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A new collective view of oceanography of the Arctic and North Atlantic basins

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ABSTRACT

We review some historical aspects of the major observational programs in the North Atlantic and adjacent regions that contributed to establishing and maintaining the global ocean climate monitoring network. The paper also presents the oceanic perspectives of climate change and touches the important issues of ocean climate variability on time scales from years to decades. Some elements of the improved understanding of the causes and mechanisms of variability in the subpolar North Atlantic and adjacent seas are discussed in detail. The sophistication of current oceanographic analysis, especially in connection with the most recent technological breakthroughs – notably the launch of the global array of profiling *Argo* floats – allows us to approach new challenges in ocean research. We demonstrate how the ocean-climate changes in the subpolar basins and polar seas correlate with variations in the major climate indices such as the *North Atlantic Oscillation* and *Atlantic Multidecadal Oscillation*, and discuss possible connections between the unprecedented changes in the Arctic and Greenland ice-melt rates observed over the past decade and variability of hydrographic conditions in the Labrador Sea. Furthermore, a synthesis of shipboard and Argo measurements in the Labrador Sea reveals the effects of the regional climate trends such as freshening of the upper layer – possible causes of which are also discussed – on the winter convection in the Labrador Sea including its strength, duration and spatial extent. These changes could have a profound impact on the regional and planetary climates. A section with the highlights of all papers comprising the Special Issue concludes the *Preface*.

Ocean climate monitoring of the North Atlantic from a historical perspective

The ocean imposes a profound impact on the global environment and especially on the global climate. The *climate* is formally defined as the ensemble of states that the major components of the planetary *climate system* – ocean, atmosphere, cryosphere, biosphere, landmass and its waters – transit through within a certain period of time (Monin, 1986). The processes within each component of the climate system are determined by the specific properties and nonlinear dynamics of each component and, at the same time, are strongly influenced by the interactions with other components as well as by radiative forcing from outside of the climate system. The Earth's climate is a nonlinear dynamical system that is inherently multi-scale with large numbers of degrees of freedom and complex interaction between its elements (Palmer, 1999; Hauser et al., 2015). In many instances, the stories of the long-term (decades and longer) climate changes are mostly drawn on the oceans' canvas.

Understanding the coastal waters and their variability was critical for both human activity and safety long before regular observations of the interior parts of the ocean basins, far from the shores, became viable. However, a full recognition of the deep ocean's significance for planetary climate dynamics came only in the last century. A first major step in this direction was the fundamental work of Bjørn Helland-Hansen and Fridtjof Nansen, two great Norwegians who mightily contributed to many important chapters of early 20th-century oceanography. Their manuscript '*Temperature variations in the North Atlantic Ocean and in the atmosphere. Introductory studies on the cause of climatological variations*' was first published in 1917 and three years later was translated into English (Helland-Hansen and Nansen, 1920). Ranking each pair of synchronous air and sea surface temperature measurements as a single observation, the authors identified, processed and analyzed 20,415 observations collected between North America and Europe

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during a thirteen-year period – from 1898 to 1910. Completed long before the advent of powerful computing technologies and automated data collection and processing systems, this work remains a superb example of thoroughness of data collection and analysis using limited resources, technologies and opportunities. Many of the important findings presented by these researchers still fascinate those analyzing long-term records of oceanic and atmospheric temperatures and provide useful information about the past climate state and the realities of its assessment. In particular, they point to the time when the accuracy of temperature measurements increased from ±1 °C or ±0.5 °C, to ±0.1 °C. It was also noted that the higher, ±0.1 °C, accuracy of the more recent of the 1898–1910 observations was "hardly doubtful." Finally, Helland-Hansen and Nansen averaged their data over two-degree geographical cells, which they called *fields*, over a fairly broad area covered by the most common shipping routes (most observations were conducted by voluntary observing ships steaming between the continents). Based on those averaged values, they constructed line graphs and contour plots depicting variability of temperature in space and time. This first climatological synthesis of a very large, by the measures of its time, archive of raw oceanographic measurements can be viewed as a reference point for measuring the progress of the ocean climate science over more than one hundred years.

Over the past century, the ocean observations provided a rather comprehensive view of the ocean climate characteristics and dynamics. In the North Atlantic, many major national and international monitoring and research programs, including the *International Ice Patrol* (IPP) *Survey*, *Ocean Weather Ships* (OWS), *Mid-Ocean Dynamics Experiment* (MODE), *Polygon*, *POLYMODE*, *SECTIONS*, *World Ocean Circulation Experiment* (WOCE), *Climate Variability* (CLIVAR) of the *World Climate Research Programme* (WCRP), *Atlantic Zone Off-Shelf Monitoring Program* (AZOMP) of the *Department of Fisheries and Oceans* (DFO) of Canada, *Rapid Climate Change Programme* (RAPID) and Argo – to name just a few – contributed to multiyear monitoring of the ocean and advanced our understanding of its dynamics and impact on climate. A few of these observational efforts in the North Atlantic are briefly outlined below; see also a concise review by Kieke and Yashayaev (2015).

