THE ROLE OF OCEAN CURRENTS IN ARCTIC CLIMATE CHANGE

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Abstract
Water very efficiently absorbs solar radiation. Therefore, the seas and oceans are huge reservoirs of heat. They gather heat in the summer, and transfer it to the atmosphere in the winter. But the seas and oceans are dynamic structures, water is in constant motion. The article describes how oceanic currents are generated and how the heat contained in the oceanic water spreads on the whole Globe. Special attention has been paid to the Arctic. On the one hand Arctic is a great heat receiver, on the other, these processes play a role of a generator of the oceanic currents of large scale – the Thermohaline Circulation. Paper describes the study of Thermohaline Circulation, its climatic significance, today’s status and predictions for future.

key-words and Key concepts
climate, ocean currents, Thermohaline Circulation, Arctic. Climatic role of the ocean, wind and thermohaline forcing of global circulation.

INTRODUCTION
The most recent observations in climate change are very worrying. Until recently there was no certainty whether the climate is, in fact, warming, or whether it is just a temporary fluctuation. Today we know that these are no longer just normal weather anomalies. We have evidence that the globe is getting warmer and that we, the human race, are the ones responsible for it. In 2007, the fourth report of the Intergovernmental Panel on Climate Change, showed a very small margin of error, the probability that global warming is caused by the emission of greenhouse gasses was calculated at over 90%. The fifth report, from 2013, confirms these findings. As far as the direct causes of global warming are known, the mechanisms and long-term effects of this process are yet to be studied and fully understood. The Earth’s climate has proved to be an incredibly complex phenomenon, dependent on a large number of factors and processes.

The ocean is one of the most significant factors which shape the climate. It has long been known that the sea causes a milder climate: winters are warmer at the seaside, and the summers are cooler compared to inland areas. The importance of the Gulf Stream for the heating of the Atlantic part of Europe has also been known. The El Niño – La Niña cycles taking place in the Pacific Ocean have far-reaching effects. However, the ocean has never been thought of as the primary factor shaping the global climate, influencing it with a broad range of processes and in various timescales. The increased interest in the climate of the past few decades has revolutionized the way we perceive the importance of the ocean. The amount of heat absorbed, stored and transported by the ocean became significant, at the same time, the potential consequences of the hypothetical changes in ocean circulation became a topic of discussion. It was also understood that the ocean influences the climate not only as a significant component of the planetary hydrological and energy cycle. It also participates in the biogeochemical cycle, in the exchange of gases with the atmosphere, which influences the greenhouse effect. The ocean is a vast reservoir, a buffer for the most common greenhouse gas emitted by mankind – carbon dioxide.

Despite the growing understanding of the role of the ocean, the fourth IPCC report, the most serious study on climate change, includes the following statement: “Although scientists now better appreciate the strength and variability of the global-scale ocean circulation, its roles in climate are still hotly debated. Is it a passive recipient of atmospheric forcing and so merely a diagnostic consequence of climate change, or is it an active contributor?”. It is not until the fifth report from 2013 that the role of the ocean is made more specific: „Changes in the ocean may result in climate
feedbacks that increase or reduce the rate of climate change. The evolution of climate on time-scales from seasons to millennia is therefore closely linked to the ocean.”.

There has been no doubt among oceanologists for a long time: the ocean is an incredibly important, active factor in the shaping of our climate. The changes we observe directly affect the ocean, but it actively responds to them and modifies them. A crucial role in these processes is attributed to the Arctic regions of the Atlantic. This was first noticed in 1920 by Norwegian researcher Fridtjof Nansen who wrote: “It is evident that oceanographic conditions of the North Polar Basin have much influence on climate, and it is equally evident that changes in the conditions of circulation would greatly change the climatic conditions.”.

The ocean’s role becomes more significant in periods of noticeable warming of the climate. In addition to distributing heat, the ocean also mitigates global warming by accumulating excess heat caused by the greenhouse effect.

**HOW THE OCEAN AFFECTS THE CLIMATE**

We usually associate the climate with the atmosphere: air temperature and humidity, precipitation, wind. However, the atmosphere is not an isolated system. It interacts with all the components of the Earth system: the hydrosphere (oceans, rivers, lakes), the cryosphere (sea ice and snow on land), the lithosphere and biosphere. All these components put together form the climate system, the elements of which interact with each other by a series of processes. (Fig. 1).

