# Physical oceanography of the Greenland Sea

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## Abstract

Ocean-atmosphere interactions in the North Atlantic are responsible for heat transports that keep the Nordic region and North Western Europe 5–10°C warmer than the average of the corresponding latitude belt. This is to a large extent due to the ocean's thermohaline circulation (THC). This circulation is driven by differences in water density, which is a function of temperature (thermo) and salinity (haline) and particularly by convection processes in the northern North Atlantic, especially the Labrador Sea and the Greenland Sea.

Therefore, the Greenland Sea has attracted much attention in the marine research community over the past decades. Scientific research in the Greenland Sea has been important to understand:

- The physical processes generating deep convection
- The role of sea ice in the deep convection process and biological production
- Uptake of carbon dioxide from the atmosphere and further transport into the ocean interior
- Variability in deep convection, especially the decrease in the Greenland Sea convection observed over the recent decades

The main incentive behind all these activities has been to understand the role of the Greenland Sea – and the rest of the Nordic Seas (Greenland, Norwegian and Iceland Seas) – in the climate system of the world.

## 1.1 General circulation

The large-scale circulation in the Nordic Seas is dominated by the warm northward-flowing Atlantic inflow, mainly on the eastern side of the Nordic Seas area, and the cold East Greenland Current flowing southward on the western side (Fig. 1.1). Atlantic Water enters the Norwegian Sea through the Faroe-Shetland Channel, following the Scottish slope, and between the Faroe Islands and Iceland, where modified North Atlantic Water feeds the Faroe Current, which flows eastward north of the Faroe Islands. The Atlantic Water flows northward along the west coast of Norway with some side branches entering the Greenland Sea area. Off Northern Norway the current splits into the North Cape Current and the West Spitsbergen Current, both entering the Arctic Ocean. The West Spitsbergen Current has several side branches feeding water into the East Greenland Current and the Greenland Sea.

