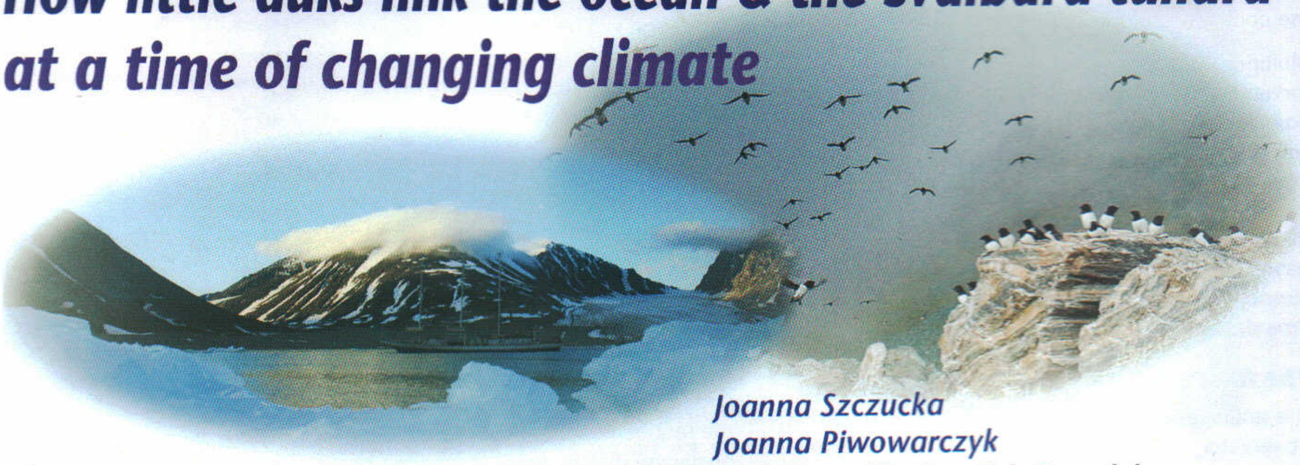
How little auks link the ocean & the Svalbard tundra at a time of changing climate



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Spectacular climate change has been observed in the Arctic during the last decade. Over that time, the temperature of Atlantic Water in the Nordic seas has risen by 0.3 °C – a huge increase in comparison with a rise of 0.06 °C over the last 50 years for the ocean as a whole. An excellent site for researching the change is the Svalbard archipelago, whose waters are strongly influenced by the cold Arctic Sørkapp Current and the warm West Spitsbergen Current. These currents not only differ with regard to their temperature and salinity, but also in the compositions of their zooplankton populations. Comparison of the marine organisms that inhabit areas with distinctive hydrological regimes is allowing us to draw conclusions about the impact of climate change on the planktonic crustaceans, the planktivorous little auks, and the Arctic tundra that is fertilised by these colonially breeding marine birds.

About our project

Long-term multidisciplinary studies of Arctic ecosystems are scarce. Since the 1970s, Norwegian and Polish scientists have been collaborating in the investigation of the fjords and coastal areas of Svalbard (which is Norwegian). Our knowledge of this region is now substantial, but is still fragmentary.

The Institute of Oceanology of the Polish Academy of Sciences in Sopot, the University of Gdansk (Poland) and the Norwegian Polar Institute in Tromsø (Norway) have a long and well established collaboration on Arctic marine ecology. As a result of this cooperation, Polish and Norwegian scientists submitted a joint proposal to the Polish-Norwegian Research Fund, to investigate how climate change is affecting a keystone species of the Svalbard ecosystem – the little auk or, in Norwegian, Alkekonge. 2008 saw the beginning of the project 'Response of marine and terrestrial ecosystems to climate changes in Arctic – links between physical environment, biodiversity of zooplankton and seabird populations'.

The photo of the vessel Oceania *in the Arctic, used in the title image, was taken by Marcin Wichoroski.*

The main objective of the project is to estimate the impact of climate warming on Arctic zooplankton communities (particularly copepods, *Calanus* spp.), little auks (*Alle alle*) and their physical environment. We are studying the interactions between water masses, marine life and terrestrial ecosystems using both direct and innovative remote sensing methods. Our goal is to obtain data on:

1. Water circulation, heat and salt transport by the West Spitsbergen Current, distribution and properties of water masses, and exchanges between fjords and the deep sea;
2. Optical parameters relating to the living conditions of phytoplankton and zooplankton;
3. The structure of the plankton community;
4. The breeding acitivity, feeding ecology and behaviour of little auks, as well as the characteristics of the various colonies.