![Figure 1. Schematic view of the components of the global climate system, their processes and interactions. Source: IPCC 2007.](image)

The ocean has always affected the Earth’s climate system and it continues to do so today. It is an extremely important, if not the most significant, element of the system. The ocean (and the life it produced) created the atmosphere and has shaped its composition over billions of years. It remains so today, by transforming energy and matter the ocean continues to be an active participant in the occurring changes. The ocean is a part of a system which interacts with the atmosphere, lithosphere and cryosphere through a broad spectrum of processes and a chain of various interactions. In order to understand its significance, it is enough to mention that:
The ocean covers 71% of the area of the globe and contains over 97% of all the water on Earth.

The global hydrological cycle is dominated by evaporation from the ocean.

Most of the energy of sunlight that reaches the Earth is absorbed in the surface layer of tropical oceans.

The ocean gives off heat by evaporation, water vapor gives off latent heat to the atmosphere by condensation.

The evaporation-condensation process in the equatorial region of the ocean initiates the global large-scale atmospheric circulation by creating circulating Hadley cells.

The condensation of water vapor at higher latitudes causes storms and strong winds.

The ocean additionally heats the atmosphere by emitting infrared radiation.

The ocean controls CO₂ content in the atmosphere and dominates the global carbon cycle.

Oceanic phytoplankton has a significant effect on cloud formation by increasing SO₄ content in the atmosphere.

Sea ice dramatically changes the albedo of water surface; most of the sunlight that reaches it is reflected back.

The ice forming process produces denser deep ocean water which slowly flows through oceanic basins and initiates deep ocean circulation.

Drifting sea ice transports fresh water from polar regions to the tropics.

Most of the excess heat generated by global warming is stored in the ocean.

The ocean transports enormous amounts of heat through a system of ocean currents.

This list shows that the ocean plays a number of important roles in the shaping of the climate. Two of the most significant roles being:

1. The regulation and mitigation of the climate by absorbing excess heat during the summer, storing it and returning it when the atmosphere is cooler.

2. Redistribution of heat in large-scale ocean circulation.

Figure 2. Energy accumulation within the Earth’s climate system. Estimates are in 10²¹ J, and are given relative to 1971 and from 1971 to 2010, unless otherwise indicated. Components included are upper ocean (above 700 m), deep ocean (below 700 m; including below 2000 m estimates starting from 1992), ice melt (for glaciers and ice caps, Greenland and Antarctic ice sheet estimates starting from 1992, and Arctic sea ice estimate from 1979 to 2008), continental (land) warming, and atmospheric warming (estimate starting from 1979). Uncertainty is estimated as error from all five components at 90% confidence intervals.
WHAT POWERS THE OCEANIC CIRCULATION?

Movement of the ocean is caused by many processes. The primary force driving the movement of surface layer currents is the friction of wind against the surface of the water. The ripples that appear further increase friction and make the surface more susceptible to wind. Wind blowing at a constant speed of 100 cm/s for 12 hours produces a current of merely 2 cm/s. Despite that, most surface layer currents that occur in the upper 100 m are wind-driven (Fig. 3). Changes of flow patterns are caused by the Coriolis effect. The effect is caused by the rotation of the Earth. This force causes particles on the surface of the Earth to be deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The further away from the equator, the stronger this effect becomes. The result of the Coriolis effect is that the average water flow is perpendicular to the driving wind direction.

Figure 3. Wind direction (gray arrows) and large-scale surface ocean currents. Warm currents are marked red and cold currents blue. Source: https://www.pmias.com/ocean-currents-factors-responsible-formation-ocean-currents-effects-ocean-currents/.

The structure of large-scale surface circulation is also determined by the shape of ocean basins. Further analysis allows us to identify several common features for all oceans. The most important of those is the presence of large subtropical ocean gyres above and below the equator in the Atlantic Ocean, the Pacific and the southern Indian Ocean. They circulate in an anticyclonic manner – clockwise in the northern hemisphere and counterclockwise in the southern hemisphere. At the western edges of the basins the currents flow towards the polar regions carrying warm water. These currents are much more powerful than in other regions and are among the fastest in the world’s oceans. In the North Atlantic Ocean, this current is the Gulf Stream – a flow that modifies the climate of the entire region, and its extensions – the North Atlantic Current, the Norwegian Atlantic Current and the West Spitsbergen Current reach even further north and significantly affect the Arctic climate. In tropical regions, along the eastern edges of ocean basins, a system of permanent currents and winds leads to the creation of the largest deserts of the world due to the lack of moisture in the air. Wind-driven surface currents usually have speeds of several dozen centimeters per second, reaching sometimes over one hundred centimeters per second.

