The Arctic: Nansen's Upside-Down Ocean

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ABSTRACT

The Arctic Ocean is located at the North Pole, sometimes considered the top of the world. Yet this ocean has been called an "upside-down" ocean by famous oceanographer Fridtjof Nansen. Around most of the globe, the surface ocean is warmed by the sun and loses freshwater through evaporation, making it warmer and saltier than the waters below. In the Arctic, cold, fresh water lies above warmer saltier water that comes from south of the Atlantic. We explain why the Arctic is stratified in this way, how climate change is affecting it and why it matters to us.

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1 INTRODUCTION

The oceans cover 70% of the globe and most of this water is found at the low to mid-latitudes where the sun warms the surface ocean. All this sunshine also drives evaporation which removes freshwater from the ocean's surface, leaving behind the sea salts. This means that in most oceans, we expect to find warm and salty water at the surface while deeper water tends to be cooler and less salty. So, when the Norwegian explorer, Fridtjof Nansen sailed into the Arctic Ocean on his quest to reach the North Pole in 1893-1896 (Fig. 1) and found cold fresh water at the surface with warmer saltier water below, he described the Arctic as an 'upside-down' ocean (Nansen, 1898). This early observation of Arctic Ocean water column structure has been confirmed by numerous oceanographic measurements since, and remains true today. Nansen also already knew that the Arctic Ocean was covered by sea ice, and that a Transpolar Drift of this ice exists which would carry his expedition from Siberia across the North Pole back toward Norway. While they missed the Pole by only a few hundred kilometres, the expedition generated a wealth of new findings and provided important basic knowledge for modern-day Arctic Ocean science.

Since Nansen's time, the Arctic has experienced climate change at twice the rate of lower latitudes and lost a lot of perennial sea ice. Arctic Ocean climate change effects are not limited to the sea ice, but are also beginning to become important below the surface. Some answers about just how climate change is affecting the modern-day Arctic sea ice, ocean, and ecosystem will come from the "MOSAiC" expedition (https://follow.mosaic-expedition.org/), launched in October 2019, which began a repeat of Nansen's drift (Fig. 1). In the meantime, to understand how climate change might affect the subsurface ocean, we must consider why there are layers of different water types (or water masses) in the Arctic Ocean and think about where they came from.

2 ARCTIC OCEAN WATER COLUMN STRUCTURE

2.1 Temperature, Salinity and Stratification

Seawater density depends on both its salt concentration (salinity) and its temperature. As water temperature increases, it expands and its density decreases, making it lighter. Dissolved salts add mass and increase the density of seawater. The temperature effect on density dominates in warmer waters (¿5C), which cover most of the global ocean. So, you will typically find warm water overlying colder water regardless of salinity, which actually varies very little from about 34 g/kg to 37 g/kg as long as you are far enough away from freshwater sources like rivers and ice.

In cold waters such as those of the Arctic Ocean, the salinity effect on density dominates over temperature. Here, you will find cold and fresh water at the surface that has origins in sea ice melt and Arctic river runoff (Fig. 2). Below the very cold fresh surface layer, is saltier, denser but warmer water that has come from the Pacific or Atlantic (saltiest) Oceans. When these warm salty water masses mix with the cold fresh surface layer above, they form an intermediate layer known as the Arctic halocline across which there is a large salinity gradient (Fig. 2). This gradient forms a barrier, which prevents that warm deep waters from melting the sea ice. Below the Atlantic Water, the Arctic Ocean is filled with a fresher and cold (¡0C) water mass known as Arctic deep water.

2.2 Sources of freshwater, saltwater and heat

Arctic rivers are the major source of freshwater, providing 10% of global river run-off to an area that accounts for 6% of the area of the globe covered by water. This makes the Arctic Ocean the freshest of all the global ocean basins. Fresh river water is dispersed by winds, tides and continental shelf sea circulation away from the estuaries and a lot of it ends up piled into the middle of the Beaufort Gyre. Some of the river water mixes with saltier seawater on the continental shelf seas, gaining density and ends up in the Arctic halocline, rather than at the surface.