Investigations are carried out in areas adjacent to four Spitsbergen fjords representing different climatic (hydrological) regimes and biota (Figure 1). The most southerly study area is adjacent to Hornsund fjord in south-west Spitsbergen, where there is a large little auk breeding population. This area is mainly influenced by the Arctic Sørkapp Current and to a lesser extent by the West Spitsbergen Current, which carries water from the Atlantic. In the other three sites, Atlantic water masses dominate. In the central region of western Spitsbergen there are small scattered little auk colonies (study sites, Isfjord and Kongsfjord), whereas in north-western Spitsbergen (study site, Magdalenefjord) a large little auk breeding population is maintained. The differences in the sizes of the various colonies are assumed to be related to the distances to the nearest good feeding grounds.

The 'ocean climate' in a given region depends on how flow rates of currents are influencing the hydrological structure and properties of the local water column. In the vicinity of Spitsbergen, the ocean climate is influenced by Atlantic waters that flow from the south and are relatively warm and saline, and by waters that flow from the Arctic and are colder and less saline. The West Spitsbergen Current transports Atlantic waters throughout the region where our studies are being conducted. Both the temperature of these waters and the intensity of their flow have increased significantly in recent years. Small volumes of Atlantic water have begun to enter the fjords, and change the climatic conditions in Spitsbergen as well as the hydrology and ice cover in the fjords. These changes are having a significant impact on the local ecosystems.

As will be discussed later, light is also an important factor controlling the living conditions of plankton throughout the water column. There is a strong correlation between the availability of light at various depths and the spatial distribution, species composition and biomass of phytoplankton populations and of the zooplankton that feed on them. Underwater visibility also determines the feeding conditions for predators, including the planktivorous little auks.

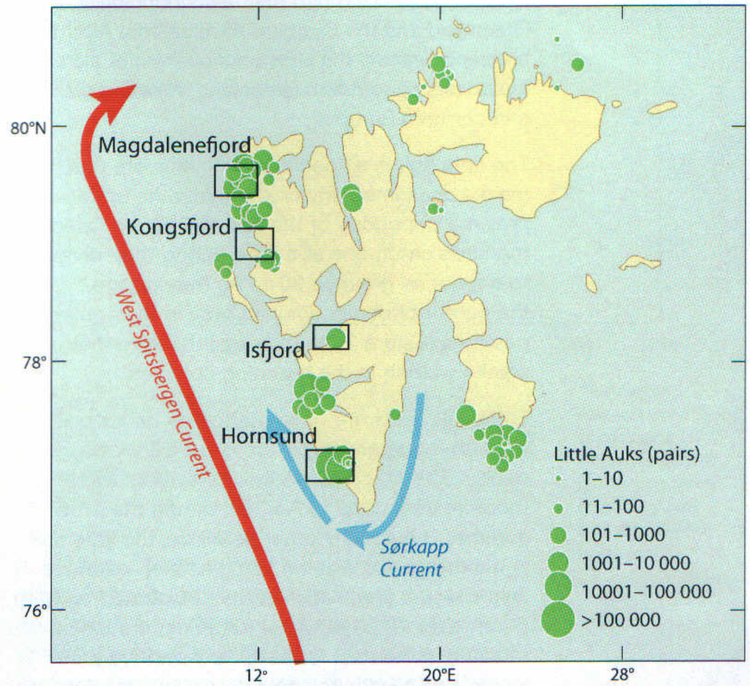


Figure 1 *Map of Svalbard showing the main currents, the positions of little auk colonies and the four fjords investigated within the Alkekonge project.*

Sizes of little auk colonies reflect distances to the nearest good feeding grounds

What little auks really like to eat

The zooplankton – a diverse group of animals that drift passively in the water column, and range in size from microscopic flagellates and minute crustaceans, to giant jellyfish – play a significant role in the food web of the whole Arctic ecosystem linking producers and consumers. The large zooplankton crustaceans that dominate Arctic waters are rich in calories and make an excellent food source for planktivorous seabirds such as the little auk. Off Svalbard, there has in recent years been an increase in the abundance of Atlantic crustaceans, which has been expected to stimulate a shift in the food web towards increasing populations of planktivorous fish and, consequently, of piscivorous birds, such as guillemots and kittiwakes.