Ocean currents occur also at depths of thousands of meters. These currents are caused by different mechanisms than surface currents. The movement of water is caused by differences in
density, resulting in horizontal pressure differences. Because water density is determined by temperature (Latin: *thermo*) and salinity (Latin: *haline*) this type of circulation is called thermohaline circulation (THC) (Fig. 4).

![Thermohaline circulation diagram](image)

**Figure 4.** Global thermohaline circulation. Surface currents are marked with red lines, deep currents are marked with blue lines. The main areas where deep water is formed are marked with yellow circles. Source: [http://worldoceanreview.com/en/wor-1/climate-system/great-ocean-currents/](http://worldoceanreview.com/en/wor-1/climate-system/great-ocean-currents/).

The differences in temperature and salinity are made possible by the existence of climate zones. Ocean water cools in the polar regions (the Arctic and Antarctic). Sea ice forms on the surface. When sea ice forms, most of the salt is pushed out and back into the water. The water below sea ice has a higher concentration of salt and is more dense, as a result it sinks into the depths below. This is called convection. Surface water then replaces the sunken water until, after some time, it also becomes salty and dense enough to sink. This process initiates both surface currents as well as deep ocean currents which together form the “global conveyor belt”. It begins in the polar regions of the North Atlantic and in the Arctic Ocean. From there the dense deep water masses flow southwards, until they reach the edge of the Antarctic. The water is cooled again in the Southern Ocean which strengthens the global conveyor belt. Flowing along the edge of the Antarctic, the deep ocean current splits into two and turns north, flowing into the Pacific and Indian Oceans. Upon reaching the northern parts of these basins, the currents make a loop and flow back towards the equator. Deep water is warmed along the way, it becomes less dense and rises to the surface in the eastern parts of the basins in a process called *upwelling*. Then the surface water flows to the South Atlantic, finally reaching the North Atlantic where the loop begins again. The movement of water in the conveyor belt is much slower than in surface currents – at speeds of several cm/s. It is estimated that it takes 1000 years for a water particle to complete the cycle. Despite this, it is responsible for the movement of huge amounts of water – 5000 thousand times more than the Niagara Falls. Warm water carries heat from the tropics which is then released at mid and high latitudes. The scale of this heat transfer is well illustrated in an image created by Stefan Rahmstorf (Fig. 5) a well know climatologist. The entire north-west region of Europe is 5-10 °C warmer than it would otherwise be based on its geographical location.
EARLY STUDIES OF OCEANIC CIRCULATION

In 1751 captain Henry Ellis, commander of a British ship carrying slaves found that water extracted from the depths of the ocean is ice-cold. The vessel was on the 25th parallel north at the time of the experiment. The crew extracted seawater from various depths with the use of a specially designed bucket with a system of valves and measured its temperature. In a letter to the author of the experiment the captain wrote: “The cold increased regularly, in proportion to the depths, till it descended to 3,900 feet: from whence the mercury in the thermometer came up at 53 degrees (Fahrenheit); and tho’ I afterwards sunk it to the depth of 5,346 feet, that is a mile and 66 feet, it came up no lower”. This was the first recorded deep ocean water temperature measurement, giving an immediate result of great significance: deep ocean water is cold. This was the first documented observation of the effects of thermohaline circulation. The correct explanation for this phenomenon was published in 1797 by inventor and physicist Benjamin Thompson: “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”.

The growth of maritime shipping lead to the continuously improving understanding of the oceans. In 1832 James Rennel, a surveyor for the Royal Navy and East India Company, published a map of the surface currents of the Atlantic Ocean. This map was the first to show the possibility of exchange between the North and South Atlantic and elements of THC.

Many theories were developed in the wake of the gathered empirical information about the ocean. In 1845, the Russian-German physicist Heinrich Lenz further developed Thomson idea by building a conceptual model of two circulation cells located symmetrically in relation to the equator, where upwelling takes place near the equator, downwelling occurs in polar regions, cold water is moved near the ocean bottom, and compensating warm surface flows towards the poles.

The great oceanographic expeditions of the second half of the 19th century and first half of the 20th century produced new maps and three-dimensional sketches of global ocean circulation. Such schematics were created after the Challenger expedition (1872-1876), Valdivia expedition (1898-1899) and Meteor expedition (1925-1927). At the same time, researchers became aware of the importance of ocean circulation in shaping the climate.

