Sea Ice – a very special matter

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One of the most important characteristics of the polar oceans and marginal seas is their seasonal or perennial sea-ice cover. Sea ice is frozen seawater which forms as a result of the prevailing cold air over those ends of the Earth. It is thus different from icebergs, ice shelves, glaciers, and ice sheets, which form from the accumulation and compaction of snow. Sea ice plays important roles for the polar and global climate and ecosystems, and for human activities in the polar regions. Due to its whitish colour and snow cover, sea ice has a high albedo (reflectivity) and reflects most of the radiation emitted from the sun. This is in contrast to the low albedo of the ocean surface, which absorbs most of the solar radiation, resulting in a feedback process of accelerated ice melt due to increased absorption of solar radiation once the area of sea ice decreases. This process is important for changes of global climate, but also for the seasonal melting of the ice cover. Sea ice is an important habitat

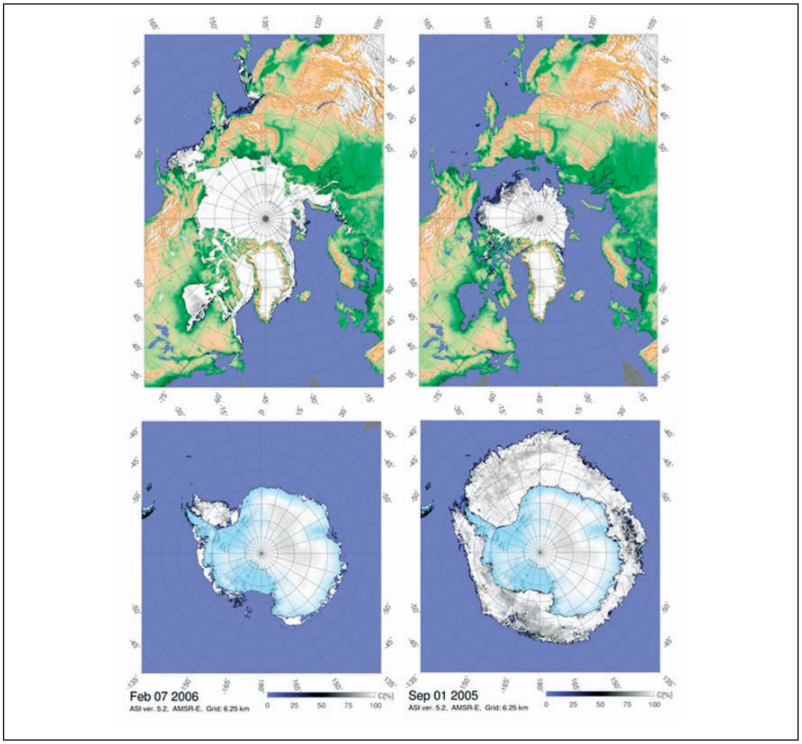

Fig.1:
Maps of the Arctic and Antarctic sea ice coverage, demonstrating the large seasonal variation between February and September. Maps show ice conditions in 2005 and 2006. Figures courtesy of Lars Kaleschke, University of Hamburg, extracted from http://www.seaice.de.

for a rich variety of organisms described in this book. It is also an important hunting, resting, and denning platform for mammals such as polar bears and seals, and birds including penguins. Sea ice is also used by humans as a platform for hunting and travel, but it is also a hazard for marine shipping and offshore operations.

Sea ice – an endangered species?