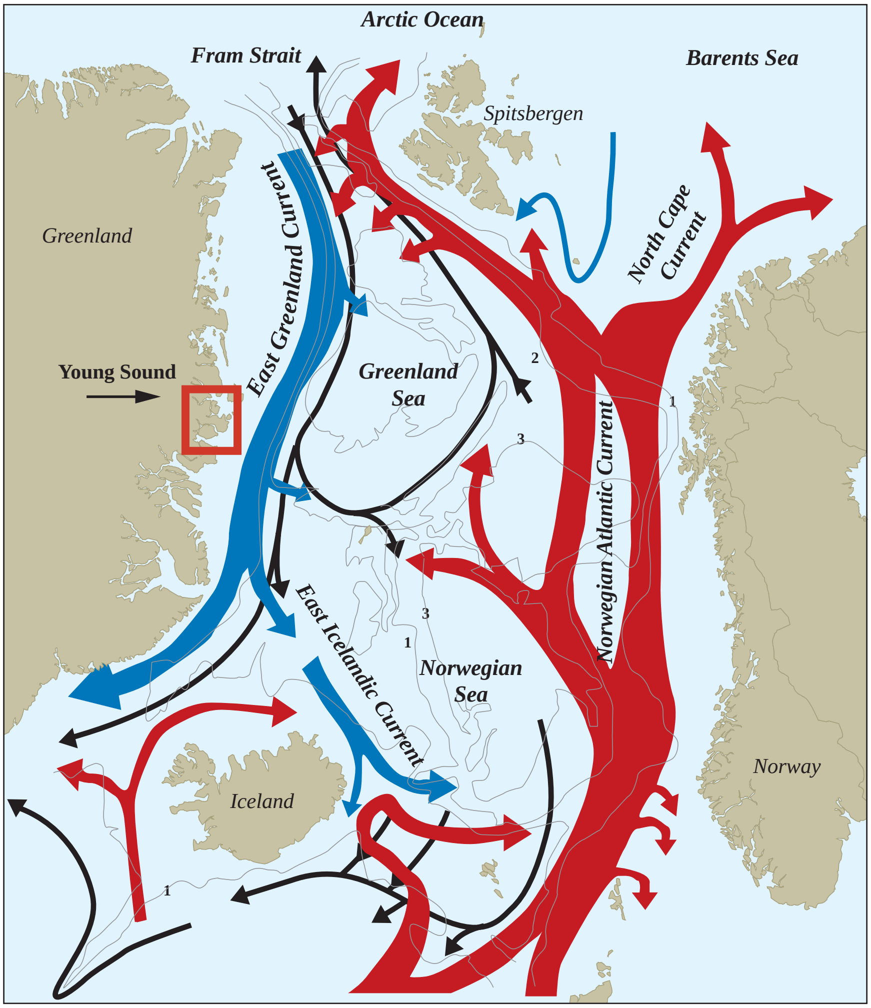


**Figure 1.1** Ocean currents in the Nordic Seas. Blue arrows represent cold water masses and red arrows represent warm water masses.

In its upper layers, the southward-flowing East Greenland Current consists of cold Polar Water of low salinity, including large amounts of sea ice, from the Arctic Ocean (Aagaard & Carmack, 1989). In its deeper strata, there is also a transport of intermediate and deep water from the Arctic Ocean. A relatively warm intermediate layer with water of Atlantic origin returns from the West Spitsbergen Current and partly from the Arctic Ocean. Below, deep water formed in the Arctic Ocean, primarily Eurasian Basin Deep Water (Swift & Kolterman, 1988) can be traced all the way to the Denmark Strait (Buch et al., 1996) and constitutes an important contribution to the deep water in the Nordic Seas. The main side branches of the East Greenland Current are, firstly, the Jan Mayen Current, which brings all three water masses into the cyclonic circulation in the Greenland Sea Basin. Secondly, further south, the East Icelandic Current, which carries a somewhat varying combination of the same water masses from the East Greenland Current into the Iceland and Norwegian Seas (Buch et al., 1996). The remaining part of the East Greenland Current leaves the Nordic Seas through the Denmark Strait to supply fresh water to the sub-Arctic gyre in the North Atlantic as well as dense overflow water, which contributes to the deep western boundary current in the North Atlantic.

A distinct hydrographical regime lies between the regions dominated by the Polar and the Atlantic water masses (Fig. 1.2). In this hydrographical transition zone, the upper-layer water is warmer and more saline than that of the East Greenland Current, though still cooler and less saline than the Atlantic water. Helland-Hansen & Nansen (1909) used the general term ”Arctic Water” to distinguish the upper layer water of this transition region from those of more direct polar

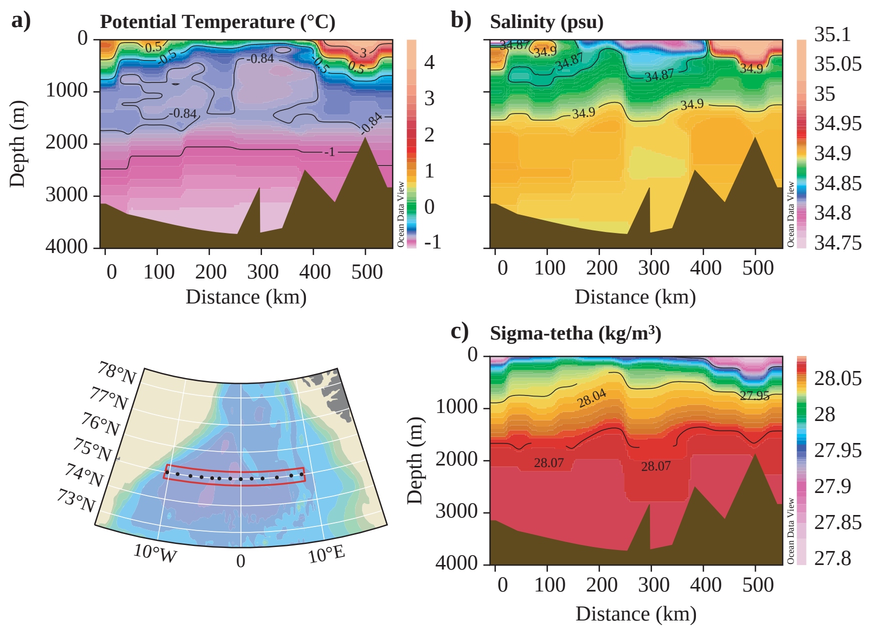


**Figure 1.2** Vertical distribution of **(a)** potential temperature, **(b)** salinity and **(c)** density across the central Greenland Sea

