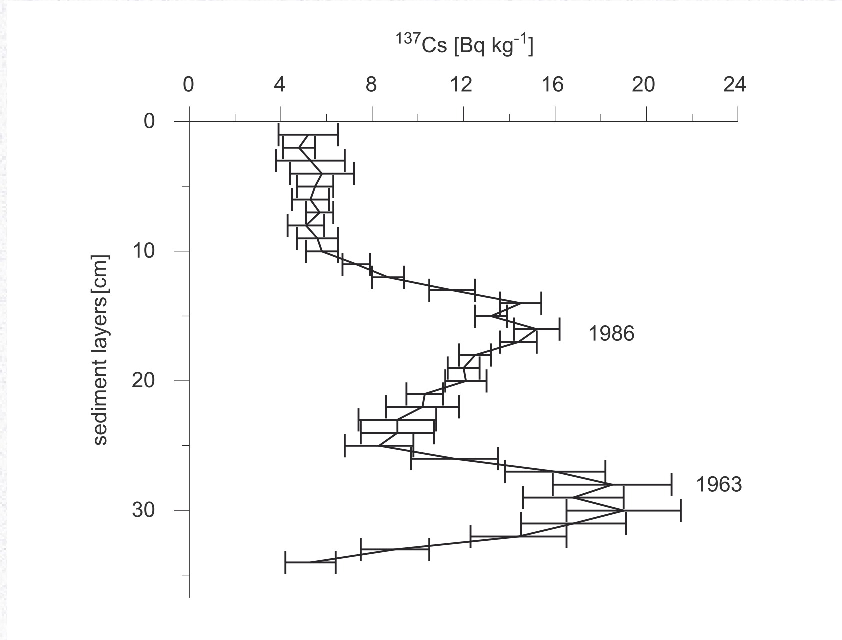
Radioactive carbon ($^{14}C$), which has a half-life of 5,740 years, is used most widely. This isotope is produced in the upper layers of the atmosphere when neutrons bombard nitrogen isotopes ($^{14}N$), and its quantity in the Earth's atmosphere is known and remains at relatively stable proportions in comparison to the stable carbon isotopes of $^{12}C$ and $^{13}C$. Throughout their lives, living organisms exploit all of the available carbon isotopes, and at the moment of death the isotope compositions of shells, bones, or wood mirror precisely those in the surrounding environment. Whereas stable carbon isotopes remain unchanged, half of the radioactive carbon decays over 5,740 years. Sediment layers are dated by measuring radioactive carbon decay. This method performs well within a range of 75,000 years. Radiocarbon dating requires additional calibration because one of the factor that impact it is past solar activity. When solar winds increase, plasma concentrates along the force lines of the Earth's electromagnetic field, and colliding cosmic rays produce the phenomenon of the aurora borealis. During these periods, the production of radioactive carbon decreases. However, sometimes very distant astrophysical phenomena such as supernova explosions or gamma ray bursts increase the amount of cosmic radiation, and the production of radio carbon in the Earth's atmosphere increases. The figure opposite presents the calibration curve used in radiocarbon dating calibration calculations. This graph illustrates the strong flattening of the curve about 10,000 years ago that renders calculating precise dates in this period problematic.

The radioactive lead isotope $^{210}Pb$ is used for dating within a period of 100 years. It is in the natural uranium-radium range, and the amount of it in bottom sediments depends on the quantity of the longest-living primordial radionuclide, i.e., $^{226}Ra$. $^{210}Pb$ remains in radioactive equilibrium with $^{226}Ra$ in the deeper sediment layers because it is formed there continually. A certain excess of $^{210}Pb$ is found in the surface sediment layers because it is taken up from the water by sedimenting particles. This lead, generally in a gaseous state, is found in both the atmosphere and water. Sedimenting particles take up this extra lead, and dating is done by calculating its decay in the sediment layers. Because the half-life of $^{210}Pb$ is about 22.26 years, after approximately 100 years the extra part of radioactive lead is too small to measure.

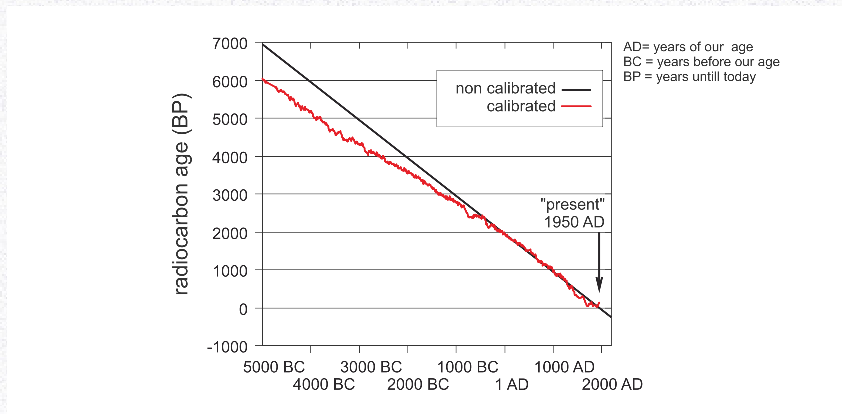
Radionuclides that enter the environment from either nuclear tests or accidents are often used when dating contemporary sediments. European Arctic sediments exhibit a distinct peak in cesium ($^{137}Cs$) following the intense nuclear testing conducted on Novaya Zemlya in 1952 with a maximum in 1963, and another peak in 1986 after the Chernobyl nuclear power plant catastrophe. The figures opposite illustrates an example of dating contemporary sediments using $^{210}Pb$ and $^{137}Cs$.

In addition to the methods described above, many other radioactive isotopes with substantially longer half-lives are used to date rocks of different ages. The uranium-thorium dating method provides the absolute dates of rocks rich in calcium carbonate within a range of 500 to 50,000 years, while the potassium-argon method can date rocks that are millions of years old. However, the rubidium radionuclide $^{87}Ru$, with its half-life of more than 48.6 billion years, is used to date the oldest rocks, which are over 100 million years old.






This figure illustrates the activity of cesium $^{137}Cs$ in the sediment layers of Adventfjord on Spitsbergen. The two distinct peaks in the activity of this artificial radionuclide indicate the sediment layers deposited on the fjord bottom during the Chernobyl nuclear power plant catastrophe and during the intense nuclear testing period conducted by the USSR in the 1960s. Since all of the sediment layers studied contain radiocaesium, the deepest layer studied was deposited on the fjord bottom in the year following the first above-ground nuclear test on Novaya Zemlya in 1952 (Zajączkowski et al. 2004).




Calibration curve for the radiocarbon dating scale. Data sources: Wikimedia Commons (Stuiver et al. 1998).

## Arctic carbonate banks

Tomasz Borszcz

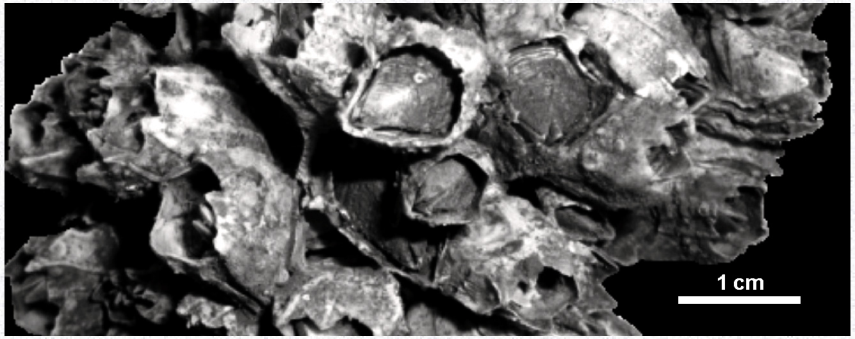
Every year large numbers of Arctic sea urchins, mussels, and barnacles die, but what happens to their shells afterward?

Taphonomy, the scientific discipline of studying the decomposition of organisms, can respond to this question. The answer lies at the bottom of the open sea dozens of kilometers away from the shores of the Svalbard Archipelago. This is where dead shells are deposited forming vast shoals full of complete and broken shells. Dating indicates that these remains can survive on the seabed for more than 9,000 years. Because of their size and mineral composition, these deposits are known as "carbonate platforms" or "carbonate banks". They can be as thick as a few meters with surface areas many thousands of times larger than a football field. The vast cemetery at the Svalbard Bank in the Barents Sea is currently inhabited by dozens of benthic organism species. The species composition differs from that of the shell bed and reflects the selectivity of the formation of the fossil record. The presence of encrusters such as bryozoans, calcareous algae, and barnacles is noteworthy. Empty shells and fragments provide habitats for various organisms, including encrusters. This type of recycling, also known as taphonomic feedback, occurs when the shells of once-living organisms remain in an ecosystem making life possible for future generations. The shell surfaces are marked by traces of bioerosion, including drilled holes, pits, or burrows that were made by predators when the shells were still occupied by living organisms or by algae and polychaetes after their inhabitants had died. The matting and etching marks also visible on shell surfaces provide evidence of transport from places where the organisms had lived to where the shells were found in samples. Because of the lack of calcium carbonate precipitation from seawater and strong local currents that preventing diagenesis, these shells lie loose on the bottom. Above all else, it is the balanuliths, known as the "crowns of the Arctic", that command the most attention on the carbonate platforms. These three-dimensional mobile structures form when barnacle clusters separate from their original substrates such as stones or other shells, and are subsequently overgrown by other organisms like bryozoan colonies, hydrozoans, or polychaetes tubes. Computer microtomography is used to revealed their complex genesis involving many generations of barnacles.