At that time, oceanographic studies of the North Atlantic area were launched, initiated by northern European countries and Russia. In 1861, Danish admiral Carl Irminger described an ocean current which was later named after him. The Danish expeditions discovered the Greenland-Iceland and Greenland-Scotland ridges. In 1868, a British expedition found the first evidence of arctic and Atlantic water masses in the South Shetland Trench.
Swedish and Russian expeditions focused mainly on the Spitsbergen region. It was discovered in the beginning of the 20th century that the West Spitsbergen Current (WSC) carries Atlantic water into the Arctic Ocean, and that some of that water might recirculate back south with the East Greenland Current (EGC). This discovery confirmed the origin of the relatively warm water masses observed in the East Greenland Current by the Danish expeditions.

Another significant expedition was Fridtjof Nansen’s 1893-1896 Fram expedition in which the plan was to freeze the ship Fram into the Arctic ice sheet and float with it over the North Pole. The expedition provided basic information about the Arctic Ocean, the geography and hydrography of the basin. During his voyage, Nansen became certain of the extraordinary importance of the exchange between the Atlantic and Arctic Oceans.

In the year 1900, Norwegian scientists received the SS “Michael Sars”. After four years of research, Helland-Hansen and Nansen presented a detailed description of the hydrographic conditions of the Nordic Seas which became the primary source of information about the physical oceanography of these areas. The quality of the results and the relevance of their work amazes scientists to this day.

In 1905, Russian researcher Nikolai Knipovich described very cold (bordering on freezing temperatures) and very salty deep sea water as a product of the displacement of salt from sea ice forming in the Barents Sea.

In 1909, based on the observation of the cold bottom waters of the Greenland Sea, Nansen presented the first classic model for the forming of Greenland Sea Deep Water (GSDW). By doing so, Nansen sparked the nearly century-old discussion about the origin and significance of GSDW and the process of deep convection.

In the early 1920s, American geologist Thomas Chamberlin formulated the idea that climate change is caused by changes in global ocean circulation.

After a scientifically active period of the early 20th century came a period of stagnation for the research of the Nordic Seas. Data was collected only in the years 1935-1936 in the Norwegian Basin, and after that in winter in the early 1950s. The winter data didn’t produce the expected results – no homogenous column of cool water was found, and so deep convection was determined to be an insignificant process.

**CURRENT VIEWS ON THERMOHALINE CIRCULATION**

During the 1950s, American oceanographer Henry Stommel did pioneering work on a 3-dimensional map of the ocean floor and ocean circulation. In the year 1957, he revolutionized the concept of Atlantic circulation, and in 1961 he introduced the concept of “thermohaline circulation”.

It was not until more than 100 years after Thompson’s work, in 1987, that the circulation theory of the Ocean Conveyor Belt was formulated. American researcher Wallace Broecker, in 1987 presented the concept of a system of surface and deep-water currents connecting all the oceans and transporting salt and heat between them. This revolutionary idea had as many followers as it had opponents. Broecker postulated that changes in Atlantic thermohaline circulation led to the rapid and widespread climate changes experienced by the North Atlantic during the recent glacial periods.

The following years saw numerous variations of the idea of a comprehensive circulation system interconnecting the World Ocean, as well as improved and corrected schematics, new terms and so on. The primary force and the fundamental processes behind this circulation are still disputed today. Finally – in the period of noticeable warming of the climate, the role of ocean currents in the shaping of the climate has become widely discussed, especially the importance of the Ocean Conveyor Belt, including the possibility of its change or even cessation. The Arctic Ocean and the adjacent seas – a key region for this circulation became a primary object of research for oceanographers, meteorologists and climatologists.

Today’s views on the Global Ocean Conveyor Belt differ from those presented by Broecker. Thermohaline circulation became the leading theory for global ocean circulation, while the north-south movement of water in the Atlantic Ocean is attributed to Meridional Overturning Circulation (MOC) also called the Atlantic Meridional Overturning Circulation (AMOC). The role of the
Atlantic Ocean, and especially the processes taking place in its northern regions – the Nordic Seas and the Arctic Ocean, is regarded to be the mainstay of sustaining thermohaline circulation.