Another source of freshwater for the central Arctic basins is the very low salinity sea ice that drifts over from the continental shelf seas where they are formed. During sea ice formation, ice crystals form from seawater that rejects most of its salt as dense brines. The dense brines fall through the water column below, mixing with the cold fresh shelf water and forming dense shelf water that eventually slips down the continental slope and fills the deep Arctic Ocean.

The saltiest water in the Arctic comes from the Atlantic Ocean, where it enters the Arctic through Fram Strait between Greenland and Svalbard, and also the Barents Sea Opening, between Svalbard and mainland Norway (Fig. 1). Due to the rotation of the earth, Atlantic Water deviates to the right after leaving Fram Strait to follow the continental slope around the Arctic in an anti-clockwise manner. Although near the surface as it enters through Fram Strait, Atlantic Water rapidly subducts below the lighter fresh cold Arctic surface waters as it flows east. Slightly fresher warm Pacific Water joins this anti-clockwise circumpolar circulation when it enters the Arctic through Bering Strait, settling just above the Atlantic Water.

3 THE ARCTIC INFLUENCE ON GLOBAL CIRCULATION

As the Pacific and Atlantic Water circulate around the Arctic, they are subject to various mixing processes during which they lose heat and salt to the other Arctic water masses, sea ice and the atmosphere, eventually exiting the Arctic through the Canadian Archipelago or as a deep cold fresh current in western Fram Strait. This transformation of warm salty Atlantic/Pacific waters into colder fresher water masses represents a transfer of heat from lower to higher latitudes by the ocean-atmosphere climate system. The exchange of the inflowing near-surface warm water for a denser deeper outflow through Fram Strait is also the northernmost component of the global ocean heat conveyor belt which regulates global climate.

4 CLIMATE CHANGE IMPACTS ON THE ARCTIC OCEAN, ICE AND ECOSYSTEMS

Over the last few decades since satellites have been making global measurements, Arctic sea ice has experienced a precipitous decline (Fig. 3 and Stroeve et al., 2007). New sea ice forms every winter, but the melt season has arrived earlier and lasted longer in recent years. This increased melt, together with greater wind-driven export of the floating sea ice through Fram Strait has resulted in ever decreasing minimum summer sea ice extent, usually achieved in September. As we have lost sea ice extent, we have also lost sea ice thickness as the older multi-year ice has been exported from the Arctic.

Recent research points towards multiple causes of the sea ice loss. White sea ice reflects a lot more solar radiation back out to space as compared to darker open water which absorbs solar radiation. As more water is exposed by sea ice melt, more heat is stored in the ocean, rather than reflected out to space. This extra stored heat is then available to further melt the ice creating a negative feedback (Perovich et al., 2008). More open water also means greater areas over which wind energy can be transferred to the ocean to mix up the different layers and may allow more of the subsurface Atlantic/Pacific heat to reach the surface. At the same time, the temperature of the inflowing Atlantic Water has been rising and the ocean is carrying more heat northward. In summary, there is more heat arriving in or absorbed by the Arctic ocean and more opportunities to bring that heat in contact with the sea ice.

Disappearing sea ice results in greater areas of seawater, where the ocean and atmosphere can exchange heat and freshwater directly. In practice, as the seawater is typically warmer than air temperatures, the ocean is an increasingly important source of heat for the atmosphere and regional air temperatures have warmed in response. Disappearing sea ice also means more light penetrates the ocean for longer periods, providing more energy for photosynthesis by sea ice algae and phytoplankton which is reflected in increases in primary productivity estimated from satellite measurements (Arrigo and van Dijken, 2015). These satellite-derived estimates of primary productivity are higher than expected from the increased light availability alone, implying that mixing up of warm nutrient-rich Pacific and Atlantic Waters is also occurring. As oceanographic conditions change in the Arctic, we have also seen a change in phytoplankton species, with the smaller-cell-sized species that favour nutrient-rich conditions becoming more dominant (Li et al., 2009). The repercussions of this species shift in the Arctic on larger organisms that depend on these primary producers at the bottom of the food chain continue to be a focus of many scientific studies. Meanwhile, the detrimental effect of sea ice loss on ice-dependant hunters such as polar bears, seals and walruses is already apparent, and fish species from the lower latitudes are migrating here in increasing numbers.

