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Towards "Atlantification" of the Arctic Ocean: Insights from Three Decades of Atlantic Inflow Observations

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1. INTRODUCTION

The Arctic is warming faster than the other regions on Earth due to amplification of anthropogenic climate change by sea ice loss and its impact on albedo feedbacks and heat uptake by the upper ocean. The physical environment of the Arctic Ocean is rapidly changing under ongoing warming. Not only air temperature is rising faster than average and sea ice is shrinking, thinning and its seasonal cover is lasting shorter but profound changes are also observed in the upper ocean climate and dynamics. The upper ocean heat content is rising to due advection of warmer waters from lower latitudes and increased solar warming. Warm and salty anomalies progressing from the North Atlantic into the Arctic Ocean through Fram Strait and Barents Sea result in "Atlantification" – a change toward more Atlantic conditions.

Understanding variable properties and dynamics of the Atlantic water (AW) poleward inflow is one of key prerequisites to elucidate mechanisms behind the new, warmer regime of the Arctic Ocean. As the AW progress northwards, its properties are modified by ocean-air interactions, mixing, and lateral exchanges. Vertical structure of the water column and density stratification set up the depth of winter convection and access to oceanic heat carried by the Atlantic inflow.

We present results from nearly three decades of hydrographic surveys, covering the AW inflow in the eastern Norwegian and Greenland seas, and the eastern Fram Strait up to the southern Nansen Basin. Interannual to decadal variability is analyzed with a focus on the en route modifications of AW properties in the Fram Strait Branch and varying ocean heat content. After leaving Fram Strait, the part of AW enters the Arctic Ocean along different pathways north of Svalbard. Strong ocean-sea ice interactions and lateral exchanges lead to substantial local modification of the Atlantic inflow before it continues farther eastward. Observations from year-round moorings deployed north of Svalbard since 2012 are used to describe changes in the AW vertical structure and dynamics and their links to the upstream conditions and atmospheric forcing.

2. INCREASING ROLE OF THE ATLANTIC INFLOW TO THE ARCTIC OCEAN

The spatial and temporal variability of the poleward flow of Atlantic water (AW) results in significant changes in the amount of oceanic heat delivered with the Fram Strait and Barents Sea branches to the Arctic Ocean. Understanding ocean circulation, the pathways of different Atlantic water branches, and the modification of Atlantic water properties during its northward transport is essential for estimating the impact of oceanic heat, mass, salt, and carbon transport on both local and pan-Arctic climate.

Recent studies show that the increasing temperature of Atlantic water entering the Arctic regions contributes to the retreat of the sea ice cover north of Svalbard and a rise in air temperature (e.g., Onarheim et al. 2014). Observations indicate that the oceanic heat flux significantly contributes not only to the melting of sea ice north of Svalbard (Renner et al. 2018) but may also play a crucial role in sea ice loss in the Eurasian Basin, where Atlantic water heat can more easily reach the under-ice boundary layer when ocean stratification weakens and the Atlantic water layer shoals (Polyakov et al. 2017).

Changes in Atlantic water temperature also affect the amount of oceanic heat used to melt sea ice in the regions north of Svalbard, while the resulting variations in the amount of surface freshwater from ice melt alter ocean stratification and heat fluxes toward the atmosphere and ice. Changes in the stratification of Atlantic waters entering the Arctic Ocean through Fram Strait influence the upper ocean circulation and the outflow of modified Atlantic and Arctic waters into the North Atlantic. A series of processes related to the propagation of temperature anomalies in the Arctic Ocean – especially in the Barents Sea and the Eurasian Basin – are collectively referred to as "Atlantification", as first introduced by Polyakov et al. (2017) to highlight the role of Atlantic waters in the sea ice retreat in the European Arctic Ocean.

However, the propagation of ocean heat and freshwater anomalies is strongly modulated by regional processes and interactions that are not necessarily directly associated with the inflow of Atlantic water. As a result, the long-term warming trend of the inflowing waters is overlaid by short-term pulses of rapid temperature increase or decrease, or freshenung events, originating from both advective processes and local interactions between ocean, sea ice, and atmosphere. "Atlantification" is thus a cumulative result of long-term changes and superimposed sequences of warm/cold anomalies that modify both the total ocean heat budget and its redistribution along various Atlantic water transport branches. Changes in upper ocean stratification, driven by temperature and salinity anomalies altering the water column's density structure, amplify ocean-ice-atmosphere interaction processes and increase heat fluxes, thereby reinforcing ongoing changes.