or Atlantic origin. This Arctic domain is bounded to the east and west by regions of increased horizontal gradients in water properties, i.e. fronts. However, the temperature, salinity (T,S) property contrasts across these fronts vary seasonally and regionally. Both these boundary regions have by various authors been termed ”the Polar Front“, but Swift & Aagaard (1981) distinguished between the two by naming the front between the Polar and the Arctic domain ”the Polar Front“, while the front between the Arctic and the Atlantic domain is called ”the Arctic Front”.

Generally, it can be stressed that the Arctic domain is not simply the product of smooth transition between Atlantic and Polar influences, but rather an individual regime, locally modified, bounded by fronts, and only loosely connected to either of the bordering domains. In the Arctic domain a characteristic vertical progression of relatively dense water overlies the deep water.

In the vertical, the surface water of the Arctic domain is followed by a temperature minimum at 75–150 m, a temperature and salinity maximum at about 250 to 400 m, and, finally, the deep water. A crucial feature of the Arctic domain is that the vertical stability in the upper water stratum is lower than in the adjacent domains, while the density of the upper layer is overall quite high. Thus, winter cooling at the sea surface can produce very dense water, perhaps including deep water.

## 1.2 Water Masses

The dominant water masses in the Greenland Sea area are:

**Atlantic Water (AW):**
AW is traditionally defined as any water with salinity greater than 35.0. Upon entry into the Iceland and Norwegian Seas, AW has a temperature of 6–8°C and a salinity range of about 35.1–35.3. Because AW seldom, if ever, is cooler than 3°C and because a clear connection with AW can be observed in some water with salinities below the above-mentioned range, Swift & Aagaard (1981) expanded the traditional definition of AW to include all water warmer than 3°C and more saline than 34.9.

**Polar Water (PW):**
PW is defined as any water less saline than 34.4. Generally, the temperatures of this water are low, normally below 0°C, but because the layer is thin and strongly stratified, summer temperatures of 3 to 5°C in the surface are not unusual. Summer salinities as low as 29 have been observed in the western Greenland Sea. The Young Sound fjord is connected to the East Greenland Current and in direct contact with PW. Further details about water-column properties in the fjord are presented in Chapter 3.

Satellite image showing ice conditions late July in the surroundings of Young Sound.

**Arctic Surface Water (ASW):**
ASW is the water found at the surface in the Arctic domain during summer. The temperature is greater than 0°C for the salinity range 34.4 to 34.7 and greater than 2°C for the range 34.7 to 34.9.

**Arctic Intermediate Water (AIW):**
According to Swift & Aagaard (1981) AIW can be divided into upper AIW and lower AIW.

**Upper AIW:**
Temperatures are below 2°C and salinities from 34.7 to 34.9. This water mass is often found at the sea surface during winter.

**Lower AIW:**
Temperatures are in the range 0–3°C and the salinity is greater than 34.9 psu. This water mass is believed to be produced by the cooling and sinking of AW, especially in the northern Greenland Sea.

**Greenland Sea Deep Water (GSDW):**
GSDW is the densest water in the Greenland Sea. Its salinity is 34.895 and the temperature is -1.24°C. GSDW is found only in the central gyre of the Greenland Sea.

**Norwegian Sea Deep Water (NSDW):**
NSDW is the densest water mass in the Norwegian and Iceland Seas, but is also found around the periphery of the Greenland Sea. NSDW is slightly more saline than GSDW, namely 34.91 and has a temperature close to -1°C.

**Arctic Ocean Deep Water:**
Rudels & Quadfasel (1991) introduced three deep water masses of Arctic Ocean origin:

Upper Polar Deep Water:
$-0.5^{\circ}C < T < 0^{\circ}C$, $34.90 < S < 34.93$
Canadian Basin Deep Water:
$-0.8^{\circ}C < T < 0.5^{\circ}C$, $S > 34.92$
Eurasian Deep Water:
$T < -0.8^{\circ}C$, $S > 34.92$

These three water masses leave the Arctic Basin through the Fram Strait and flow southward in the western part of the Greenland Sea.