5 ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

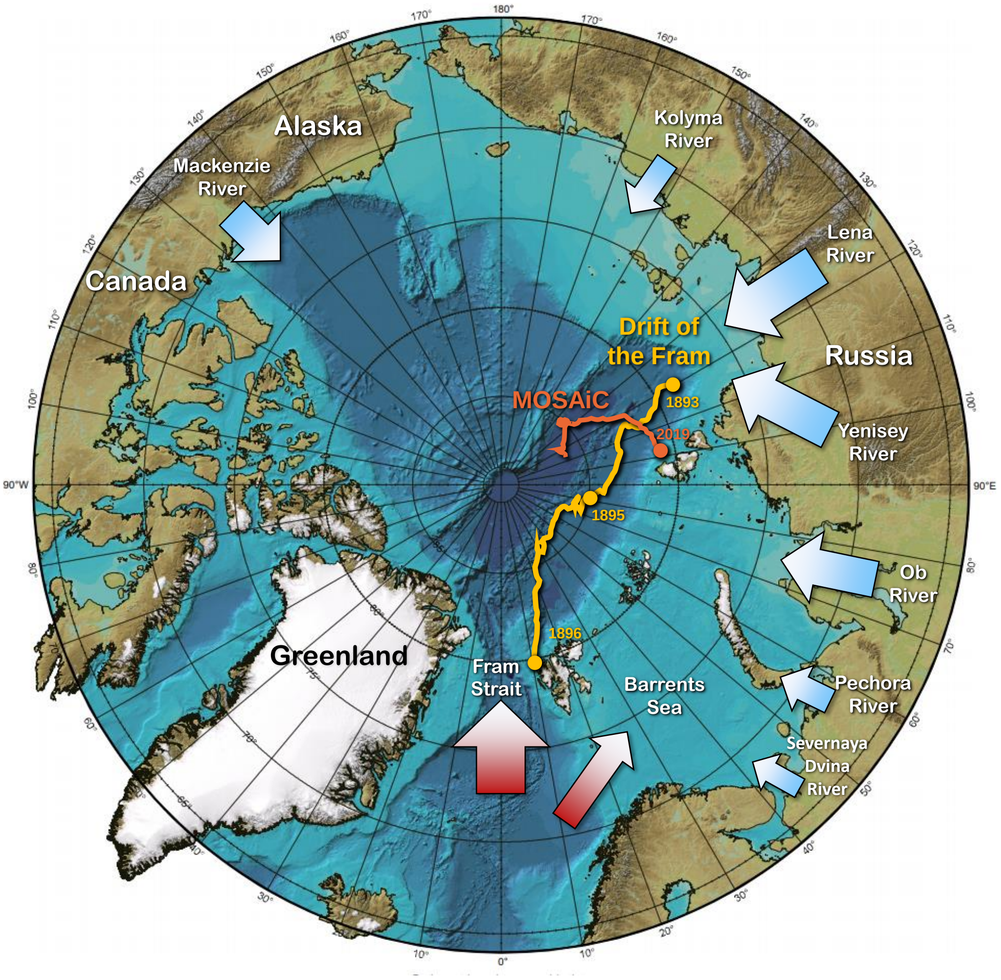

Figure 1. Map of the Arctic Ocean and surrounding shelf seas. Overlaid are the path of Nansen's voyage (yellow); and the current track of the MOSAiC drift, from the beginning of October 2019 up to the end of November 2019 (orange). Approximate locations of river outflow and relative size of the rivers is shown by the light blue arrows. The inflow pathways of the warm and salty Atlantic Water are shown by the red arrows.