The little auk is the most abundant seabird in the Northern Hemisphere. It is considered a keystone species in Arctic ecosystems, with a total population estimated at several tens of million pairs. It is

Figure 2 ***Left*** *A little auk consuming a large euphausid.* ***Right*** *A little auk about to enter its nest and feed a chick with the contents of Its gular pouch. A little auk's gular pouch can contain as many as 3800 small crustaceans, weighing as much as 10g. (Photos by courtesy of Cornelius Nelo)*

Little auks feed voraciously during the breeding season

a small, dove-sized bird that nests principally on Greenland and the Svalbard Archipelago. After the breeding season, the little auks overwinter along the coasts of southern Greenland, Newfoundland, and northern Europe.

The little auk is a specialized planktivore that mainly consumes tiny crustaceans. Its preferred prey are copepods of the genus *Calanus*, which the birds catch one at a time during their dives to depths as great as 30 m. As they forage, the parent birds accumulate prey in their gular pouches (Figure 2), then carry it back to their chicks waiting in the breeding colonies.

Little auk nests are usually situated under boulders on mountain slopes covered with rock debris. The breeding period lasts about three months, from June to August, during the Arctic summer. Like many other seabirds, the little auk is monogamous. Each nesting season a female lays a single egg, which is then incubated by both parents for 29 days. After hatching, the chick remains in the nest for about a month, requires intense care from its parents and initially needs to be brooded. Food is delivered to the chick five to eight times a day. About one week before fledging the female abandons the chick, and the young bird eventually leaves the colony and flies out to sea, guided by the male parent.

The Arctic ecosystem is most dynamic within the transitional zone where water from rivers and glaciers, carrying abundant mineral and organic material, mixes with coastal water. The physical characteristics of marine waters determine the productivity of the phytoplankton, and hence also the distribution and species of zooplankton, which in turn determine the quality and quantity of the food available to the planktivorous birds. The cold Arctic waters are inhabited by two large species of copepod: *Calanus glacialis* and *Calanus hyperboreus*, which are the preferred food of the little auk. The Atlantic water mass is predominantly inhabited by smaller copepod species such as *Calanus finmarchicus*, which are of lower nutritional value to the birds. Because the little auk is a specialized planktivore, it is a sensitive indicator of change in the marine environment. During the warming period (1870–1930) which followed the Little Ice Age (1650–1850), the cold Arctic currents shifted away from the coasts of Iceland and southern Greenland, and the little auks deserted these areas.

Large breeding colonies of little auks have a substantial positive impact on impoverished Arctic terrestrial ecosystems. The little auks consume large quantities of food, and at the peak of their foraging activity, they can remove up to 24% of the copepod standing stock of the feeding ground. The droppings of the masses of seabirds that feed at sea and nest on land, enrich the tundra around the breeding colonies. The minerals in their guano, discarded prey, eggs, dead chicks and adult birds all contribute to the fertilisation of the soil. Little auks nest in enormous colonies, and these are often significant distances from the coast, so as they fly in, they fertilise extensive areas of tundra that would otherwise revert to barren, rocky deserts (Figure 3).

Alkekonge – the observations

Profiles of temperature, salinity and current flow are recorded from the surface to the sea-bed at depths down to 4000 m. Each deep profile takes several hours to be completed, and the data are transmitted via a conducting cable to a shipboard computer, where they are archived and analysed. During a typical month-long oceanic cruise, about 200 profiles, are collected. The data are analysed to identify the structure and properties of the water masses, the current structure and the locations of oceanic fronts and gyres. Probes towed behind the ship take measurements at various depths over the shelves and in the fjords, providing a detailed picture of the exchange and mixing processes of water masses. Since 2004, a substantial warming of the West Spitsbergen Current has been observed and the summer isotherm of 5 °C at 100 m depth has moved northwards by 4.5°. Warm water has extended in over the shelf and has been advected into the Svalbard fjords. In summer 2006, the temperature of Atlantic Water at the core of the West Spitsbergen Current reached a record high value. This warming influenced the weather conditions in the Svalbard area, and reduced the ice-cover within the fjords and in the adjacent sea