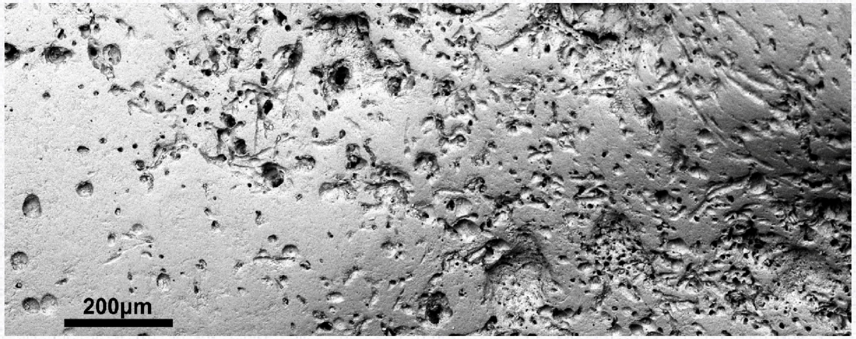
Arctic shell beds hold a variety of valuable information that is of interest to biologists, climatologists, ecologists, geochemists, sedimentologists, and paleontologists. Since water can easily penetrate the spaces between large shell fragments, these banks are also important as three-dimensional, permeable matrixes. Just like in sewage treatment plants, microorganisms inhabit the banks and consume suspended matter so the banks function as huge biocatalytic filters. Banks of carbonate shells also play important roles in the carbon cycle.



Sample of live macrofauna and dead shells aboard the r/v Oceania in the Barents Sea (photograph Ingrid Elingsen)




Balanulith – a cluster of barnacles colonized by a succession of organisms (photograph Tomasz Borszcz)




Magnified surface of an empty shell with traces of bioerosion left by other living organisms. (photograph Tomasz Borszcz)

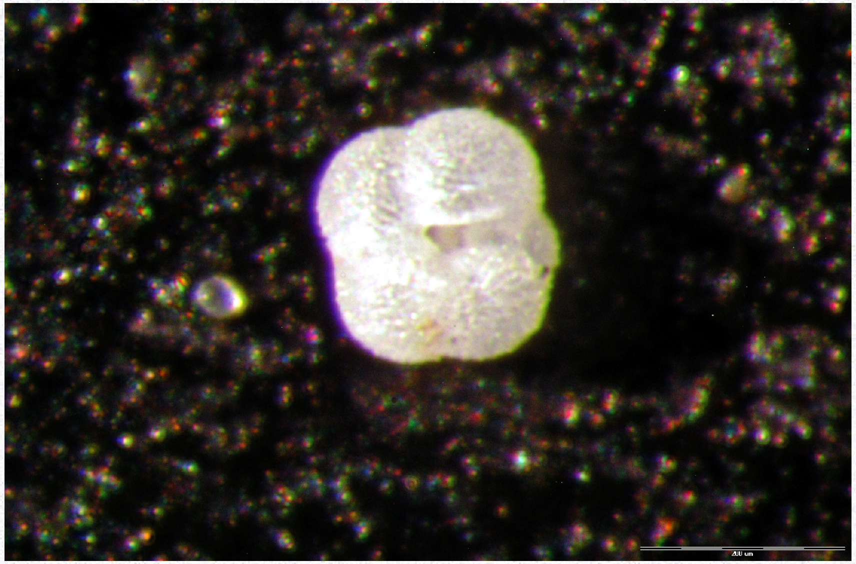
## Paleoceanography

Marek Zajączkowski

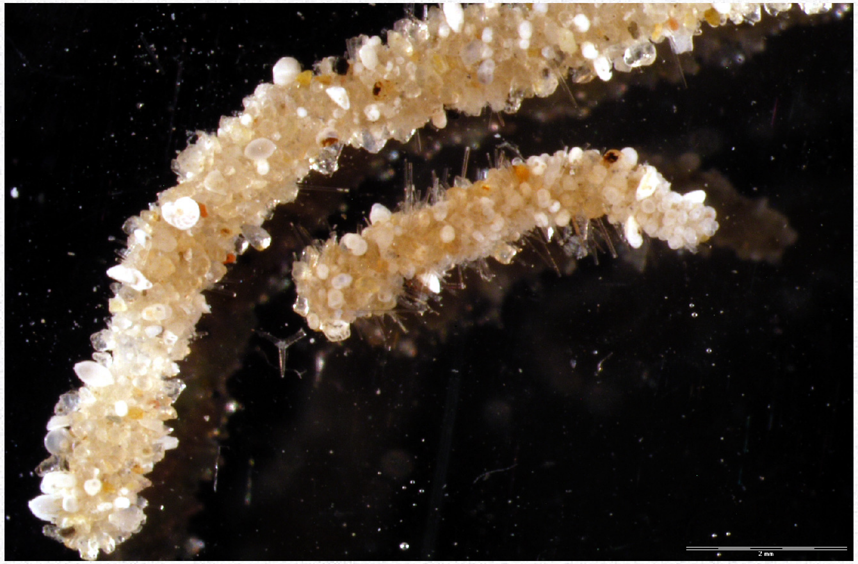
Paleoceanography is the scientific study of the history of the oceans which focuses on historic oceanic water circulation, sedimentation processes, biological processes, and temperature and salinity regimes. All of these parameters are of fundamental significance in shaping Earth's climate. The history of these phenomena are recorded in marine sediments and can be read using a variety of indicators. Foraminifera are one of the most frequently used tools for this type of study in the Arctic region since their calcium carbonate shells are preserved in the marine sediments in excellent condition for thousands of years and as fossils for millions of years. If we know the environmental preferences of the various species of these organisms, then we can recreate the conditions in which they lived. The arrangement of cells in the shells of some of these species change in response to environmental stimuli. One example is Neoquadrina pachyderma (photograph): when this organism inhabits cold, Arctic waters the shell coils to the left, while in warmer environments, such as in Atlantic waters, they coil to the right. By analyzing the proportion of left- and right-coiling shells in sediment layers, we can reconstruct the surface water temperatures of the ocean and, thus, the layers in which these organisms lived before falling to the sea bottom.

The history of ocean temperatures can be reconstructed more accurately using the stable oxygen isotopes $^{16}O$ and $^{18}O$ that are contained in the calcium carbonate shells of foraminifera. The quantities of these isotopes on Earth are constant, but their distribution varies depending on many factors, including glaciation. Water molecules with lighter oxygen isotopes evaporate more easily, which is why water vapor above both oceans and inland fresh waters is isotopically lighter. If nothing disrupts the return of these waters to the ocean, then the isotope composition of the seas remains unchanged. But if the land is covered by glaciers, a large portion of light oxygen isotopes are trapped in the ice, and oceanic waters become enriched with a large portion of heavier oxygen isotopes. The shells of foraminifera, which inhabit these environments, are also enriched with the heavier oxygen isotope. Based on isotopic analyses, IRD fractions, and the species composition of foraminifera, Gerard C. Bond of Columbia University in New York determined in 1997 that over the past 12,000 years the temperature of the surface waters in the northern Atlantic varied cyclically. He estimated the cycle to be approximately 1,470 (±500) years long. Changes in the temperatures of the surface layers of the ocean indicate changes in the climate practically throughout the entire Northern Hemisphere of the Earth. This discovery was further confirmed during analyses of ice core samples from central Greenland. The record of stable oxygen isotopes in the ice permitted tracking cyclical changes in air temperature that occurred over the past 125,000 years. Age in this instance is limited by the thickness of the Greenland ice sheet. Scientists are not in agreement as to the cause of this phenomenon. Many researchers agree with the hypothesis that climate cycles correspond strictly with changes in thermohaline circulation, which is the large-scale circulation of oceanic waters caused by changes in temperature and salinity. However, other scientists ascribe this phenomenon to changes in solar activity, or the 1,800 year cycle of oceanic currents linked to the geometric movement of the Moon around the Earth.





*Neogloboquadrina pachyderma* left-coiled (photograph M. Zajączkowski).



*Mediomastus fragilis* (photograph M. Zajączkowski).

## Primary production in the Arcic

Józef Wiktor

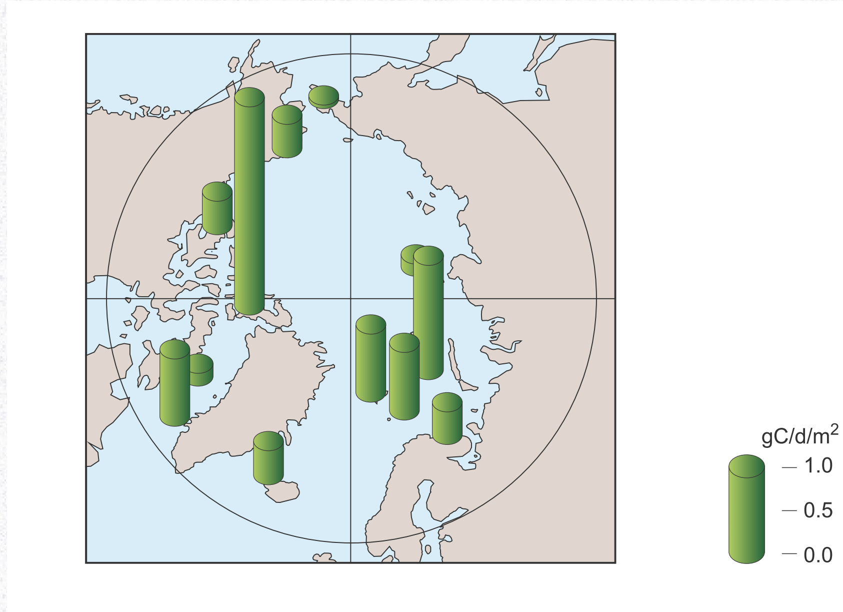
In a nutshell, primary production is the amount of organic matter produced by autotrophic organisms through photosynthesis. Sunlight, and especially the spectra between 400 and 700 nm, is used to perform photosynthesis. Unlike other places on the earth, where solar radiation reaches the surface of the planet throughout the year, the polar areas experience extreme seasonal variability in light intensity. This is because of the phenomena of the polar night and day. The time spans of total darkness and midnight sun depend on latitude; they last longer with closer proximity to the pole, where the Sun does not set for six months, and then it does not rise for another six months. Further, even when the Sun is visible above the horizon, this does not necessarily mean that its life-giving light penetrates the waters. In the polar regions, even in the summer the Sun is relatively low above horizon, and sun rays reach the sea surface at an acute angle, which means that most of its radiation is reflected.