The maximum ice coverage, which is reached in March in the Arctic and in September in the Southern Ocean, amounts to approximately 16 millions km^2 and 19 millions km^2, respectively (Fig.1). However, sea ice is subject to a strong seasonal cycle and its coverage reduces to approximately 6 and 3 million km^2 during summer. This large seasonal cycle of sea ice coverage makes the detection and interpretation of climate-related trends difficult. In the past 30 years, since satellite observations are routinely available, the ice coverage of the Arctic Ocean strongly declines during summer, with an average rate of -11.1 % per decade. However, in 2007 and 2008 this trend was drastically exceeded when sea ice extent reduced to record lows of only 4.13 and 4.52 million km^2, 20 % less than that of previous summers, and

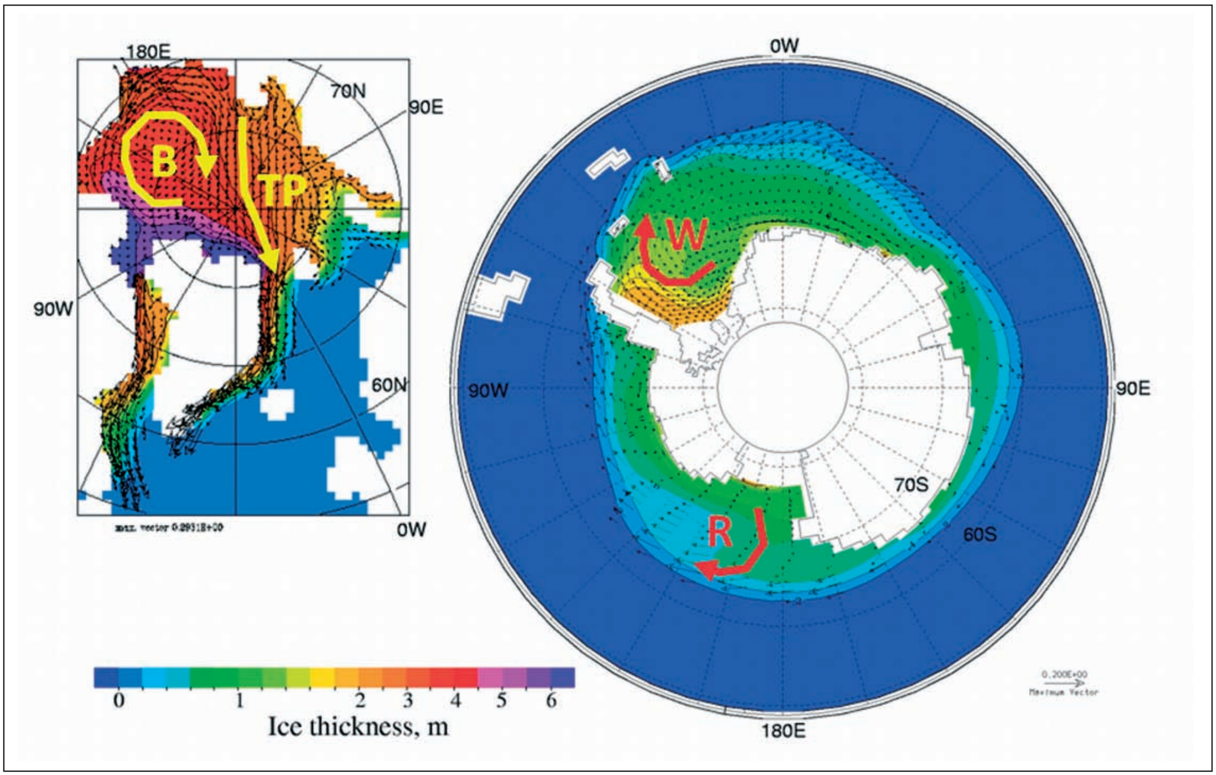

Fig. 2:
Computer simulation of mean Arctic and Antarctic sea ice drift and thickness. Bold arrows show mean drift patterns of the Beaufort Gyre (B), Transpolar Drift (TP), and Weddell (W) and Ross Gyres (R).

raising concerns that the Arctic Ocean might become ice free during summers within the next few decades. However, predictions of the future fate of sea ice might be cautioned by the fact that the Arctic winter ice coverage decreases at a much slower pace of only -2.8 % per decade. And in contrast to the Arctic, sea ice coverage of the Southern Ocean increases slightly, with 0.6 and 3.4 % per decade in the winter and summer, respectively.