## 1.3 East Greenland Current

With respect to Greenland and the Young Sound Area, the part of the Greenland Sea attracting the greatest interest is the East Greenland Current, because of its effects on much of the Greenland coastline – especially due to the large amounts of sea ice it carries along with it. These concentrations of ice make great parts of the east coast of Greenland unnavigable, except for a couple of months a year.

The East Greenland Current is composed of three water masses. The upper 150–200 m is occupied by Polar Water (PW). The temperature varies between 0°C and the freezing point for sea water. During summer, there is usually a temperature minimum at about 50 m, while, in winter, the temperature is uniform from the surface to about 75 m with a value close to the freezing point of sea water. The salinity shows great variations within this region of PW. At the surface nearest to the Greenland coast salinities below 30.0 are found, while, at the bottom of the layer and close to the Polar Front (PF), salinities reach 34.5.

Underneath PW a body of both upper and lower AIW is found extending down to approximately 800 m. A temperature maximum can be observed throughout the year in the depth interval 200–400 m.

The third water mass is actually a combination of the different deep water masses mentioned above. Normally, the salinities observed are within the range 34.88–34.90, indicating that the water mass is GSDW, but occasionally salinities between 34.90–34.94 are observed, indicating the presence of NSDW and deep water masses of Arctic Ocean origin.

**Current velocities**

Estimation of current velocities can be made either by direct measurements or by dynamical calculations based on hydrographical observations; both kinds of observations are, however, hampered in the East Greenland Current system in the Greenland Sea area due to presence of sea ice throughout most of the year. During the Greenland Sea Project in 1987-1994, current meter moorings were deployed at 75°N; which is just north of Young Sound. Based on these observations the following conclusions can be drawn (Fahrbach et al, 1995):

- The long-term mean currents, determined as averages over the duration of the time series, are generally parallel to the depth contours. Cross-isobath flow was usually negligible.
- A current core with a maximum velocity of up to 0.30 m $s^{-1}$ is found at a distance of approximately 45 km from the shelf break and extending to a depth of 2400 m (Fig.1.3).
- On the shelf, mean currents are 0.10 m $s^{-1}$.
- The time series reveal significant fluctuations of various timescales from tides to long-term trends, superimposed on the average currents. Variations of velocities on timescales of a week to a month, which represent current eddies and meanders, are up to 0.30 m $s^{-1}$. The fluctuations are most intense in the upper layer over the slope where maximum currents of 0.60 m $s^{-1}$ were observed.
- Seasonal variations are displayed in most records. Normally, the currents are stronger in winter than in summer. In some years, the winter maximum split up into two well-separated maxima in autumn and spring. On the shelf, monthly mean currents attained minimum values of less than 0.05 m $s^{-1}$ in August and a maximum of nearly 0.20 m $s^{-1}$ in February.
- The tidal currents were dominated by the M2 (lunar-semidiurnal) constituent, with a magnitude of about 0.05 m $s^{-1}$. The S2 and K1 constituents were also significant. The semidiurnal (M2 and S2) constituents were significantly baroclinic and decreased with increasing depth. The diurnal (K1) constituent increased slightly with increasing depth.

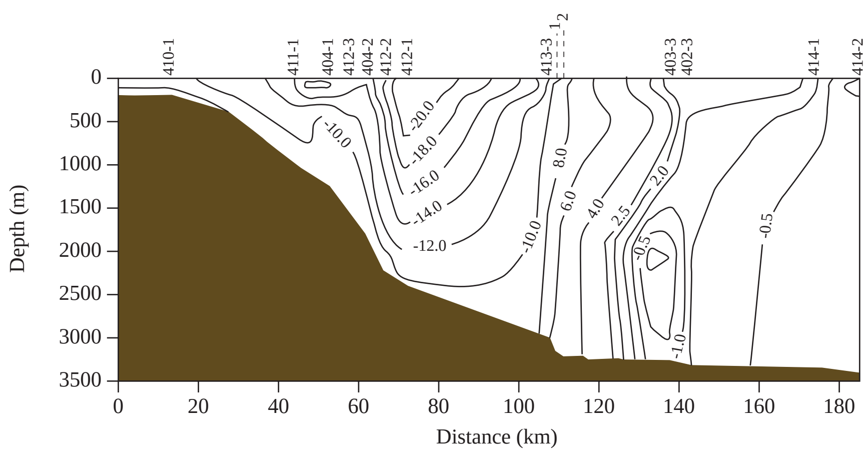


**Figure1.3** Vertical distribution of current velocities at 75°N. From Fahrbach et al. (1995) Current velocities are in cm $s^{-1}$.