Since the surface area of the marine Arctic is only 2.6 % of the World Ocean, its primary production is not impressive. Of the 400 billion tons of organic carbon assimilated by the World Ocean, only 300 millions tons (0.08%) are assimilated by Arctic waters. The Central Arctic Basin, which is half of the total area, is located off of the continental shelf. The organic matter produced there in the euphotic layer, which is that into which light penetrates, sinks down irrevocably to depths of 4,000 m. The other half of the area is located over shallow shelves, where the deposited organic matter can be mineralized, or transformed into simple compounds, resuspended from the bottom, transported to the surface, and then reused by primary producers. This process is reflected in the amounts of carbon assimilated by autotrophs. In the shelf seas, as much as 279 million tons of organic carbon is produced, as compared to the approximately 50 million tons (over five times less) produced in the central basin.

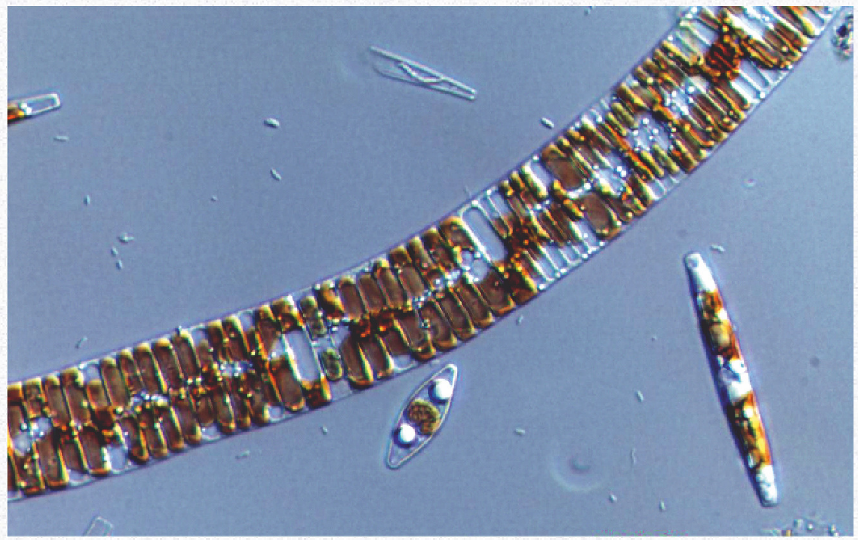
The cells of the planktonic autotrophs in shallow areas can survive winter on the bottom, and are again transported to the photic layer by storms, which are quite common there. The water column of the central basin hosts few organisms. The majority of organisms it does host are associated with sea ice, which, in turn, in usually comes from the shelf seas where freezing occurs the earliest. Half of the organic carbon is produced by ice-associated algae in the central basin.

The primary production rate varies seasonally, and it is reflected in the qualitative-quantitative composition of the microplankton community. There is no production during the polar night, but then when it peaks during the bloom, the maximum is 5,000 mg * C * $m^{-2}$ * $day^{-1}$. During the summer, this falls to a value of between 100 mg * C * $m^{-2}$ * $day^{-1}$ and 400 mg * C * $m^{-2}$ * $day^{-1}$, while in the fall it drops even more to 50 – 300 mg * C * $m^{-2}$ * $day^{-1}$. These values refer to the shelf seas. The production rate in the central basin in spring does not exceed 10 mg * C * $m^{-2}$ * $day^{-1}$ under the ice, while at the bottom 10 cm of the ice column it can simultaneously reach values as high as 300 mg * C * $m^{-2}$ * $day^{-1}$.






Primary production in Arctic (compilation from different sources, illustration S. Węsławski).



*Fragilariopsis* - one of more than 300 diatom species associated with the sea ice (photograph J. Wiktor).

## Unicellular plankton

Józef Wiktor, Agnieszka Tatarek

Every system requires energy to function. This is also true of ecosystems, and the most obvious source is the Sun. The problem is how to store energy. Some organisms develop a number of specializations that allow them to utilize the Sun's energy to feed themselves, and these are called autotrophs, or primary producers. On land these are mainly plants, but in the oceans this niche is occupied by single-celled organisms that include protists and bacteria, which are the unicellular ancestors of plants. They compensate for their minute sizes by occurring in high abundances, and they are responsible for the surprisingly high share of about half of global organic carbon production. These microscopic beings are the foundation of all trophic relationships in the seas. In the high Arctic beyond the frontier of the forests, even near-shore terrestrial ecosystems are dependent on the energy produced by microplankton and then transported from the sea to the land.

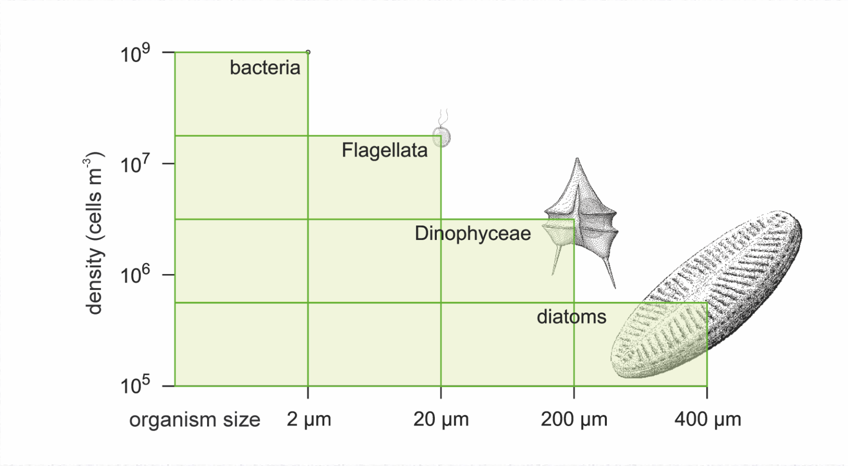
Unicellular plankton does not consist solely of primary producers, and many species, which have either lost the ability to photosynthesize or never could, feed on autotrophic plankton.

The term "unicellular plankton" is a broad one that includes a variety of forms and sizes, and it can be divided into smaller fractions, as follows: ultraplankton ( < 1 µm ), pikoplankton ( < 3 µm ), nanoplankton (3 µm – 20 µm), and microplankton ( 20 µm > ). On a human scale, these sizes range from that of a small fish to that of a small town. The abundance of these species depends on how large the cells are: the smaller the cell, the more cells there are. Because of this, the smallest species contribute the largest share to the total biomass of unicellular plankton.

The smallest planktonic protists in the Arctic are flagellates that are as small as 3 micrometers, and this makes it difficult, if not impossible, to determine their taxonomic affinity under a microscope. Among theses flagellates are species that feed on bacteria and organic particles, as well as autotrophic ones. At the other end of the scale one finds organisms measuring somewhere between 500 and 1,000 micrometers. Again, theses giants can be autotrophic or heterotrophic. The first group is represented mainly by diatoms, while the second comprises dinoflagellates and ciliates that feed on smaller representatives of unicellular plankton. The unicellular plankton of Arctic waters belong to three kingdoms. Plantae is represented by green algae; Chromista by diatoms, dinoflagellates, haptophyta, ciliates, and cryptophyta; and Protozoa includes euglenophyta and choanoflagellates.

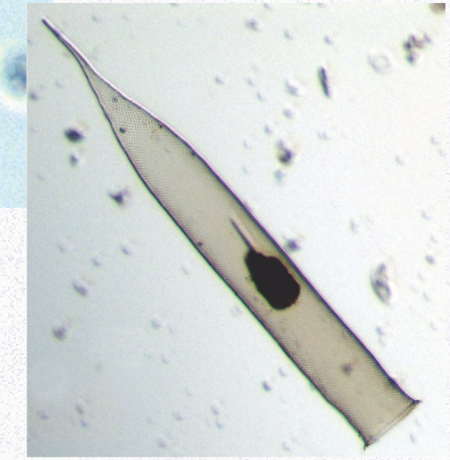
One of the most outstanding features of the Arctic is its very strong seasonal environmental changes that facilitate subsequent changes in plankton composition and abundance. During the winter polar night, the number of individuals rarely exceeds 500 cells per liter of water, and most of those found are minute flagellates. This is not surprising, because there is no light for primary producers, and barely any food for any others. Most of the cells have already died and sunk to the bottom. The rest are frozen in the ice, or lying on the bottom waiting for more advantageous conditions and slowly consuming their stores. In the spring, the Sun rises and stays in the sky longer. This is when the the massive proliferation of some autotrophic species happens. The algae bloom begins on the submerged sides of floating ice, and then it moves into the water column. These organisms are mainly diatoms, which zooplankton consume eagerly. Zooplankton, in turn, is prey for larger animals. That which is not consumed or recycled in the water column, sinks to the bottom and provides benthic communities with fresh supplies.






Density of unicellular plankton is inversely proportional to the size of the organism (illustration S. Węsławski)


dinoflagellate – *Gymnodinium* sp. (photograph J. Wiktor)



ciliate – *Parafavella* sp. (photograph J. Wiktor)

## Zooplankton

Sławomir Kwaśniewski

Zooplankton, from the Greek *zoon* or animal, is a taxonomically and structurally diverse group of heterotrophic organisms that dwell suspended in waters at all depths, have limited mobility against water currents (*planktos* or drifter), and live as plankton for part of or throughout their lives. Zooplankton is categorized according to different criteria, the first of which, for practical reasons, is size, as follows: pico-(<2 µm), nano-(2-20 µm), micro-(20-200 µm), meso-(0,2 - 20 mm), macro-(2-20 cm), and megazooplankton (> 20 cm). Zooplankton organisms play important roles in biogeochemical cycles since they are consumers of the first and subsequent levels and also serve as food for other predators inhabiting the water column and the sea floor.