According to today’s knowledge and views on climatic phenomena, THC is the main mechanism driving ocean currents. The cooling of water and forming of sea ice at high latitudes increases the density of water to a point which allows the initiation of deep convection and other processes, together called thermohaline ventilation (Fig. 6). In the northern hemisphere, deep water is formed primarily in the northern Atlantic Ocean in regions separated from the southern parts by the Greenland-Scotland Ridge (GSR). 75% of Atlantic water flowing over the ridge and into the Arctic Ocean is transformed into dense and salty North Atlantic Deep Water (NADW). On the other end of the circulation loop, in the tropical zones of the Pacific and Indian Oceans, the processes of vertical circulation cause an increase in the temperature, a decrease in density and the consequent upwelling of deep water. As a result of cooling and ventilation at high latitudes, and heating and vertical circulation at low latitudes a horizontal difference in water density is created which forces the surface flow of warm and salty water towards the poles and a deep flow toward the equator. The primary water mass created in the chain of processes of ventilation and water flowing over the Greenland-Scotland Ridge is the North Atlantic Deep Water which supplies most of the deep water of the world’s oceans. Global Ocean.

![Figure 6. AMOC. The process of NADW formation (Hansen et al., 2004)](image)

This simplified description of the functioning of THC does, however, have its opponents. The differences in opinion are a result of the fact that THC is a much more complicated process that the sketch presented above. All of its stages are connected by strong feedback loops which makes determining a chain of cause-and-effect very difficult. Thermohaline ventilation processes are considered principal here. It is the process of convection in the Arctic that generates horizontal differences in density and pressure that drive the exchange between the Arctic and the Atlantic. Thanks to their high salinity (despite mixing with less saline waters from the surrounding seas), surface waters in the north Atlantic reach a density high enough to sink to the bottom, replacing the water masses residing there, and making way for water arriving from the south. This is the origin of the term *thermohaline* circulation, as the process is driven by differences in salt content and the density of seawater. The phenomenon of a stable global circulation of the oceans is often compared to the operation of a thermodynamic machine fueled by the cycle of heating/evaporation at low altitudes and cooling/condensation at high altitudes. This view bears a resemblance to atmospheric circulation – Hadley cells.
The most important difference between the atmosphere and the ocean is that, unlike the atmosphere, the ocean is heated and cooled only on the surface, and a stable vertical stratification occurs in almost all its volume. Thermohaline ventilation – contact areas where deep ocean water reaches the surface, can only occur in specific, limited areas. In the northern hemisphere, these areas are the Labrador Sea, the Greenland Sea and the continental shelves of the Arctic Ocean, in the southern hemisphere ventilation occurs near Antarctica – in the Ross Sea and Weddell Sea (Fig. 4). Despite a direct connection with the Arctic Ocean and sufficient cooling, there are no convection sites in the Pacific Ocean, as surface water in the pacific is not salty enough to reach deep water densities. The Indian Ocean is closed from the north so it cannot participate in the described processes.

The areas where surface water descends into the depths are the “flywheels” of thermohaline circulation. The potential energy of water masses is converted here into the kinetic energy of ocean currents. From the point of view of the formation of the THC and the climate of our hemisphere, the North Atlantic along with the Nordic Seas are the most important reservoirs, and the Greenland-Scotland Ridge is the most important underwater landform. The flows that occur above this ridge – deep currents flowing south, and compensating surface currents flowing north, determine the amount of volume and heat exchanged between the North Atlantic and the Arctic Ocean along with the Nordic Seas.

Apart from the vertical exchange of water (convection) and the currents it causes, there is another significant type of circulation in the Arctic – horizontal estuarine water circulation. Warm and salty Atlantic Water (AW) mixes with freshened surface water in the Nordic Seas and Arctic ocean, after which, cooled and less salty, it flows back south in a process called recirculation. The cold, low-salinity East Greenland Current flows southwards from the Arctic Ocean as well. These two types of circulation, which form the unique current system and ocean conditions of the Arctic, are sensitive to climate change.

There has been a lot of misunderstanding and confusion around THC. It is often the case that wind-driven currents such as the Gulf Stream are identified with THC. These two circulations overlap locally in the surface layer and both transport Atlantic Water northwards. However, they have a different range, other routes, and above all, different mechanisms that drive them. THC is also often identified with AMOC, both names are used interchangeably. THC is mainly a physics-based idea which focuses on global ocean circulation driven by thermohaline forces. AMOC, on the other hand, covers the total of all north-south flows, and the driving forces behind them are not distinguished here. Contrary to THC, the surface section of AMOC includes wind-driven currents while deep currents are the effect of overturning. Therefore, the idea of AMOC includes, in a simplified way, both wind and thermohaline circulation.