What goes around comes around

The understanding of the present rapid changes is hampered by the fact that the ice is only a thin layer on the deep waters, between less than a metre and a few metres thick. Thus, it can easily be moved around by winds and currents. As a result of mean sea level pressure patterns and winds, prominent drift systems exist both in the Arctic and Southern Ocean, such as the Beaufort Gyre and Transpolar Drift in the Arctic, and the Weddell and Ross Gyres in the Antarctic. The mean ice drift speed ranges between 0.05 and 0.15 m/s, or several kilometres per day. Drift and divergence lead to the relocation of ice to lower latitudes where it melts, preventing most ice from growing older than a few years at maximum, with consequences for its role as a habitat. In addition, due to ice drift the retreat of an ice edge or of the sea ice covered regions in general may be a result of both melting and/or advection. Ice drift also results in ice deformation where ice floes are pushed onto each other or against coasts. This can be seen in the Arctic Ocean along the coasts of Greenland and Canada, against which ice is permanently transported by the prevailing drift systems. Deformation and horizontal compression lead to significant thickening of the ice, and the thickest ice is consequently found there and not at the North Pole or along the coasts of Siberia where the coldest air temperatures are observed (Fig. 2). Similarly, deformation along the Weddell Gyre results in very thick ice along the Antarctic Peninsula. Variations in the direction and intensity of the ice drift due to changes in wind patterns can therefore be more important for changes in ice thickness and volume than changes of air temperature. However, in contrast to the generation of thick ice in convergent drift regimes, ice motion and deformation also cause the formation of

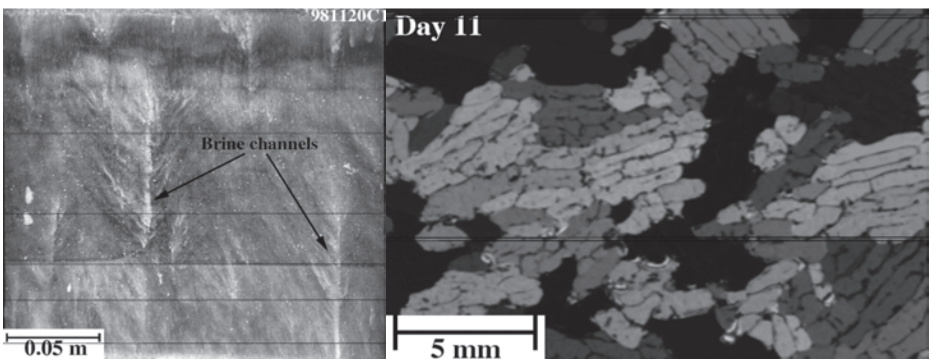

Fig. 3:
Left: Photograph of a 2 cm thick, vertical slice of ice extracted from an ice sheet, showing tree-like brine channels which emerge from just below the ice surface and penetrate through the ice to the bottom. Right: Photograph of a 0.2 mm thick, horizontal ice thin section viewed between crossed polarisors, and showing the typical microscopic structure of columnar ice, with lamellae of ice crystals appearing in different grey tones, and thin layers of brine in between. Note different scales of photographs.

regions of open water where the ice diverges. The most prominent and recurring regions of open water within the pack ice zone are called polynyas and extend along the coasts upstream of the major drift systems e.g. along the coasts of Siberia or in the southern Ross and Weddell Seas. These polynyas are regions of extensive ice formation and export. They are also important feeding grounds for birds and mammals relying on access to water for their hunting and fishing.

From the macroscopic to the microscopic

The seasonal advance and retreat of the vast sea-ice zone has fundamental consequences for the climate and oceanography of the respective regions. Not only does the ice increase the regional albedo, it also prevents heat flow from the warm water under the ice to the cold air above, resulting in colder air temperatures.