In the Arctic and subarctic seas, zooplankton is represented by both unicellular and multicellular organisms. The unicellular organisms include representatives of the kingdoms Chromista (Phylum Foraminifera/foraminiferans, Cryptophyta/cryptomonads, Myzozoa/dinoflagellates, Ciliophora/ciliates) and Protozoa (Sarcomastigophora/radiolarians). The multicellular organisms from the kingdom Animalia include Cnidaria/jellyfishes, Ctenophora/comb jellies, Platyhelminthes/flatworms, Mollusca/molluscs, Annelida Polychaeta/polychaetes, Arthropoda Crustacea/crustaceans, Bryozoa/bryozoans, Chaetognatha/chaetognaths, Echinodermata/echinoderms, and Chordata Tunicata/tunicates. In the broad definition of zooplankton, larval and juvenile fish (Chordata Pisces) are also included as ichthyoplankton. The taxonomic composition of unicellular zooplankton comprising the categories of pico-, nano-, and microzooplankton, has not been well studied; however, there is scientific evidence that these organisms, as they function in the microbial loop, are the main consumers of primary production in pelagic ecosystems.

The most important multicellular organisms in the zooplankton of the European Arctic seas are crustaceans, among them copepods, including *Calanus finmarchicus*, *C. glacialis*, and *C. hyperboreus*, *Metridia longa*, *Paraeuchaeta norvegica*, *Pseudocalanus minutus*, *Microcalanus pygmaeus*, *Oithona similis*, and *Triconia borealis*. These species constitute the bulk of the mesozooplankton, a biotic assemblage representative of the main animal primary level consumers, and they comprise typically herbivorous (*Calanus*), omnivorous (*Metridia*), and predatory forms (*Paraeuchaeta*). The mezozooplankton also includes cladocerans, ostracods, appendicularians, and chaetognaths.

Typical zooplankton comprises holoplankton organisms, which live in planktonic mode throughout their life history. In addition to the taxa mentioned above, several others are also included such as jellyfishes, siphonophores, pteropods, euphausiids, amphipods, and rotifers. Meroplankton is a separate category that includes organisms that adopt a planktonic lifestyle only at certain stages of their life history. The meroplankton in the European Arctic seas is represented by larval stages of benthic organisms such as bivalves, polychaetes, cirripedes, bryozoans, and echinoderms. Meroplanktonic organisms are also those jellyfish species that go through the polyp stage, as well as developmental stages of benthic decapods and salps. Pseudoplankton, or tychoplankton, are also noted and include organisms that lead a planktonic lifestyle occasionally or temporarily.

Zooplankton is also categorized by a) the type of habitat the organisms occupy such as zooplankton of the epipelagic, mezopelagic, or bathypelagic zones, neustonic zooplankton of the surface layer, or epibenthic zooplankton of the bottom layer, b) feeding preferences including zooplankton that feed on plant or animal food, omnivores, or detritivores, and also c) food acquisition – phagotrophic, filtering, or predatory zooplankton.



*Calanus finmarchicus* and *C. glacialis* are two of the most characteristic, important copepods of the Arctic and subarctic seas.



*Paraeuchaeta barbata* and *Oithona similis* are two copepods that illustrate body size range.

Nauplius Cirripedia and the postlarval form of Polychaeta are characteristic representatives of meroplankton.



*Boroecia maxima* is a planktonic ostracod typical of the zooplankton of the mezopelagic zone, which is the middle depth of the ocean.

## Macrozooplankton

Marta Głuchowska

Plankton organisms larger than 2 cm that are visible to the naked eye are defined as macrozooplankton. The number of species in this group, in comparison to mesozooplankton (0.2-20 mm), is considerably low. Macrozooplankton consists of organisms that are rich in energetic reserves such as crustaceans (euphausiids, amphipods, larvae of decapods). Others, like pteropods, ctenophores, cnidarians, tunicates, and arrows, which body includes over 90 % of water, are often referred to gelatinous zooplankton.

Euphausiids, commonly known as krill, are pelagic crustaceans that have a transparent shrimp-like body and bioluminescent organs. Adult specimens usually grow to the size of 2-5 cm. The term krill originates from the Norwegian *kril*, which means "small fish fry". Euphausiids from the genus *Thysanoessa* are crucial consumers of primary matter produced by phytoplankton. Moreover, they are food for fish, birds, and mammals, and, thus, constitute an essential element of the food web. Worldwide, there are 85 known species of euphausiids, of which only eight are found in Arctic and sub-Arctic waters.

Important species of macrozooplankton include the amphipods *Themisto libellula* and *T. abyssorum*, the adult specimens of which are a few centimeters long. Many scientists believe that these crustaceans, together with euphausiids, perform similar roles in the Arctic and sub-Arctic food web as that of krill in the Antarctic.

Pteropods, commonly known as "sea butterflies", have adapted to pelagic life through the evolution of their foot into two wing-like flaps that facilitate swimming. The herbivorous *Limacina helicina* and the predatory *Clione limacina*, which feeds on the former, are abundant in Arctic waters.

Although there are not many ctenophores in the Arctic, some species can occur in large numbers. A characteristic feature of their morphology is the presence of eight rows of cilia, which are used for locomotion. The most beautiful, and also the most abundant, ctenophore in Svalbard waters is *Mertensia ovum*. Its two contractile tentacles make it easier for it to hunt its prey, which is mainly small copepods. Large Beroe cucumis of up to 30 cm are devoid of tentacles and feed on other ctenophores.

Cnidarian macrozooplankton species are typical jelly fish, and can paralyze and kill their prey using cnidocytes. Representatives of the two dominant classes, hydrozoans and scyphozoans, range in size from a few mm to 2 m. The majority of these predatory species occur in the upper 50 m of the water column. The most abundant hydrozoan in the Arctic is *Aglantha digitale*, but the boreal scyphozoan *Cyanea capillata* is often noted in the waters surrounding Svalbard.

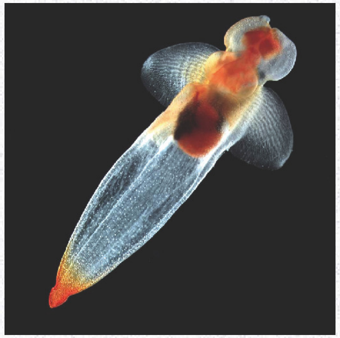
Sea arrows from the phylum Chaetognatha – arrow worms, have a transparent and elongated body reaching sizes of up to 5 cm. The two dominant species in the Arctic are Parasagitta elegans, which is more common in cold waters, and *Eukhronia hamata*, which is characteristic of warmer Atlantic waters. Both species are carnivorous predators that feed on small planktonic crustaceans.

Depending on the species, appendicularians are either classified as meso- or macrozooplankton. They have short oval bodies with relatively long tails. The majority of species build characteristic mucus "houses" that serve both feeding and body protection functions. Only a few species are noted in Svalbard waters, and they appear in large numbers in summer, especially in the surface waters.



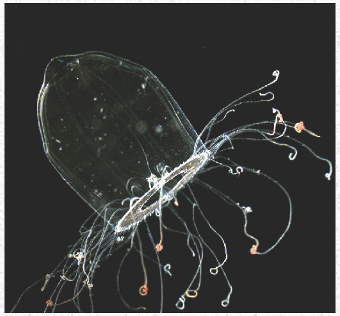
*Thysanoessa inermis* is the most important euphausiid of Arctic-boreal origin in Svalbard waters (photograph R. Hopcroft).

*Themisto libellula* is a crustacean characteristic of Arctic waters (photograph R. Hopcroft).



*Clione limacina* is a predatory pelagic sea butterfly (photograph R. Hopcroft).

*Beroe cucumis* is a ctenophore that feeds on other ctenophores (photograph K.A. Raskoff).



*Aglantha digitale* is the most abundant hydrozoan in the Arctic (photograph K.A. Raskoff).

*Parasagitta elegans* is a arrow typical of cold waters (photograph R. Hopcroft).

## Ice flora and fauna

Marta Głuchowska

Sea ice is a year-round, drifting platform rich in food. In Arctic waters, 25 % of the organic matter is produced by ice algae comprised mainly of diatoms and autotrophic flagellates. The annual primary production of the sea ice ranges from 5 to 15 $g \cdot cm^{-2} \cdot year^{-1}$, and the spring bloom begins much earlier there than in the water column. The organic matter accumulated in the sea ice originates from local production as well as it is added by waves and animal migration.

Not only do heterotrophic protists, fungi, and bacteria live under the ice and in its cracks and crevices, but so do multicellular animals. Some of these organisms are permanently linked with this habitat, and are autochthonous, while others inhabit the sea ice only temporarily, and are allochthonous.

The brine-channel systems are inhabited by small animals such as rotifers, nematodes, and turbellaria. The abundance and biomass of ice fauna, or cryofauna, similarly to ice algae, increase with ice thickness and are highest in the bottom parts of the ice where stressful fluctuations in temperature and salinity are smaller and the ice spatial structure is more sophisticated.

The border between the ice and water is an important habitat for many arctic species, especially for large herbivorous amphipods of the family Gammaridae - *Gammarus wilkitzkii*, *Apherusa glacialis*, *Onisimus nanseni*, and *O. glacialis*. The species composition and distribution depend on various factors, among which the origin and age of ice as well as the physical and biological properties of surrounding waters seem to be of major importance. The biomass of ice fauna in the multi-year pack ice located north of Svalbard can reach as much as 6 $g \cdot m^{-2}$ (wet weight). In terms of both abundance and biomass, *Gammarus wilkitzkii*, the largest ice-associated crustacean, is dominant here. The cryofauna in the one-year ice in the southeastern part of the Barents Sea does not exceed 2 $g \cdot m^{-2}$, and Apherusa glacialis is the most abundant species.

Large numbers of copepods, as well as many other pelagic organisms such as pteropods, siphonophores, tunicates, arrow worms, amphipods, and the larvae of benthic organisms are observed in water column under the sea ice.