Water transport (in rivers or ocean currents) is measured in m$^3$/s, a commonly used unit is the Sverdruk (1 Sv=10$^6$ m$^3$/s). 1 m$^3$ of fresh water weighs an average of 1000 kg, seawater weighs approximately 1027 kg. The amazon, the largest river in the world, transports an average of 120 000 m$^3$ of water each second, which is equal to 0.12 Sv. Ocean currents have much higher flows. It is estimated that the northern part of AMOC generates a flow of around 17 Sv, 140 times more than the Amazon river. This illustrates the sheer volume of water and heat transported by the global conveyor belt.
OCEAN CURRENTS IN THE ARCTIC

The arctic and subarctic, and especially the Nordic Seas (Norwegian Sea, Iceland Sea and Greenland Sea), are linked to the global climate system mainly by balancing the heat the system receives at low latitudes and releases at high latitudes. This heat is accumulated and transported by the atmosphere and the ocean. Only 3–5% of the heat supplied by the ocean-atmosphere system to the polar regions comes from oceanic advection, however, oceanic processes have unusual importance in the formation of the Arctic climate. The ocean's heat capacity is 1000 times that of the atmosphere. The heat absorbed at low latitudes is stored, transported and released, often with great delay, in another region.

Most of the heat is collected in the top 700 meters of the ocean, but a portion of it is transported from surface waters to deep layers. On the 30th parallel north, currents from all the oceans carry 2 PW (2 \( \times 10^{15} \) W) of sensible heat from the tropics to the polar regions – an amount equal to atmospheric transport. On the 60th parallel north, 0,4 PW of heat is transported towards the Arctic, mainly by the warm and high salinity Atlantic Water. During the northward transport of AW, heat fluxes of 200 W m\(^{-2}\), delivered by the ocean in winter, warm the atmosphere and modify its circulation. As a result, the Arctic Ocean receives significantly less heat than the Nordic Seas. Oceanic transport of heat to the AO, through the Fram Strait is equal to 16–41 TW (1 TW=10\(^{12}\) W). Nonetheless, even this diminished amount of heat is essential for the balance of the climate system.

Water masses and currents in the North Atlantic, Nordic Seas and Arctic Ocean are closely related to the bathymetry of these waterbodies – the shape of the coastline and depths. The Arctic Ocean is actually a vast mediterranean sea enclosed by Eurasia from the east, and North America from the west (Fig. 7). Between them is the world’s largest island – Greenland. Between Greenland and North America located is the Canadian Arctic Archipelago – a shallow region with hundreds of islands and narrow straits. The central and western parts of the Arctic Ocean consist of deep basins with dozens of ridges crossing them, the eastern part comprises of wide, shallow shelves. Situated on the edges of the shelves, near the Eurasian Basin, are the arctic archipelagos of: Svalbard, Franz Josef Land and Severnaya Zemlya.

The Arctic Ocean is connected to the Pacific via the narrow and shallow Bering Strait. The water exchange here is limited due to the size of the strait. Much better access to the Arctic Ocean is from the Atlantic side. There is a deep and relatively wide passage between Spitsbergen and Greenland called the Fram Strait. It is over 300 km in width which allows a two-way water exchange: the inflow of warm and salty water from the Atlantic into the Arctic Ocean at its eastern side, and the outflow of cold and less saline Polar Water at its western side (Fig. 8). The warmer water causes the eastern side of the strait to remain ice-free even during the winter. In addition, Atlantic Water reaches the Arctic Ocean through the Barents Sea, Polar Water flows out through the Canadian Arctic Archipelago.
Figure 7. Bathymetry of the Arctic Ocean and North Atlantic. Source: International Bathymetric Chart of the Arctic Ocean (IBCAO).
Figure 8. Layout of major surface currents in the Nordic Seas and the Arctic. Red lines – warm and saline surface water from the Atlantic, green lines – Pacific water. Author: Agnieszka Beszczynska – Möller.

Atlantic Water reaching the Arctic forms the surface branch of AMOC. It is carried from the tropics by the Gulf Stream and its extension – the North Atlantic Current. Further north, the system of current becomes more complicated (Fig. 9). The warm currents divide into a series of branches.