Photo: Søren Rysgaard

Pack ice in the Greenland Sea.

## Sea Ice

The sea-ice cover along the east coast of Greenland can be divided into 4 zones, each with their own characteristic features and dynamics:

### Landfast ice

Landfast ice is ice that grows seaward from a coast and stays in place throughout winter. Normally, it breaks up and drifts away or melts in spring, but may, under exceptional circumstances, stay in place all summer and thus survive into the second, or subsequent, years. The ice-free season grows rapidly shorter with increasing latitude, which is not surprising as the mean temperature in January falls from -4°C at Angmagssalik to below -18°C in North East Greenland. More details about sea ice in Young Sound are presented in Chapter 4.

### Transition zone between coastal fast ice and the main body of pack ice

In many places within the Arctic, this zone is characterized by exceptionally heavy ridging, caused by the shoreward set of the polar pack as it circulates in the Beaufort Gyre (Wadhams, 1983). In the East Greenland Current there is no shear zone in this sense. The only area where it exists is the north coast of Greenland as far east as the Nordostrundingen. South of this point the East Greenland ice is in a state of almost free drift under wind and surface current, and an actual shear point, where internal stress integrated over a large area drives a consolidated ice field against the coast, never develop except locally around off-lying islands. Instead, a characteristic phenomenon of the winter and spring transition zone in East Greenland is the intermittent presence of open water, either as well-defined polynyas or as a continuous strip of open water seaward of the fast ice edge.

### Pack ice

The drifting pack ice in the East Greenland Current is composed of ice floes originating from various places in the Arctic region. Three main types of pack ice have been defined (Wadhams, 1983):

- Paleocrystic ice is partly very old ice from the Beaufort Gyre, which has circulated for many years in the Canada Basin before crossing into the Trans Polar Drift Stream and exiting the Arctic Ocean with the East Greenland Current, and partly ice which has undergone heavy deformation in the

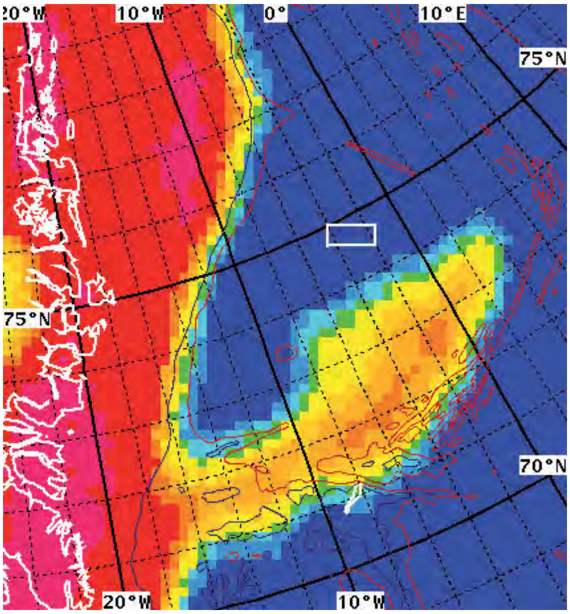


**Figure 1.4** Odden Ice Tongue. Based on satellite observations analysed at the Danish Technical University (Leif Toudal).

North Greenland offshore zone before entering the Fram Strait via the Nordostrundingen.

- North Pole ice is ice of slightly more recent origin from both the Beaufort Gyre and the more distant parts of the Eurasian Basin (e.g. the northern part of the East Siberian Sea and the Chukchi Sea).
- Siberian ice is first- and second-year ice formed in the near-shore and shelf areas of the Soviet Arctic or in the region immediately north of the Fram Strait. In addition, young ice is found in the pack in winter, forming continuously in leads and polynyas, as they open up. Thus, the winter pack at the latitude of the Denmark Strait contains a significant portion of ice, which has formed south of the Fram Strait. Due to turbulence, which results in much churning and meandering of the ice, and the overall southward drift, ice of all types is mixed irretrievably together.