Under-ice fauna serves as an important source of food for fish, sea birds, and mammals. The polar cod (*Boreogadus saida*), which feeds on copepods and amphipods, is a key species for the Arctic food web. Huge under-ice shoals of polar cod and ice amphipods are easily accessible, calorific food for predatory birds and mammals. Polar bears and seals use the ice pack as a platform for relaxation, reproduction, and feeding.

The reduction of ice cover observed in recent years poses a significant threat not only to ice fauna, where many endemic species are found, but also to dependent predators.



Gammaridae – a key for ice ecosystem amphipod families inhabiting the border between ice and water (photograph S. Harper)

*Apherusa glacialis*
(photograph Bluhm & Gradinger)

*Gammarus wilkitzkii*
(photograph Raskoff)

*Onisimus nanseni*
(photograph S. Kwaśniewski)

## Meiofauna

Lech Kotwicki

Meiofauna forms comprise the most numerous ecological group of seabed organisms inhabiting a spatial range from tidal flats to the ocean deeps. Almost all taxonomic groups are represented in the meiofauna, and is represented by organisms that can pass through mesh size of 0.5 mm and are retained on 0,03mm mesh. The average density of meiofauna is a few thousand specimens per $10cm^2$ of sediment surface. The most numerous are Nematoda, which comprise from 50 to nearly 100% of the meiofauna density. The next are the minute Harpacticoida crustaceans that belong to Copepoda. In coastal areas where permeable sediments prevail, other taxonomic groups such as flatworms belonging to Turbellaria, can occur abundantly. The density and taxonomic structure of the meiofauna depends on food accessibility and the physicochemical properties of the sediments. Organisms living in porous sediments have special adaptations that allow them to inhabit interstitial spaces. These can include elongated, elastic bodies, dorso-ventral flattening, armor, and internally placed organs and musculature, all of which permit free movement through the sediments.

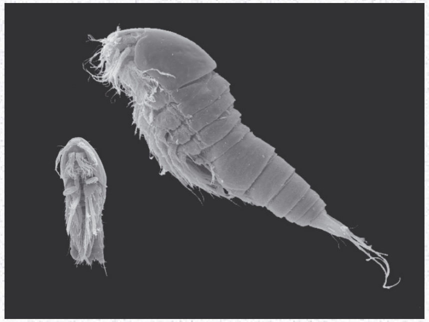
The main food source for meiofauna is fine organic particles, or detritus, unicellular organisms like bacteria and diatoms, as well as dissolved organic matter that is absorbed thorough body walls. Carnivory is also common, especially among nematodes and flatworms.

The meiofauna is linked significantly, both directly and indirectly, with key processes occurring in the sediments. These include organic matter decomposition, nutrient turnover, and the stimulation of bacterial growth. Meiofauna is a good food source for larger organisms like macrofauna and small fish. It can also serve as an indicator of environmental conditions, because it reacts quickly to changes in the environment. The many species of meiofauna are very abundant, so it is possible to find specific species that react to specific stressors.

The occurrence of meiofauna in the Arctic does not differ from other regions in terms of biomass or density. In Svalbard Archipelago coastal waters, where food is abundant, meiofauna can number over 10,000 ind/$10cm^2$, which is comparable to that in similar habitats in temperate regions. The shallowest waters that freeze to the bottom every winter can be temporarily devoid of meiofauna until the melting season finishes, then meiofauna recolonizes defaunated sediments in just a few days.

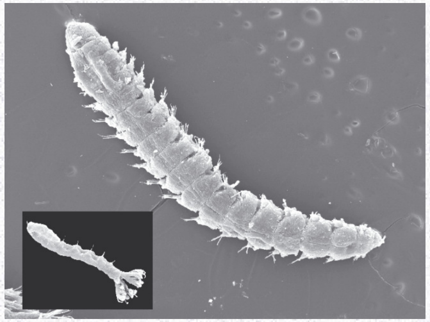


Nematoda

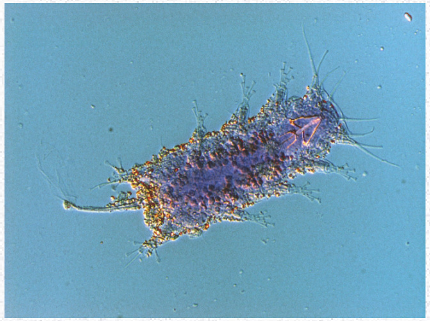


Harpacticoida

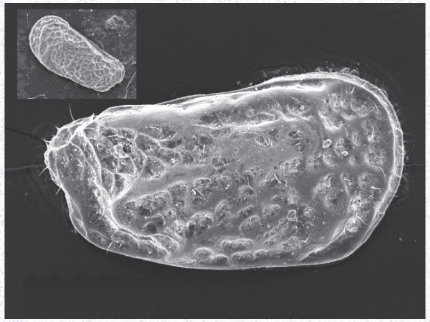
Turbellaria



Poychaeta



Tardigrada



Ostracoda

photography IO PAN

## Soft bottom macrofauna

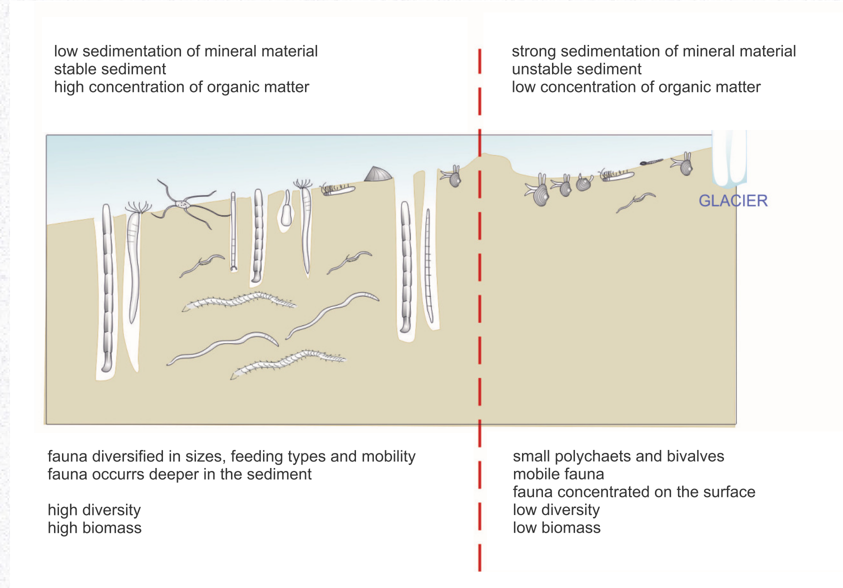
Maria Włodarska-Kowalczuk

Macrozoobenthos is an ecological group encompassing relatively large (sizes exceeding 0.5 mm, "macro-"), animal ("-zoo-") organisms dwelling on the sea bottom ("-benthos"). In comparison to that inhabiting the lower latitudes, the macrozoobenthos of the Arctic remains poorly studied. There are even fewer reports on biota inhabiting the basins of the central Arctic Ocean that are nearly inaccessible because of depths of about 4000 m and multiyear ice cover. Approximately 4,500 macrozoobenthic species have been recorded in the Arctic, while deep-sea species comprise only 10 % of these records.

The majority of the ocean floor surface area is covered with sediments, and this type of benthic habitat is referred to as the soft bottom. The macrobenthic communities of the soft bottom are dominated by annelid worms, mostly polychaetes, and shell bearing molluscs such as bivalves and gastropods. Benthic communities are dependent on the organic matter that is produced in the euphotic zone by photosynthetic phytoplankton populations. The amount of organic materials sedimenting to the bottom depends both on the magnitude of pelagic production and water column depth. Thus, the highest macrozoobenthos biomass values in the Arctic are noted in sediments of the highly productive Chuckhi Sea, which is relatively shallow at an average depth of 50 m, where macrofauna can comprise up to 4 kg per square meter. The benthic standing stocks decrease with increasing depth, and in the deep sea sediments of the central part of Arctic Ocean the biomass of macrozoobenthos does not exceed 5 g per square meter.

The transport of terrestrial material into the sea is important for the functioning of marine ecosystems in coastal waters. Glaciers are characteristic features of Arctic landscapes. Tidal glaciers, which are those terminating in the sea, impact the functioning of coastal ecosystems since they transport large amounts of fresh meltwater and mineral materials to the sea as well as produce icebergs. Benthic communities in near glacier areas, or glacial bays, have to survive in unstable sediments that can be easily relocated by gravity flows or iceberg scoring, and they face a constant rain of sedimenting mineral particles and poor supplies of organic matter since primary production in these surface waters is hindered by high turbidity and salinity fluctuations. Macrobenthic communities in glacial bays are impoverished in terms of diversity and biomass. The fauna is dominated by species that are adapted to survive under conditions of high mineral sedimentation and low supplies of organic matter; thus, small, mobile detritus feeding polychaetes and bivalves actively foraging for food on the sediment surface are found here. Glacial disturbances eliminate a range of organisms that are common in stable sediments located far from glaciers, such as large polychaetes penetrating deep into the sediments, sedentary invertebrates inhabiting tubes or burrows, and species that employ filtering organs to obtain food particles.






Macrozoobenthic community structure in glacial bays and non-impacted subtidal soft bottom habitats (illustration M. Włodarska-Kowalczuk).

Representatives of soft bottom macrozoobenthos:
1) *Buccinum undatum* (photograph Piotr Bałazy) – a predatory gastropod moving across the sea floor in search of its prey, a bivalve buried in the sediments;
2) *Pectinaria hyperborea* (photograph Kajetan Deja) – a sedentary polychaete dwelling in tubes built of mineral grains feeding on organic particles sedimenting from the water column.