The most important branch of the inflow of Atlantic Water, flowing along the continental shelf of the Norwegian and Barents Seas, flows directly into the Arctic Ocean through the Fram Strait. It is a sequence of the Norwegian and Shetland currents, along with the eastern part of the West Spitsbergen Current. The Norwegian Sea receives 3.5-4 Sv of water and over 140 TW of heat, the Arctic Ocean receives nearly 2 Sv of water transporting 36 TW of heat through the Fram Strait. A smaller current branches off near Norway and flows through the Barents Sea. The distance it travels is greater which causes it to release more heat, therefore, the water it carries is cooler as it reaches...
the Arctic Ocean. At the edge of the Eurasian Basin, both flows join again and encircle the entire Arctic Ocean (Fig. 8).

Figure 9. Main flows of Atlantic Water in the Nordic Seas:
IC – Irminger Current,
NIIC – North Icelandic Irminger Current,
NAC – North Atlantic Current,
NwAC – Norwegian-Atlantic Current,
NwASC – Norwegian Atlantic Slope Current,
WSC – West Spitsbergen Current)
(Source: Walczowski, 2014)

The second important branch of the transport of Atlantic Water in the Nordic Seas runs between Iceland and the Faroe Islands and further north over a system of underwater ocean ridges. These are the Faroe Current, the Norwegian Atlantic Current and the western branch of the West Spitsbergen Current. The Faroe Current carries approximately 3.3 Sv of water and 110 TW of heat. This branch merges partially with the eastern branch near Spitsbergen. A vast majority of water carried by this system of currents flows back south before reaching the Fram Strait. Even though it doesn’t reach the Arctic Ocean, it has great influence over the regional, and possibly global, climate. The recirculation of warm water allows for most of the basin to remain ice-free throughout the year. Heat fluxes releasing heat to the atmosphere moderate the winters in the entire eastern part of the basin. The salty Atlantic Water sinks after winter cooling and is an important component of deep water – the initiator of thermohaline circulation.
HOW ARE OCEAN CURRENTS MEASURED?

Measuring the amount of water and heat transported by ocean currents is one of the most difficult tasks faced by oceanographers. This is due to both the nature of ocean currents – their high spatial and temporal variability, and the technology and means of measurement available today. Recent years have brought significant progress in this area, but we still have a lot to do.

The movement of water is measured with a current meter. In the past, these were mechanical devices, recording spot measurements of the speed and direction of the current. The development of electronics allowed for more precise measurements and more efficient data recording. The field was revolutionized with the introduction of the Acoustic Doppler Current Profiler (ADCP). The measurement is performed remotely, using the Doppler effect generated in an acoustic wave emitted by the meter and reflected from particles floating in the water. The ADCP allows for the simultaneous measurement of currents in different cells, in a water column 50 – 400 m high. As a result, the ADCP can replace a series of spot measurement current meters. In general, current meters are mounted on subsurface buoys anchored to the seafloor. This sort of measurement is easier, the vector of the current is measured in relation to the immobile seafloor. Ship mounted measurements are also conducted. These measurements are more complicated because we record the relative velocity of the current which is the sum of the velocity of the current, and the ship.

Unfortunately, single spot measurements do not provide information on the total mass and energy transport of the studied ocean current. This is why, in important places such as straits, scientists position a line of buoys perpendicularly to the researched current (Fig. 10). This kind of equipment must contain a current meter, to measure the water transport, as well as instruments for measuring temperature and salinity, to measure the transport of heat and salt. These installations are very expensive and their resolution is usually far from perfect. That is why the estimated volumes of transport usually have a large margin of error. In addition, in the Arctic such installations must be fully submerged in order to avoid collision with drifting sea ice, or freezing into the permanent ice cover. This makes remote data transfer impossible, all instruments must be retrieved and exchanged every year, or operated on site.

Figure 10. A series of anchored measuring rods across the Fram Strait operated by the Alfred Wegener Institute (AWI) and the Norwegian Polar Institute (NPI) since 1997. In 2010-2011, spot metering, ADCP, and temperature and salinity recorders were installed there. The measurements were assisted by Seaglider autonomous submarines. Source: Beszczynska-Möller et al., 2011.
Another revolution in oceanography was caused by the Argo system. It is a system of autonomous profiling buoys which drift freely in the ocean (Fig. 11). A standard Argo buoy carries out measurements from the surface to 2000 m deep. The data collected is then transmitted to reception centers via satellite. The real-time data allow for much more accurate weather forecasts and a better assessment of the ocean’s thermodynamic state. The buoys cannot be steered, but currently there are 2000 Argo boys in service which provides sufficient cover of the researched areas. The exception being the Arctic, where due to the presence of ice, the working time of the buoys is heavily limited.