In addition, the formation of sea ice results in the rejection of saline brines. When ice crystals form from water molecules, the seawater's salt ions are not incorporated into the ice crystal's molecular lattice due to their significantly larger atomic diameter. While most salt is expelled from the forming sea-ice sheet, some is retained within the ice, inter-secting the freshwater ice crystals as layers, pores, pockets or channels of brine (Fig. 3). The amount and geometry of the brines remaining in the ice depend on the intensity and history of the actual ice growth. For example, the salinity of young sea ice ranges between 8 and 16 parts per thousands (ppt), compared to 34 ppt of typical seawater i.e. 50 to 75% of the sea waters salt content is rejected during ice formation. As this brine is denser than the seawater below the ice, it can cause unstable layering of the upper water layers and can eventually result in convection and the formation of cold deep water which contributes to maintaining the global thermohaline ocean circulation. This process is particularly important in polynyas with their strong ice production throughout the winters.

However, in the course of a winter an ice cover continues to desalinate further by brine drainage and expulsion. When the ice cools as it becomes thicker, the brine and surrounding ice maintain phase equilibrium i.e. coexist in solid and liquid forms. The freezing temperature of brine decreases with increasing salinity.

Therefore, when ambient ice temperatures decrease, ice growth takes place within all pores, decreasing the volume of brine and increasing its salinity. Thus, the brine remains liquid. Organisms

Fig. 4:
Pancake ice field cover vast expanses of the Southern Ocean during the advance of the ice edge in autumn.

living in the pore network within the ice are therefore not only subjected to changing temperatures, but also to varying salinity and available space. Increasing brine salinity and decreasing pore space lead to further ejection of brine by gravity drainage and expulsion as less and less pore space remains available within the ice when pores continue to solidify. Apart from decreasing porosity, also the connec-tivity (permeability) of the pores reduces with continued cooling.

Therefore brine motion and exchanges of nutrients by convection or diffusion within the pore network are successively limited, again with consequences for the survival of ice organisms. In summer, the ice warms and pores widen, leading to further brine drainage. In the Arctic, melting is typically so strong that the remaining brines and nutrients are flushed out by percolating melt water of snow and ice, resulting in essentially fresh (salt-free) upper ice layers.

When the ice edge advances in fall, the ice cover expands over vast regions of the open oceans. Before ice can form, the upper tens of metres of the water column must first cool to reach their freezing temperature of -1.8°C. The density of seawater increases with decreasing temperature, and therefore surface cooling leads to convection of the cold surface water to deeper layers. Eventually, the thick mixed surface layer reaches its freezing temperature throughout, and massive amounts of ice crystals begin to form simultaneously in the whole upper water column. These frazil crystals rise to the water surface and form thick layers of slush ice. Under the impression of waves and swell, the slush aggregates into circular, consolidated pans of ice. These pans are pushed against and rafted on top of each other and collect more and more slush ice, thereby growing in diameter and thickness. The bouncing and flushing of more and more frazil crystals result in the formation of their characteristic risen rims. Therefore, this ice is called pancake ice (Fig. 4). It is particularly typical for newly formed ice in the Southern Ocean, which is exposed to the turbulent waters of the Furious Fifties. With further ice formation, pancakes consolidate further and further and eventually form large ice floes.

The original frazil origin of pancake ice floes is preserved in a typical, granular crystal structure. During their rise through the water column, frazil crystals can scavenge algae and sediments and transport them to the water surface. These organisms can then seed the