Conditions in the nearby ocean indirectly affect the productivity of the Svalbard tundra

Figure 3 *The relationship between oceanographic conditions off Svalbard, zooplankton, little auk populations and the Arctic tundra. The tundra ecosystem is not self-sufficient in nutrients, but during the little auk breeding season, nutrients from the ocean are transferred to the land, allowing it to become green and productive.*

(Photos by courtesy of Dariusz Jakubas, Sławomir Kwaśniewski, Cornelius Nelo and Mateusz Ciechanowski)

areas. Consequently, during the following two winters there was little or no ice within the West Spitsbergen fjords. Similar warming occurred again in 2009. Figure 4 shows the properties of Atlantic Water carried by the West Spitsbergen Current between 1996 and 2009, as measured across the line of latitude 76° 30' N. Mean volume and heat transports fluctuate from year to year, but the general trend is increasing in both cases.

in glaciated fjords, optical properties of the water are governed by stratification and circulation patterns. Changes in the intensity of sunlight down the water column are determined by the water transparency which, in turn, is determined by the concentrations of suspended organic particles (phytoplankton), mineral particles and dissolved organic matter. Suspended material accumulates at depths where there are strong temperature and salinity (i.e. density) gradients, and these more turbid layers attenuate the light, limiting the range of underwater visibility. There might be a two-fold link between water optical properties (here observed in terms of transparency) and little auks' feeding patterns. As lower transparency is an indication of the presence of organic and/or inorganic substances, less transparent waters might be potential feeding areas. On the other hand, less transparent water means poorer visibility, which may hamper the birds' ability to locate prey.

Marine spectro-radiometers are being used to take measurements of the intensity of sunlight penetrating to various depths in the water column. The euphotic zone is the depth over which the solar radiation available for photosynthesis falls to 1% of its value at the surface of the water. In other words, the depth of the euphotic zone is a measure of water clarity and is an important parameter affecting physical and biological processes in marine ecosystems. The depth of the euphotic zone can be measured from space, and Figure 5 shows euphotic zone depths for Spitsbergen waters as retrieved from remote sensing of ocean colour via the satellite-borne instrument, MODIS. The range of observed euphotic zone depth varies from above 60 m in Atlantic waters (darker blue in Figure 5) to just a few metres in the fjords in the vicinity of glaciers. Actually in the area very close to glaciers it can be less than 1 m, but this is not visible on the map, due to satellite pixel resolution.

Investigation of zooplankton populations

Observations of zooplankton distribution are conducted by three different methods: the traditional plankton net (WP2 and Multi Plankton Sampler), the Laser Optical Plankton Counter (LOPC) and acoustic backscatter methods (echo-sounding).

Conventional zooplankton sampling using nets requires time-consuming, labour-intensive analyses in the laboratory to identify and enumerate the zooplankton species present and provide detailed information on the composition of the zooplankton populations. Each zooplankton sample is thoroughly scanned to generate counts of the larger (total size >0.5 cm) zooplankters, which are the potential prey of the little auks. Using this method it is possible to calculate precisely the proportion of the little auks' main food – *C. glacialis* (mostly pre-adult and adult organisms) – relative to the other zooplankters, which are smaller or less caloric (including *C. finmarchicus*). A third *Calanus* species – *C. hyperboreus* – is also favoured by little auks, but it is rather rare in the surface waters over the Spitsbergen shelf studied in our project, as it is a deep-water species, typical of the Arctic.

The innovative LOPC technique has a number of advantages over traditional sampling, and its high spatial and temporal resolution compensates for the lack of taxonomic information. The LOPC measures the cross-sectional area of each plankton