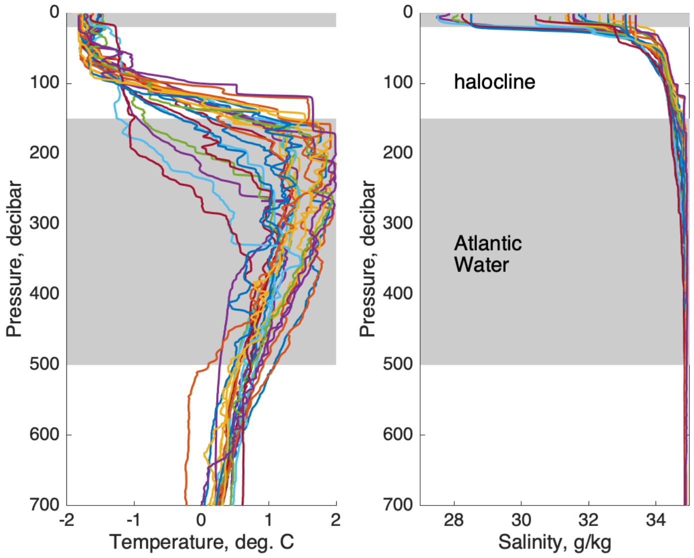

Figure 2. Measurements of water temperatures profiles in the upper 700m of the Arctic Ocean, taken in 2008 north of Siberia. Gray shading highlights the different layers of water, from top to bottom: surface mixed layer, Arctic halocline and Atlantic Water.

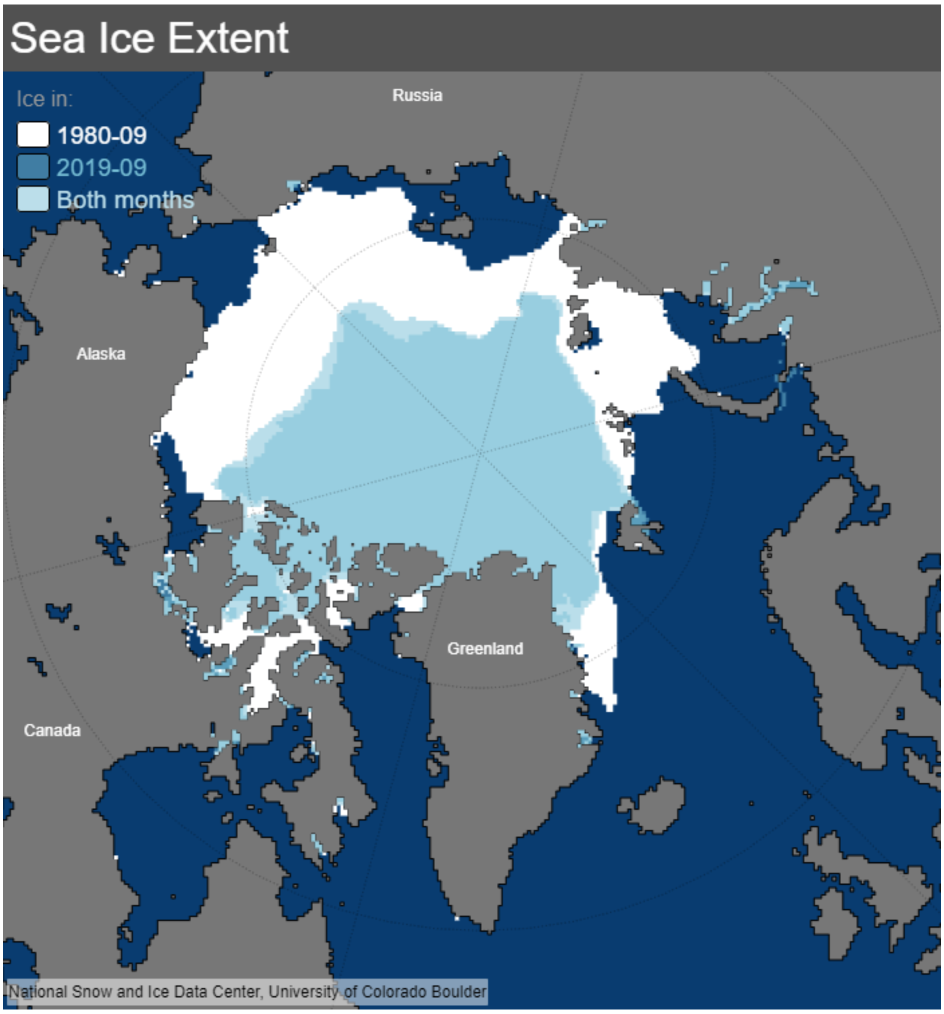

Figure 3. Comparison of the sea ice extent as measured by satellites. Figure reproduced from the U.S. National Snow and Ice Data Center.

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Figure 5. This is a figure with sub figures, **(A)** is one logo, **(B)** is a different logo.