## Arctic hard-bottom fauna

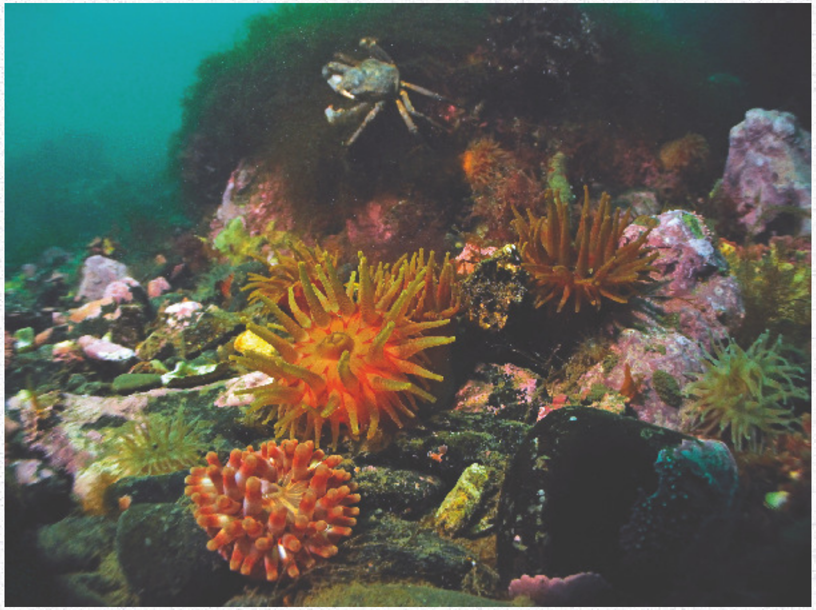
Piotr Kukliński

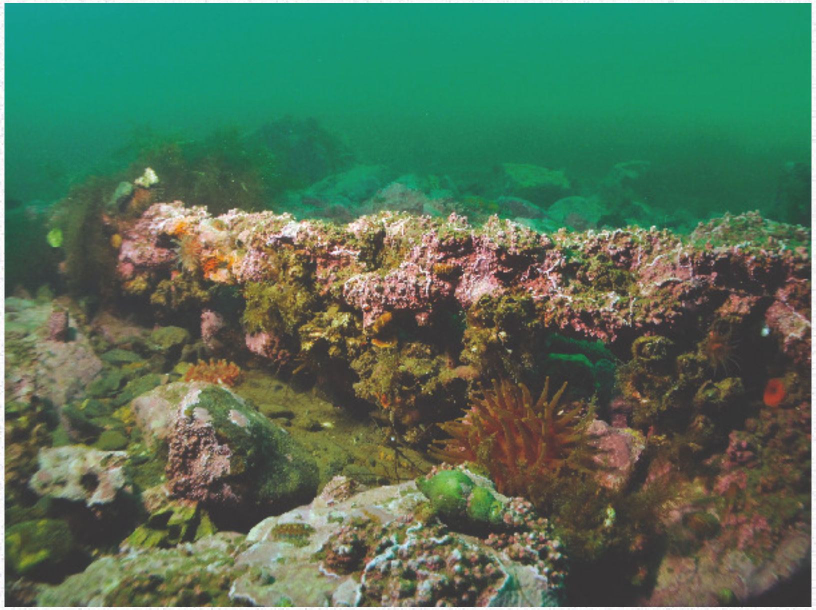
The Arctic hard-bottom fauna is considered to be less species rich than that of lower latitude temperate and tropical regions, but also than that of the Antarctic ecosystem. The most frequently cited reason for this is the geologically young age of the Arctic system. During the last glacial maximum about 14,000 to 18,000 years ago, most of the continental shelf of the Arctic was covered by ice which eradicated most marine life. Many current studies indicate that the modern Arctic fauna survived the glacial maximum at lower latitudes, in ice-free areas at higher latitudes, or in the deeper areas of the continental slope. Scientists believe that the current area of the Arctic shelf, which was freed from the ice just 6,000 years ago, is still under biological colonization from lower latitudes. Arctic hard-bottom fauna comprises all known groups of organisms from lower latitudes including Hydrozoa, Anthozoa, Arthropoda, Mollusca, Echinodermata, Bryozoa, and Brachiopoda.

Marked zonation is observed with increasing depth among hard-bottom organisms. Physical factors such as the presence of ice and the strong influence of waves exerts great pressure in the tidal zone, and species richness is low there. Mobile crustaceans are the dominant group in this area. Sedentary organisms are very rare, and, if they are present, they are usually juvenile forms that rarely reach sexual maturity in the tidal zone. Below the intertidal zone in deeper areas the hard-bottom fauna becomes richer in species, and the overall biomass is much higher. Kelp forests, which occur most often between depths of 2 and 20 m, are very important components of the shallow subtidal area. These three-dimensional structures create a unique environment inhabited by hundreds of species. In addition to rich life among the kelp, the algae itself provides substrate for many organisms. Since light is plentiful here during the summer, food is also plentiful, and this is often reflected by the high abundance and biomass of the fauna occurring here. The availability of light in this zone, however, often leads to large surfaces of rocks being overgrown by calcareous algae. These peculiar algae often outcompete encrusting fauna; therefore, many organisms can be restricted to shaded areas. Large numbers of both sedentary and mobile species are observed in this zone. The impact of waves and ice decreases with increasing depth, so in the deeper regions of the Arctic many organisms are able to grow to larger sizes thanks to the more stable habitat. The sedentary organisms in the deeper zones comprise mostly filter feeders, most of which rely on food particles falling down through the water column. In general, the deeper the ocean is, the less food reaches the bottom. Therefore, organisms inhabiting the hard bottoms of deeper zones usually occur at lower densities, grow slowly, and live longer.

Our knowledge of the hard bottom of the deep regions of the Arctic is very limited, mainly because of the complications of sampling such substrates. Sedentary organisms often occur in cavities or under bottom rock overhangs, so they cannot be collected with conventional sampling methods, such as dredges or grabs. New technologies like remote operated vehicles (ROV) will help us to gain a better understanding of these mysterious ecosystems.







photograph P. Bałazy

## Intertidal

Józef Wiktor jr

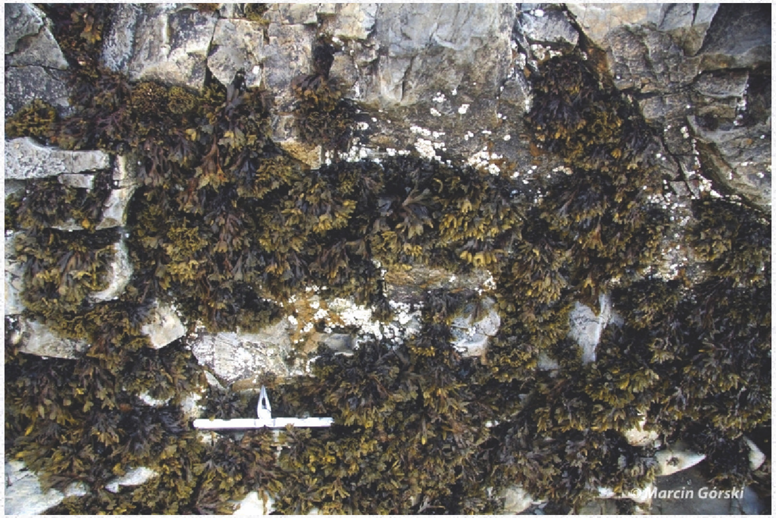
The phenomenon of tides is caused by the gravity forces of the Earth, Sun, and Moon interacting. Water surfaces rise and fall as the relative positions of the celestial bodies shift with respect to a given location. This means that narrow belts of ocean bottom, or intertidal zones, emerge regularly from beneath the waters providing us with an opportunity to observe organisms that are normally hidden from sight under water. Despite its relatively small surface area in comparison to that of the entire ocean floor, the intertidal zone plays an important role in the life of the creatures dwelling both above, on the land, and below, in the sea. Many terrestrial animals, both large, such as the wading plovers, turnstones, and sandpipers, and small, like mites and insects, forage caloric meals during low tide. Energy transfer from the productive ocean to the relatively poor adjacent terrestrial ecosystems is thus accomplished, which contributes to the significance of intertidal zones to the functioning of local terrestrial systems. On the other hand, high tides provide areas for feeding and shelter to vulnerable juvenile stages of many marine species in dense canopies of intertidal macroalgae.

The environmental conditions of the Arctic are hostile to living beings; therefore, one might think that zones exposed to the caprices of nature must be deserted of all life. During winter, the shallow waters freeze quickly along with all life that has not migrated to deeper waters. In spring, the individuals that managed to escape entrapment in the ice have to survive the danger of being scoured from the bottom by ice floes as they are shifted to and fro by waves and tides. But this is not all. The Sun provides algae with life-giving energy, but during low tide, when organisms are deprived of their protective cover of water, the Sun's heat and UV radiation can pose the deadly threat of overheating followed by desiccation. In fall, the storms and ice return. Despite such such harsh conditions, wherever it is possible, and especially along rocky coasts, life thrives and forms complex communities.

One of the characteristic features of the intertidal zone is the pattern of species occurrence. When viewing this area from a distance during low tide, sharply defined bands, each dominated by different species, are apparent. This zonation is the result of the interplay of various processes, but the two most important factors are tolerance to desiccation, which limits the upper range of distribution, and competition for light and space, which limits the species from the bottom.

Coasts comprised of loose sand and mud sediments are nearly totally lacking in macroscopic life. In such habitats, smaller fractions of organisms are more prominently represented, including meiofauna and smaller unicellular beings. But macroscopic life will thrive anywhere individuals find solid substrates to attach themselves to to prevent their removal by other environmental factors. Where waves break most violently on rocks only microbial mats of diatoms and cyanobacteria form, which provide various snails and other herbivorous grazers with sustenance. More sheltered locations are covered with macroalgal canopies of *Fucus evanescens* or *F. vesiculosus*, which both provide shelter to smaller, more fragile algae and various animal species.






Rich assemblage of fucoids and crustaceans in sheltered places

The most common type of the sea coast on Svalbard are stony and gravel beaches (photograph J.M.Węsławski).

## **Macroalgae**

Agnieszka Tatarek, Józef Wiktor, Józef Wiktor jr

Macroalgae and all the other autotrophic protists and bacteria are the foundation of all marine ecosystems. While they only inhabit 0.1 % of the ocean bottom, macroalgae contribute a 5 % share to the total global production of organic carbon. In the most instances, these macroscopic organisms belong to one of two two kingdoms – Plantae, represented by green and red algae, and Chromista, to which brown algae belong.