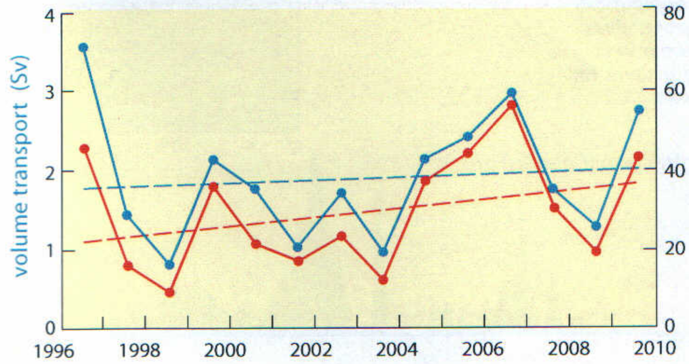
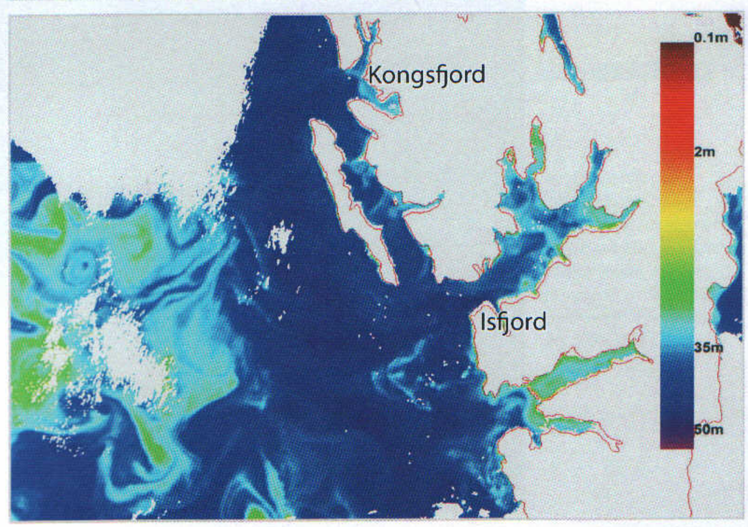


Figure 4 *Mean volume transport and heat transport of Atlantic Water in the West Spitsbergen Current. (1 Sv (sverdrup) = $10^6\,m^3\,s^{-1}$; 1 TW (terawatt) = 10^{12} watts.)*

The mean volume and heat transports of Atlantic Water fluctuate from year to year, but the trend is upwards

Figure 5 *The depth of the euphotic zone for the waters off central western Spitsbergen, retrieved from remote-sensing ocean colour via MODIS satellite data. It can be seen that the euphotic zone is shallower not only in the fiords in the vicinity of glaciers but also along the West Spitsbergen Current where phytoplankton blooms occur.*

Seawater transparency may be important in determining where seabirds choose to feed



More zooplankton in the water does not mean a better feeding ground for little auks

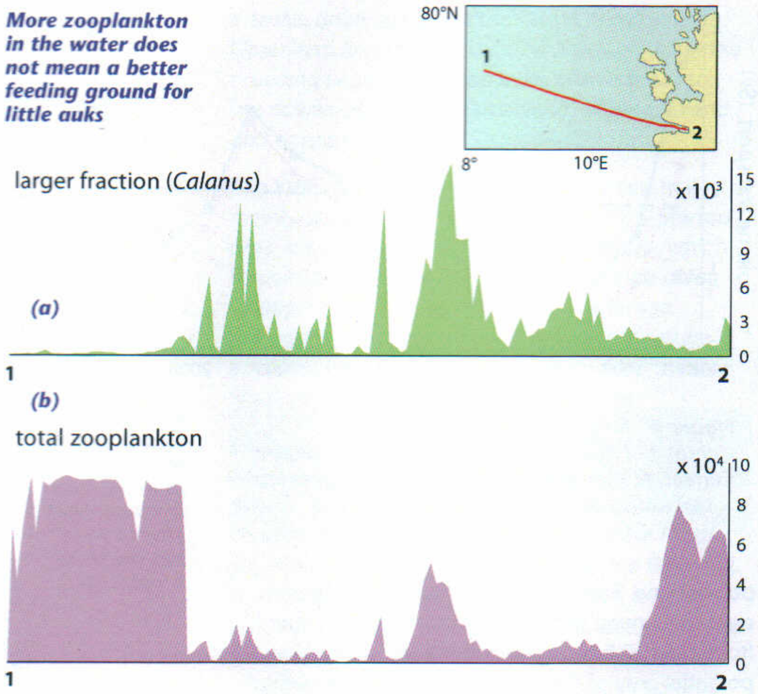


Figure 6 *Abundances of **(a)** larger zooplankton, mainly older copepodid stages of* Calanus *spp. (i.e. potential little auk prey) and **(b)** total zooplankton. Little auks need to find patches of high-quality food (the larger zooplankton fraction) which are generally not well correlated with the peaks of total zooplankton abundance. The diagram is based on continuous LOPC measurements at 10 m depth out from Magdalenefjord (35 nautical miles) in summer 2009.*

'particle' that interrupts the path of the laser beam in the sampling tunnel, and provides continuous data in real time on the abundance, size, bio-volume and shape of particles drifting in the water column. Therefore, the LOPC has the potential to map the distribution of the selected zooplankton size classes at high resolution, and so characterize foraging grounds for planktivores such as little auks.