Figure 11. Argo observation system. The buoy descends to the so called “parking depth” where it drifts for a pre-programmed amount of time (usually 9 days). After that, the buoy descends to a pre-programmed maximum depth and begins its ascent measuring the temperature and salinity in the water column. The data collected is transmitted via satellite, after which the cycle begins again. Source: http://www.argo.ucsd.edu/How_Argo_floats.html

FUTURE PREDICTIONS

The leading hypothesis explaining the rapid climate change that has taken place in the northern hemisphere over the past millennia is the change in the amount and location of deep water, formation, especially NADW, and the consequent change in the intensity and range of thermohaline circulation. Data obtained from ice cores confirms this hypothesis. Thanks to modern ice core dating technology, cores taken from the Arctic (Greenland) and the Antarctic have been precisely correlated in time. The results showed that every single temperature rise in the Arctic was correlated with a temperature decline in the Antarctic. This correlation is taken into account in present-day climate models based on the AMOC idea. A temperature rise in Greenland results in the intensification of AMOC, larger heat transfer from the tropics to the North Atlantic, and a temperature decline in the south. Furthermore, data obtained from ocean sediments shows that
significant changes in strength and range of thermohaline circulation have occurred in the past. There are three main phases of circulation:

- Heat phase, similar to the current state of North Atlantic circulation.
- Cold phase, during which deep water is formed south of Iceland.
- Transitional phase between the warm and cold phases.

The transition from the warm to cold phase can occur in a period of intensive inflow of fresh water into the ocean surface layer as a result of the melting of glaciers or rapid iceberg calving and the direct release of freshwater to the ocean. Glacial periods in North America and Europe occurred during the cold phase of thermohaline circulation.

The question is, can such scenarios happen again in the future? What is the time-scale of these changes? The global conveyor belt is a powerful but delicate process. Simulations show that its responses are non-linear. This means that sometimes a small change in external conditions can lead to a sudden “switch” between the cold and warm phases when the sensitivity threshold is exceeded. The changes that are currently being observed in the climate system may have negative and hard to predict effects on the circulation. They can affect the process in two ways: by heating the surface layer of the ocean and by freshening it. Both processes lead to the decrease of surface water density. In the Arctic, this can cause a reduction in the amount of deep water formed. An increased inflow of fresh water in the Arctic can have a particularly bad effect on global thermohaline circulation. Increased precipitation over the North Atlantic, the melting of glaciers and sea ice, increased inflow of fresh water from the great Siberian rivers – these processes are presently capable of curbing the formation of sea ice and stopping the sinking of cold water into the depths. This way, the driving force, the most important process of thermohaline circulation is being weakened or even stopped. This could cause drastic temperature changes in the northern Hemisphere, and possibly around the globe. It is without a doubt that Europe would be most affected by these changes.

The question that scientists ask themselves, regarding the future of THC and its effects on the climate, is whether or not there is a risk of exceeding the sensitivity threshold of thermohaline circulation at the present state of global warming. The answer to this question largely depends on the future changes in freshwater balance in the North Atlantic and the Arctic. Unfortunately, it is impossible to predict these changes with sufficient accuracy. The melting of Arctic glaciers, and especially the Greenland Ice Sheet, is a process of considerable dynamics. The margin of error in the estimations of fresh water inflow into the ocean is still too great. We also do not know the future greenhouse gas emissions.

The total stop of thermohaline circulation and rapid climate change in the foreseeable future seems unlikely and is present only in the most pessimistic scenarios. However, these scenarios do exist. Simulations carried out in 2017 show that AMOC could collapse 300 years after reaching an atmospheric CO2 content twice as high as in 1990. This would lead to the significant cooling of the North Atlantic and of the adjacent continents. However, much more likely than the total collapse, is the weakening of the global conveyor belt by about 20-50 %. This scenario is present in many numerical simulations. Also, scientists researching AMOC have frequently reported a decrease in its intensity, both at the surface and in the depths.

There are many questions that still remain unanswered. We do not even know whether stopping thermohaline circulation would simply cause a decline in warming or rapid cooling and a new ice age. But I am sure that we will not experience this in the nearest future.
REFERENCES