The oceans currently host about 9,000 macroalgae species, but only a paltry 150 of these, most of which are of Atlantic origin, inhabit the Arctic. Since benthic algae are dependent on sunlight, they are limited to narrow bands along the coasts, with some exceptions (such as in the Sargasso Sea), and their depth limit never exceeds 270 m in the most transparent of waters. In the Arctic, algae are not expected to occur deeper than 50 m, with optimal depths ranging from 2 to 20 m.

Like planktonic communities, benthic macroalgae communities are important components of marine ecosystems since they supply other consumers with food. Moreover, when torn from the ocean floor and transported by waves to shore, macroalgae are important sources of organic matter in near-shore terrestrial areas. Because of their large sizes, especially various species of kelp, the submerged canopies they form play similar roles in the sea to those of forests on the land, including providing shelter, food sources, and numerous microhabitats.

The rocky coasts of the Arctic are covered by dense canopies of algae, similarly to those in the temperate zone. Brown algae are the most common and abundant, and the intertidal zone is dominated by the brown algae order Fucales (*Fucus evanescens*, *F. vesiculosus*, *Ascophyllum nodosum*). From a distance, the canopies appear to form a uniform rusty coating, but closer inspection reveals a diversity of colors and forms. A palette of greens is provided by various small green algae including *Acrosiphonia* sp., *Enteromorpha* sp., and *Cladophora* sp. Pastel pinks come from coralline red algae encrusting its frond with calcium carbonate, and carmine red appears in algae such as *Porphyra* sp. and *Devalarea ramentacea*.

While the dominant color remains brown as one moves deeper into the water, the shapes begin to change. Kelps such as *Laminaria* spp., *Alaria esculenta*, *Saccharina latissima*, and *Saccorhiza dermatodea* produce big, leaf-like fronds. Growing hidden from human sight, they can often be observed (and smelled!) piling up on the shores where they have been deposited by waves. These piles of decaying matter are home for a number of small invertebrates and microbes, which are food for larger creatures.

Red algae have made their homes below the kelp forests where they play the role of forest bushes. Thanks to phycocyanin and phycoerythrin, red algae are very efficient at utilizing light, so they can thrive in poorer light conditions than can other algae. In the Arctic, species such as *Lithotamnion* spp. and *Phycodrys rubens* can be observed even below depths of 30 m. Of course, this does not imply that red algae can only dwell deep beneath the water; in the Arctic their red color is present everywhere from the intertidal zone down to water depths were light becomes insufficient.




*Saccharina latissima*


*Palmaria palmata*


*Alaria esculenta*


*Laminaria digitata*


*Fucus distichuc/evanescens*


*Acrosiphonia* sp.


*Desmaresta aculeata*


*Ulva* sp.

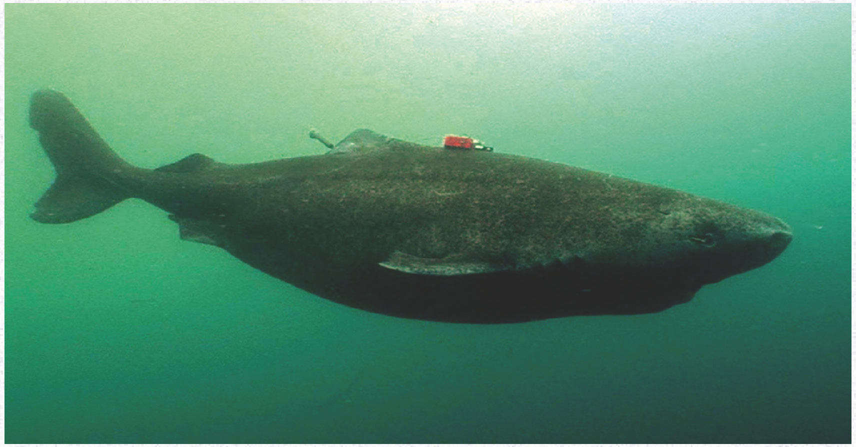
photograph J.M. Węsławski

## Fishes

Jan Marcin Węsławski

The Arctic is not very rich in fish species with just over 150 species identified in the Arctic Ocean. As a comparison, there are more than 5,000 species in the Caribbean. This poor species diversity does not mean that fishes are rare in the Arctic; on the contrary, they are abundant and play important roles in ecosystem functioning and the human exploitation of resources. Only a few species are exploited commercially. Capelin is the key pelagic species, an it is fished mainly for the industrial manufacture of fish meals and fish farm granulated feeds. The most important demersal fish are halibut and redfish, which are caught mostly at greater depths. Atlantic cod, herring, and even mackerel are becoming more common in the marginal Arctic seas. Still, the most important single fish species in the Arctic is the polar cod – a small fish measuring about 20 cm, it is the only species that occurs in large quantities beneath the ice pack. This small fish is the primary prey for nearly all Arctic seabirds, seals, and whales. Polar cod is not exploited commercially, because it is impossible to catch with nets from beneath the ice, and it is rare for it to form shoals in the pelagic zone. This is also one of the very few species of Arctic fish that has developed specific adaptations to life in low temperatures, including the presence of blood antifreeze proteins. These adaptations, which are common in the Antarctic, are the effect of the long evolutionary history of the cold southern ocean that extends back over 20 million years, while the cold Arctic ecosystem is a far younger one million years old, so there has been insufficient time for special adaptations to evolve. The largest arctic fish is the Greenland shark. It can exceed 700 kg in weight and 6 m in length. This shark is a slow-moving demersal fish that catches almost all kinds of prey from carrion to birds, seals, and other fish. The second largest arctic fish is the Greenland halibut, which is a huge flatfish up to 4 m in length. A number of small fish species inhabit the coastal waters among the stones and algae. One of these is the common snailfish, a slimy creature with suction fins that help it to stay put on stones or among the algae against water currents. The Arctic is also a unique place where one can observe the usually deep-water lanterfish, *Benthosema glaciale*, near the surface. In the Atlantic Ocean this species usually occurs at depths of 500 to 1,500 m. A few Arctic fish species, such as sculpins and snailfish, also occur in the Baltic Sea as relicts of the cold history of this young sea.





Polar shark known also as sleepey shark is a large, slow predator of the deep waters, the photographed specimen was marked by Norsk Polarinstitutt scientists (photo NPI/NRK).

The small polar cod is a basic component of the food web in the ice-covered Arctic Sea (photograph IO PAN).


Landings of capelin in the Barents Sea – after a period of overfishing combined with the impact of environmental change, the stock is beginning to recover (photograph Arctic Ocean Diversity web site).

Jan Marcin Węsławski

Arctic birds are not very diverse, and there are no more than 70 species nesting regularly in the Arctic with 36 species on Spitsbergen, 61 on Greenland, and 136 in Siberia. However, Arctic sea bird colonies are the largest known. An average gull colony on the rocks of Spitsbergen numbers from 10,000 to 20,000 individuals, while the small little auk is one of the most abundant bird species worldwide with a population estimated to exceed 30 million.

Sea birds come to the Arctic only for the summer season from June to September and gather in its coastal zones. The exception to this is the ivory gull that nests on nunataks deep inside glacier fields. Most Arctic bird species spend fall and winter in nearby ice-free maritime areas. The little auk is of special importance, as it feeds on marine plankton, and in summer it consumes almost exclusively arctic copepods that are rich in fats and polysaturated fatty acids. While wintering at sea, the little auks switch to a diet of fish. This small bird is the subject of numerous scientific studies because it used to feed on cold water plankton, and this is believed to be important indicator of the changes occurring in Arctic waters.

Most Arctic birds feed mainly on capelin and polar cod; among the most numerous are the common guillemots that can dive to depths of 40 m in search of food. Kittiwakes and fulmars do not dive preferring to collect food from the sea surface. The fulmar is one bird species that can travel up to 300 km away from its colony in search of food. Carnivores are rare among Arctic birds, but there are a few including the Arctic falcons and snowy owls, both of which inhabit the tundra. The large glaucous gulls, black backed gulls, and great skuas are all marine predators. Three species of parasitic jaegers inhabit areas adjacent to gull colonies; these expert pilots have mastered the art of chasing and robbing gulls returning to their colonies with food

Seabirds are very important for the functioning of the arctic ecosystem, because they transfer energy, in the form of food, from the productive seas to the desert-like lands. Large colonies of birds fertilize the tundra and return substantial amounts of nutrients and phosphorus back into the sea. Rich ornithogenic soils are dominated by nutrient rich plants that develop near the seabird colonies, and these comprise the main life-supporting system in the coastal zones of Arctic islands.



Green belt of vegetation marks the influence of feeding birds (photograph J. Wiktor, jr.).

Little auk feeding its young with energy-rich plankton (photograph Cornelius Nello)

Almost all of the whale species of the northern hemisphere migrate to the Arctic in summer, specifically to the margins of the Arctic ice pack, where feeding grounds are rich in food. In summer blue whales, sei and fin whales, and humpbacks feed in the Greenland and Barents seas, while gray whales and Greenland whales occur in the Pacific sector of the Chukchi and Beaufort seas. Minky whales, which are about 8 m long, are the most common whale species in the Arctic and sightings of it are frequent.