### Marginal Ice Zone

The Marginal Ice Zone is the transition zone between the pack ice and the open ocean, which, due to the interaction between the ice and open ocean as well as the interaction between the water masses within and outside the East Greenland Current, has quite different physical properties than those found in the pack ice zone. Eddies of different sizes are a common phenomenon in the Marginal Ice Zone.

A special phenomenon regarding sea ice in the Greenland Sea is the Odden Ice Tongue. The Odden Ice Tongue is a winter ice cover phenomenon that occurs in the Greenland Sea. It is about 1300 km in length and may cover an area of as much as 330,000 square kilometres (Fig. 1.4). Within a very short

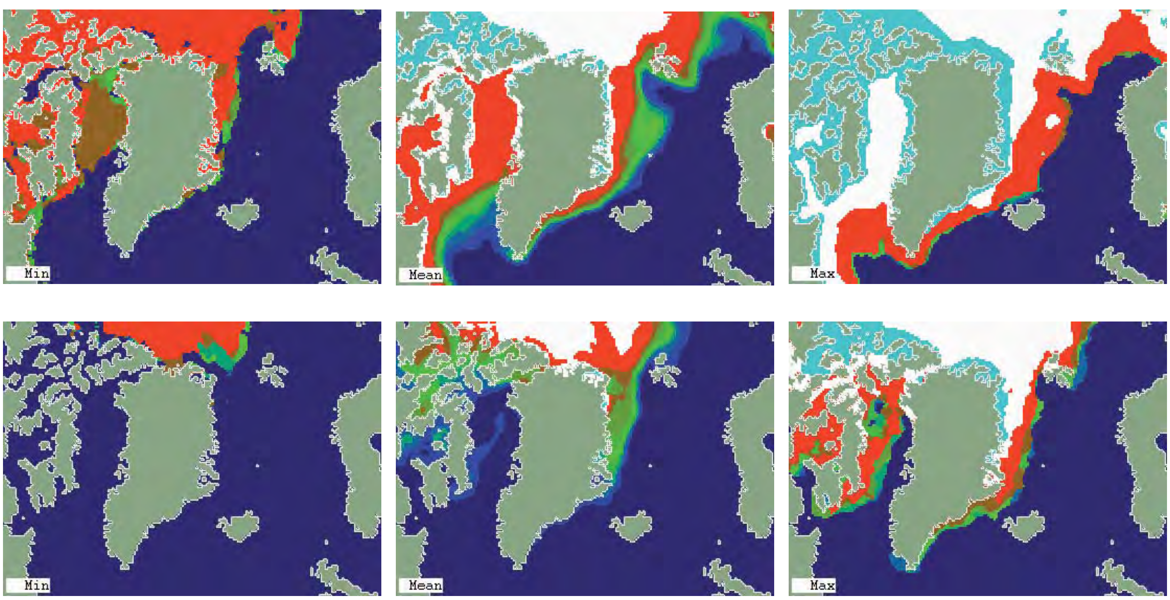


**Figure 1.5** Minimum, mean and maximum distribution of sea ice in February (above) and September (below), representing months with maximum and minimum ice distribution, respectively.

period a great part of the ice cover disappears, leaving behind a large ice tongue advancing into the Greenland Sea. The ”Odden“ phenomenon has been known for more than a hundred years, and because it appears nearly every winter, it can also be traced in maps showing the mean ice distribution. The Odden Ice Tongue phenomenon is closely related to the convection processes taking place in the Greenland Sea.

Since the distribution of sea ice is coupled to the climatic conditions of the area, great seasonal and interannual fluctuations in the amount of sea ice are observed. Statistical analyses have shown that the portion of the Greenland Sea covered with ice in years with maximum distribution of sea ice is much larger than in years with minimum distribution. The increase amounts to more than 100%, i.e. the interannual variations in ice cover are comparable with the seasonal variations within a given year (Fig. 1.5). More details about the local sea ice variability in the Young Sound area are given in Chapter 4.

## 1.4 Acknowledgements

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