3. LONG-TERM OBSERVATIONS OF THE ATLANTIC INFLOW UNDER THE IOPAN MONITORING PROGRAM AREX IN 1996–2025

The Institute of Oceanology PAS (IO PAN) core activity, the long-term monitoring program AREX, is focused on multidisciplinary observations to study the long-term changes of abiotic and biotic Arctic environment. Every summer since 1987 the extensive field campaigns have been carried out in the Nordic Seas and European Arctic from the IO PAN research vessel Oceania. The main aim of the long-term AREX program is to elucidate processes responsible for changing ocean climate and marine ecosystem in the sub-Arctic and Arctic region with a special focus on the European Arctic. To achieve this goal a large-scale study area, covering the poleward flow of Atlantic water in the eastern Nordic Seas and Fram Strait, has been selected for annually repeated ship-borne measurements on a regular grid. Most of the regularly

a) b)

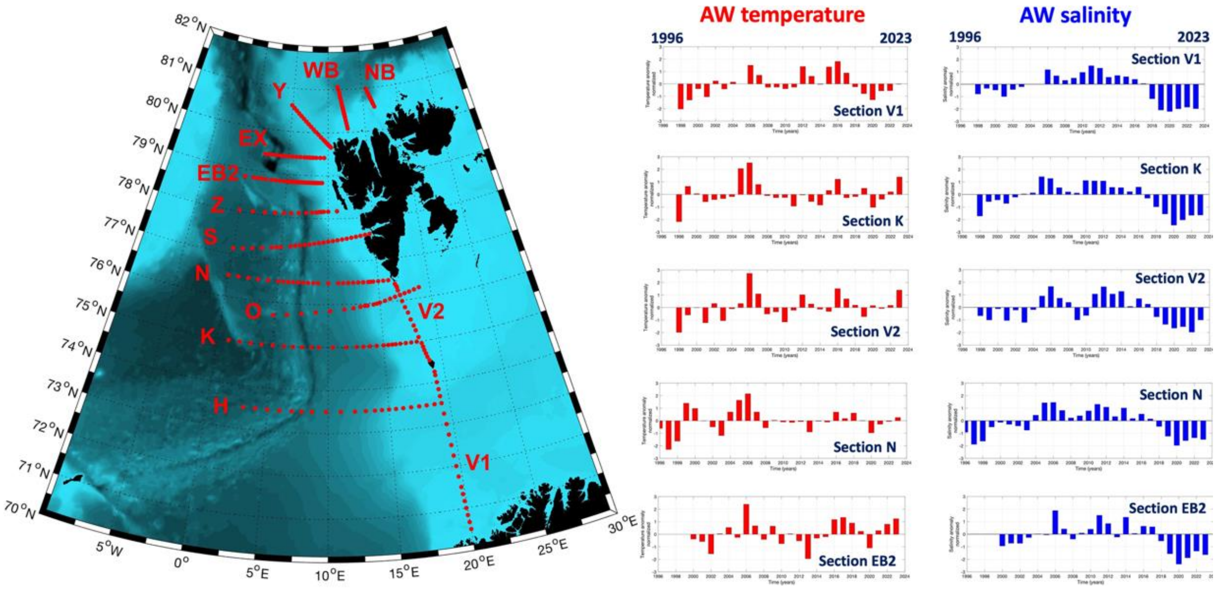

Fig. 1: (a) Regular station grid, repeated annually during the summer AREX campaigns of RV Oceania and (b) standarized anomalies of the Atlantic water temperature and salinity as measured at the main AREX sections in the Greenland Sea (section K), Barents Sea Opening (section V1), Storfjordenrenna and Sørkapp Current (section V2), the southern (section N), and northern (section EB2) Fram Strait.

repeated stations are distributed along several zonal sections, crossing the continental shelf break, and extending towards the deep basin. On the eastern side, the AREX oceanographic sections are limited by the Barents Sea shelf break and the shelf area west and north of Svalbard while to the west, the sections cross the Arctic Front, limiting the extent of Atlantic water in the Nordic Seas. The zonal sections following the Atlantic inflow from the Norwegian Sea to the northern Fram Strait allow to trace transformation of water masses originating from the North Atlantic and advected northward into the Arctic Ocean (Fig. 1).

Comparison of AW properties at the AREX main sections reveals alternating periods of warm/cold and saline/fresh anomalies (Fig. 1b). Three distinct events can be identified in the AW salinity time series: a predominance of negative anomalies from 1996 to 2003, a period of positive anomalies from 2004 to 2016, and a renewed period of strong negative salinity anomalies in Atlantic water, persisting since 2017. The time series of AW temperature anomalies show a less distinct pattern. This reflects stronger local modifications of temperature at individual sections compared to salinity, which is a more conservative tracer. Nevertheless, periods of pronounced positive temperature anomalies can be identified around 2006–2007 and again in 2016–2018. A rise in Atlantic water temperature observed since 2023 may indicate the onset of another episode of warmer water inflow from the North Atlantic. The recent increase in AW temperature, combined with the strongly negative salinity anomaly results in decreasing density of the inflowing Atlantic water and weakened stratification of the upper water column.

In our presentation we review in detail the spatial and temporal patterns of the observed AW anomalies on their way towards the Arctic Ocean and assess their impacts on the structure and variability of the Arctic Ocean Boundary Current, observed north of Svalbard with the array of oceanographic moorings.

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