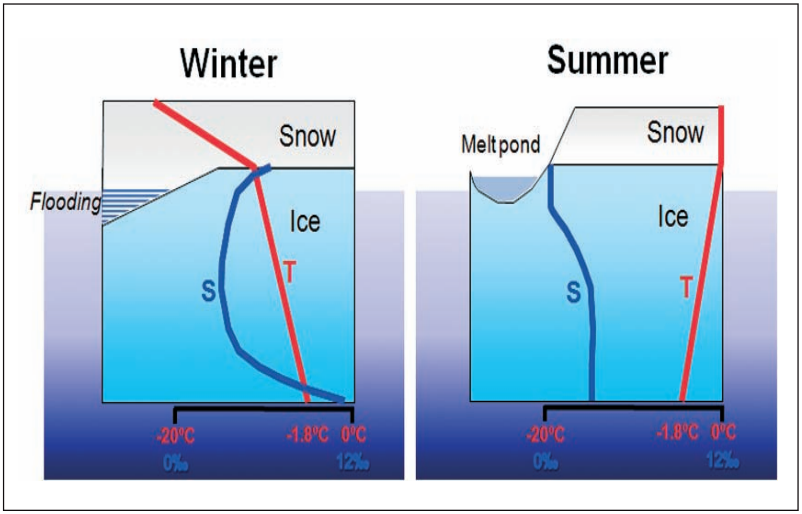

Fig. 5:
Illustration of differences of typical temperature and salinity profiles of sea ice floes in winter and summer. In winter, salinity is high and its profiles have a C-shape, and temperature gra-dients are steep with cold temperatures at the surface. Flooding might occur due to heavy snow load. In summer, the ice desalinates at the sur-face, and temperature gradients are minimal, with warmer, melting ice at the surface. Snow might melt away and melt water might collect in melt ponds covering the ice surface.

development of rich sea ice communities throughout the ice column. The crystal structure of granular ice contrasts with that of columnar ice which results from congelation growth at the ice underside under quiet conditions. Columnar ice dominates in regions of perennial ice, or after pancake ice has sufficiently consolidated and thickened. In perennial ice, algal growth is mainly restricted to the lowest layers of dendritic, columnar ice, which is also called the "skeleton layer".

Columnar ice is also characteristic for Nilas, up to 15 cm thick new ice which typically forms in leads opening within the closed pack ice zone when the ice drift is divergent. Nilas is prominent for the occurrence of finger rafting, a beautiful, block zippered regular pattern that forms when thin ice sheets floating on water collide. This creates decimetre to metre wide "fingers" that push over and under each other alternately. Nilas is also famous for the occurrence of frost flowers, surface hoar crystals of up to several centimetres in height which form due to the large temperature gradients between the thin, relatively warm ice and cold air. Their growth also benefits from the presence of liquid brine on the surface of the Nilas. Due to their high salinity and large surface area, frost flowers are important for various chemical processes altering the air over the ice, and for microwave properties which can be detected by satellites.

A not-so-cold place

Although the rich colonisation of sea ice by ice organisms and its high primary productivity appear surprising at first, they nevertheless result from the relative warmth of the ice compared to polar air temperatures. Due to its low thermal conductivity, snow significantly insulates the underlying ice from the atmosphere (Fig. 5). However, snow also absorbs most solar radiation and therefore acts as a blind for the light regime in the ice. Temperatures at the ice underside are equal or close to the temperature of the seawater, thus, organisms are hardly exposed to strong temperature variations. However, they need to cope with the permanently changing microscopic interfaces of the ice and water. When the snow cover is approximately 0.3 times as thick as the ice, its mass depresses the ice surface below the water level, leading to flooding of the snow/ice-interface by sea water, a process frequently observed around Antarctica (Fig. 5). This "warm" water causes further warming of the ice, with improved living conditions.

In summer, air temperatures over the polar oceans and even at the North Pole are often around or above 0°C. This, and high levels of radiation can lead to a reversal of temperature profiles in the ice, with surface temperatures reaching 0°C (Fig. 5). Then, internal melting leads to strong increases of porosity and permeability, and improved living conditions with sufficient resupply of nutrients. However, if melting is as strong as typically in the Arctic, where the snow and upper ice layers melt rapidly within a few weeks, meltwater can flush out any salt, nutrients and organisms which might be present in the upper ice layers.

These seasonal changes have to be remembered when discussing the biology of the polar oceans, as they affect all aspects presented in this book. Research is still only at the beginning to fully understand the processes and implications of these variations, and how conditions might differ if the polar region's climate continues to change at its present pace.