The coordinated efforts on a sustained systematic sampling of oceanic waters at fixed (standard) geographical locations or sections at predefined (standard) depths started to come together at the end of the 19th century. One of such efforts led to the commencement of the *Kola Section*, running along the 33°30′E meridian from the Kola Bay to 75°N, the first occupation of which in 1900 opened systematic data collection in the Barents Sea. This line was regularly visited, albeit with interruptions, beginning in the early 1900s; thus its other name – the *Centennial Section*. The Kola Section, together with the *IPP* sections in the western North Atlantic, one of which run across the entire Labrador Sea, the *OWS* stations and the other standard sections and stations established by programs across the globe formed an important ocean observatory. This has allowed significant observations – for example, the mapping of the passage of the *Great Salinity Anomaly* across the subpolar North Atlantic and Nordic Seas (Dickson et al., 1988), and the recording of developments in the Labrador Sea's winter convection (Lazier, 1973, 1980) – and, no less importantly, has provided a basis for climate change assessments and projections (IPCC, 2007).

Several oceanographic institutions of the *Hydrometeorological Service* and the *Academy of Sciences* of the former USSR (now in the Russian Federation and Ukraine) undertook seasonal monitoring at individual hydrographic sections, arrays of sections and station grids spread from the tropical to polar ocean regions between the early 1980s and the early 1990s. This huge monitoring effort, termed the former Soviet Union *SECTIONS* program, was primarily focused on the ocean basins and areas of overlying atmosphere that had been previously identified as critical for mid-to-long-range weather forecasts over the Eastern Europe, central USSR and beyond. It was developed in the late 1970s, implemented in the early 1980s, and run for at least a decade. The program included systematic and detailed sampling of physical and chemical characteristics of many oceanic and atmospheric '*energy-active zones*'. One of these zones is located in the Newfoundland Basin, southeast of the Grand Banks, which is one of the key regions that control the general circulation of the North Atlantic (Mann, 1967; Clarke et al., 1980). Every piece of information concerning the ocean dynamics and seasonal and longer-term variability in this area, including variations in strength and location of the North Atlantic Current, is important for forecasting advection of heat and salt to the subpolar basins, such as the Labrador Sea, and to the Nordic Seas. This region is critical for regulating the meridional and zonal exchanges and redistribution of heat, freshwater, salt and other substances in the oceans, and air–sea interaction.

The *Control Volume* component of the *World Ocean Circulation Experiment* (WOCE) very ably took over international hydrographic observations in the Newfoundland Basin after the end of the SECTIONS program. Indeed, the start of the WOCE was the true beginning of the modern era of global ocean climate monitoring, kick-starting a period of unprecedented progress in simultaneous full-depth data collection from over the entire world ocean domain. The network of WOCE sections in the subpolar North Atlantic is described by Kieke and Yashayaev (2015).

One of the most important technological and methodological advancements in this program is significantly increased accuracy and precision of oceanographic measurements – e.g., to at least ±0.0020 °C/±0.0005 °C and ±0.002/±0.001 for temperature and salinity, respectively – while achieving the high vertical resolution of at least 2 decibars (meters). As a result, the ability to track important signals in the deep and intermediate layers on interannual-to-decadal scales was gained and improved. Multi-institutional hydrographic data collected in all four deep basins of the subpolar North Atlantic revealed similar patterns of temporal variability of temperature, salinity and density of the Labrador Sea Water (Yashayaev et al., 2007b, see their Figs. 3 and 4). These important changes could not have been resolved and understood if the WOCE data-quality requirements had not been met. Through this and many other extensive international efforts, the WOCE became the most systematic and profound ocean research program of the 20th century.

Another remarkable step toward establishing a global year-round real-time ocean observing system was made in 1998, when scientists from several countries were appointed to the *Argo Science Team* (now the *Argo Steering Team*) and wrote a prospectus entitled, '*On the Design and Implementation of Argo*.' This unprecedented proposal for a global array of thousands of profiling floats – *Argo floats* – that are designed to overcome the weather, ice cover and other surface-state-related limitations to provide open-access, real-time, year-round, four-dimensional data on temperature and salinity with a high degree of accuracy was met with great enthusiasm and immediate support by the ocean- and climate-research communities. The first Argo floats were deployed in 2000, and by November 2007 there were 3000 floats in place, exactly as was envisioned in the Argo 'implementation plan'. By October 2012 it had supplied more than a million profiles – almost twice the number of hydrographic profiles from all other sources in the World Ocean Database (WOD) – and by the beginning of January 2015 the Argo array comprised 3750 floats launched by 30 nations. Most of these floats supply profiles from 2000 m (hereafter meters used instead of decibars for simplicity) up to the surface at 10-day intervals, while some others (e.g., those carrying biochemical sensors) profile the ocean and transmit their data more frequently and even as often as daily. A higher profiling frequency will lead to: substantial improvement in understanding of atmospheric forcing, biochemical