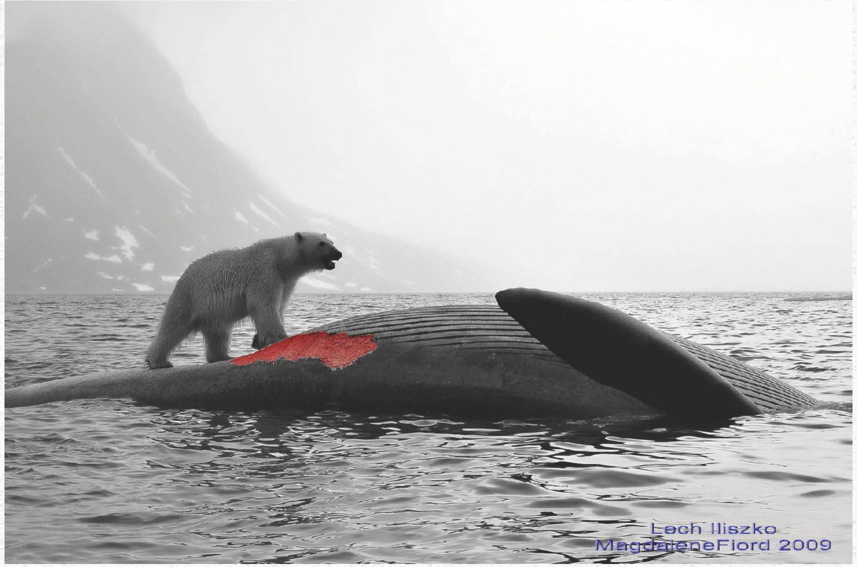
Killer whales are cosmopolitan species, yet they avoid the Arctic pack ice and are often seen in the subarctic. The small, toothed narwhal and beluga whales are typical Arctic species that live out their lives in the ice pack. Both of these animals are fish eaters, and while narwhals are more connected to the ice pack, belugas prefer coastal waters and river mouths.

Other Arctic sea mammals include the pinnipeds, the largest of which is the walrus, which came close to extinction in the European Arctic in the nineteenth century. Today, stable populations estimated at a few thousand individuals inhabit the Arctic. Walruses in the Pacific sector of the Arctic are more abundant especially along the Chukotka and Alaska coastlines. The most abundant Arctic seal species are the Greenland or harp seal, which are estimated to number seven million in the Canadian Arctic. Small ringed seals occur in the fjords and coastal waters, and they require stable ice and snow cover to build snow dens for breeding. The bearded seals are another common seal species in the shallow coastal waters of the Arctic.

Polar bears are, in fact marine animals, because, except when giving birth to cubs, they spend their entire lives on the sea ice hunting for seals. Of all the Arctic mammal species, the polar bear is most threatened by the disappearance of the ice pack, because it cannot hunt efficiently on land.

Sea mammals are not only charismatic animals that fascinate the public, they are also very important elements in the functioning of the Arctic ecosystem. The fish stocks in the Barents Sea are exploited almost equally by the fisheries, seabirds, and marine mammals, and the latter are important regulators of energy turnover through a phenomenon known as top down control. Polar waters support very efficient, contained food webs that extend from microplankton through macroplankton to sea mammals. For example, whales feed on krill that feed on diatoms, so any changes in the abundance of carnivores are transferred quickly to the lower trophic levels.






The polar bear is a carnivore inhabiting the ice pack, but it is also an opportunistic carrion feeder (photograph L. Illiszko).

Pinipeds of the Arctic – ringed seal, bearded seal, gray seal, hooded seal, Greenland sea, and walrus (illustration by S. Węsławski).

## The influence of climate change on Arctic economy, society and culture

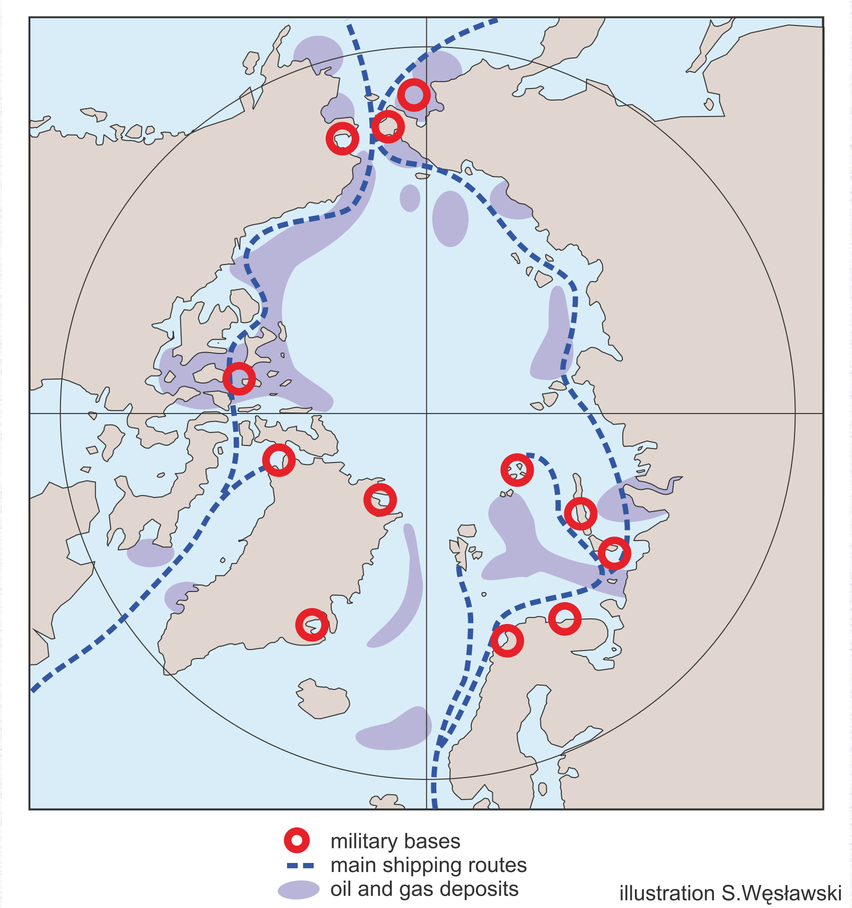
J. Piwowarczyk

**The impact of warming on the Arctic economy.** Depending on how you determine the extent of the Arctic regions, from two to four million indigenous and non-indigenous people live there on a permanent basis. In addition, even up to half a million people visit the Arctic region per year, by sea (mostly on cruise ships), air, or land. This huge amount of people may have a more negative impact on the vulnerable Arctic environment than the oil and gas industry, which – together with commercial fishing and shipping – are the major users of the Arctic. What will be the consequences of global warming for the region? First of all, its effects will not only be noticeable earlier in the Far North than in other regions, but they will be more visible. The rising sea level, the melting glaciers and permafrost will hugely affect the economy, society and culture. In some places the combination of the permafrost loss, stronger storms and higher storm surges will negatively impact the infrastructure, industry and transport. The new challenges will include the shortening of time when roads, lakes and tundra are frozen and can be used for communication and transportation. The costs of maintenance of buildings, roads, and pipelines will rise due to the reduced hardness of the soil. In some cases further, relocation will be necessary. The ice cover got progressively smaller in the past 50 years allowing longer use of new shipping routes, drilling, mining and military activities. On the other hand, reduced salinity and increased acidification will improve the fishing conditions. But opening of new marine areas for commercial use will likely lead to conflicts for space, especially for seabed exploitation. Recent estimates suggest that 13% of the world's undiscovered oil and 30% of undiscovered natural gas can be found in the Arctic, mostly offshore. These new economic activities and development of maritime transport will require new legislation devoted to maritime safety and environmental protection. The influx of tourists and longer tourist seasons, will affect the environment directly, and add a higher threat of alien species invasion. But some tourist attractions – like the tidal glaciers – may disappear during our lifetime, giving a new meaning to the term 'last minute'. Although tourism is important for the local economies, it contributes to the greenhouse gas emissions.

**The impact on the society.** Climate change will have a large impact on the social and cultural life of the indigenous Arctic people. Their identity is based on the close relationship with Nature: hunting, herding, fishing and gathering. As the temperatures will rise, they might be forced to relocate in order to preserve their traditional livelihood which depends on the land and sea fauna and traditional means of transport. However, state sovereignty and conservation measures often overshadow the claims of local communities and limit their possibility to relocate or adapt. Higher thermal stress, skin cancer, spread of zoonotic diseases, lower availability of high quality drinking water, changes in traditional dietary patterns will all negatively affect human health. The consequences for small isolated communities, with low infrastructure development and limited access to health care, may be quite severe.



**What can be done?** The need for actions at the international level and for new forms of governance – more involvement of NGOs, larger representation of the indigenous people – becomes more and more urgent. One of the forums at which this could happen is the Arctic Council. The Council has permanent participants: eight countries (Norway, Sweden, Finland, Denmark-Greenland, Iceland, Canada, Russia, the US), and the representatives of local communities, and observers. The main interests of Poland, one of the observers, are related to scientific research. Our country operates a permanent research station in Svalbard (the Polish Polar Station in Hornsund) and the archipelago is visited regularly by research ships, r/v "Oceania" and r/v "Horizon II". Polish scientists are involved in International Arctic Science Committee (IASC), and Poland participates in the formulation of the European Union policy towards the Arctic, especially regarding nature conservation, protection of the current regulatory regime, and the freedom of scientific research in the Arctic.



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## Web addresses of selected Arctic projects

Project ALKEKONGE – http://www.iopan.gda.pl/projects/Alkekonge/

Project ATP – http://www.eu-atp.org/

Project AWAKE – http://water.iopan.gda.pl/projects/AWAKE/

Project ArcOD CoML – http://www.arcodiv.org/

Polish Polar Station in Hornsund – http://hornsund.igf.edu.pl

Institute of Oceanology PAN – http://www.iopan.gda.pl

Hornsund, Marine Biodiversity Flagship site  – http://www.iopan.gda.pl/projects/biodaff/

IVth International Polar Year – http://www.ipy.org/

ARCTOS network – http://www.arctosresearch.net/

International Arctic Sciences Committee (IASC) – http://iasc.arcticportal.org/

Arctic Climate change report – http://www.acia.uaf.edu/pages/scientific.html


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This book is a kind of a field guide, uncomplete Arctic vocabulary with selected 50 issues about the marine environment. The book shows range of interest of the Institute of Oceanology PAN in this region. We want to disseminate knowledge about the marine environment and to help to create public concern about the climate change and marine biodiversity. We are all the users of the Arctic, as the climate and marine resources are factors that concern us all.

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