One of the very first attempts to re-code the data from the LOPC by inter-calibrating its measurements with data derived from traditional examination of net samples from the same station, depth and time, showed good agreement in identifying larger zooplankton species such as those mentioned above, the older copepodid stages of the three *Calanus* species – the main food of little auks.

The composition of the little auk diet is determined on the basis of samples taken from the gular pouches of parent birds returning to feed their chicks (cf. Figures 2 and 7). Little auk behaviour at breeding colonies is observed continuously for several days in order to establish the mean number of times the chicks are fed within a 24-hour

Figure 7 ***Below*** *During the breeding season parent little auks fly non-stop to the zooplankton-rich foraging grounds and back to the colony (cf. Figure 8) to feed their chicks **(Left)**.*

(Photo below by courtesy of Cornelius Nelo)

Little auk parents feed their single chick 5–8 times a day

period. Some of the birds are tagged with miniature temperature and pressure loggers and with GPS modules that provide data about the range of their foraging flights and the depths to which they dive. In Figure 8, tracks of two birds equipped with GPS-loggers show that little auks foraged at distances of about 120 km from the colony. These are the first direct measurements of distances of little auk foraging flights that have been documented.

When little auks dive to feed on zooplankton, their dive is powered by wing beats, and they can be detected underwater acoustically by the air bubbles that are released from among their feathers during the dive.. The Autonomous Hydroacoustic System (AHS) is a buoy consisting of an active section (an upward-looking echo-sounder working at a frequency of 130 kHz) and a passive (noise) section (two external omnidirectional hydrophones), both of which detect the air bubbles. Interpretation of the patterns of acoustic back-scattered echoes makes it possible to follow the trails of bubbles released from the birds' wings during diving, and to determine the depth of diving and the speed of their ascent. Analysis of the echo-sounder records showed that the birds were diving as deep as 34 m. A histogram of dive-depths obtained in this way is shown in Figure 9. Over half of the recorded events were limited to a depth of 5 m, but many deeper dives were also detected. This observation agrees quite well with data obtained in another part of the same project by Harald Steen from the Norwegian Polar Institute, using pressure loggers attached to individual birds. Figure 10 shows a 10-hour record of the position of a little auk in relation to the sea-surface, from which it is possible to deduce what the bird was doing at various times – diving, flying, floating, etc.

The effect on the tundra

The impact the little auks are having on the tundra structure is being investigated using the stable isotope ratios ^{12}C /^{13}C and $^{14}C/^{15}C$. These allow an evaluation of the degree to which the tundra ecosystem is enriched with organic material that has been transported from the ocean to the land. We compare the isotopic signal of successive links in the food web, i.e. seabirds' tissues, their food items and faeces, as well as soil invertebrates, tundra plants, herbivores and predators collected both in the vicinity of little auk colonies and away from them. On the basis of our data, we conclude that Arctic ornithogenic (bird-generated) tundra structure depends significantly on local climatic regimes as well as the intensity of fertilisation by seabirds. Plant communities in areas of ornithogenic tundra influenced by warm climatic conditions differ from those influenced by cold climatic conditions.

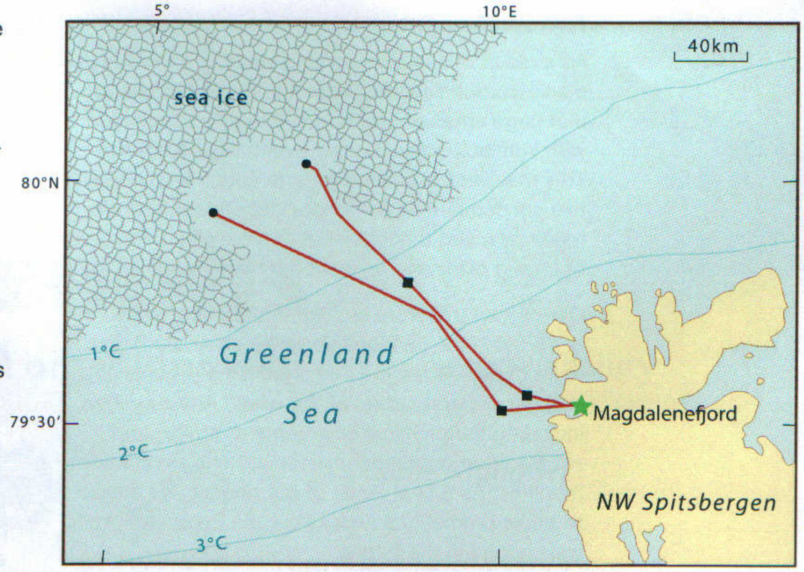


Figure 8 Tracks of two little auks equipped with GPS (July 2009). ★ = little auk colony in Magdalenefjord; isotherms: data for July 2009 from the database Reyn_Smith Olv2; sea-ice extent: data for 28 July 2009 according to the ice map from Meteorologisk Institutt, Norway.

Little auks may forage as much as 120 km from the colony

Figure 9 Distribution of the depths of little auks' dives, obtained using acoustic measurement of the bubble trails produced by little auks when they dived (cf. Figure 10).

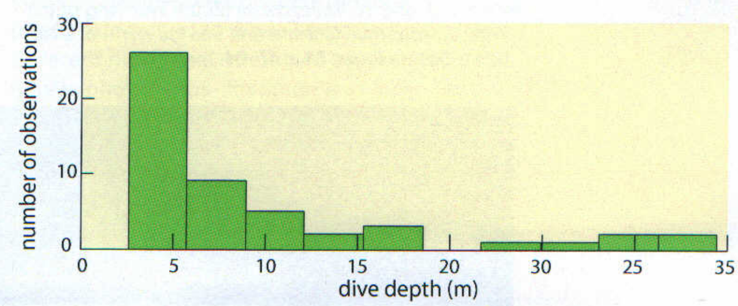
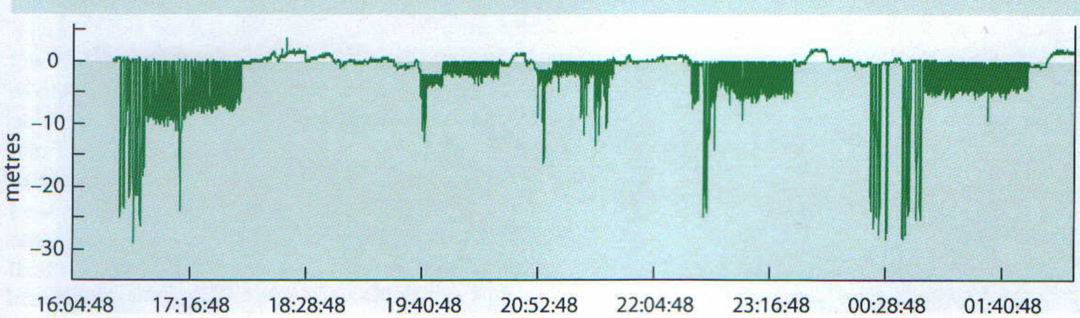


Figure 10 10-hour pressure logger record of the position of a little auk relative to the sea-surface (0).



Both methods for determining dive-depths showed that about half of little auks' dives are quite shallow, but half are down to 20–30 m

Future changes

As a result of climate warming causing a decline in planktivorous seabird populations, we can expect that large areas of ornithogenic tundra associated with little auk colonies may eventually disappear. This may lead to habitat fragmentation with negative consequences for tundra-dependent birds and mammals, and a substantial decrease in biodiversity of tundra plant and animal communities.

Our project therefore highlights the importance of studying the relationship between Arctic Water characteristics and marine organisms in achieving a better understanding of the whole Arctic system, including the physical environment, phyto- and zooplankton populations, seabirds and tundra communities. As a final result of our project, we expect to make predictions about how the European Arctic will change in the future.

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(Photo by courtesy of Cornelius Nelo)