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Studies of Labrador Sea Water formation and variability in the subpolar North Atlantic in the light of international partnership and collaboration

Dagmar Kieke [a,*], Igor Yashayaev [b]

[a] Institut für Umweltphysik, AG Ozeanographie, Universität Bremen, Otto-Hahn-Allee, 28359 Bremen, Germany
[b] Ocean Sciences Division, Department of Fisheries and Oceans, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada

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ABSTRACT

Labrador Sea Water (LSW), the lightest contribution to North Atlantic Deep Water (NADW) and one of the most prominent water masses of the subpolar North Atlantic, has seen remarkable changes over the past century. LSW originates in the Labrador Sea, where it is formed through wintertime ocean convection of varying intensity, depth and spatial extent. Formation of LSW, followed by its respective injection into the mid-depth circulation system, is mandatory for ventilating and renewing water layers of the interior ocean. Indispensably important for unraveling the history of variability in formation and properties of LSW as well as for mapping its large-scale spreading and export are sustained physical and chemical observations from the deep ocean. These observations started at the beginning of the 20th century from occasional mostly national surveys and today constitute large-scale multi-national collaborative efforts including a vast arsenal of sophisticated instrumentation. In a historical context, we revisit major milestones over the past 100 years which have established and are constantly adding to shaping today's knowledge on LSW, and present first details on the latest vintage of LSW generated during the strong winter of 2013/2014. Respective Argo data reveal mixed-layer depths greater than 1700 m marking formation of a new cold and fresh anomaly that has spread since then over the subpolar North Atlantic. We further summarize the on-going observational efforts in the subpolar North Atlantic and present a compilation of hydrographic standard lines that serve to provide top-to-bottom information on NADW components.

Introduction

Over the past century, the western subpolar North Atlantic attracted a close attention concerning different kinds of ocean observations, making it the best-studied and monitored basin of the world ocean. The initial efforts that started the century of intense international and multidisciplinary oceanographic field research in the subpolar North Atlantic have their roots in navigation, including insuring save and secure waterways, and exploration. Identifying ice extents and iceberg dangers are of critical importance as they pose a threat to commercial shipping, fishing, oil exploration and other public, industrial, and economical needs involving the ocean. The fishing industry itself has seen remarkable changes through this period. The most dramatic impact of economy and even demography had the shutdown of fish catches e.g. in Canadian waters in the 1980s to 1990s due to overfishing and spatial shifts of fish populations prior to and following the collapse (Rose et al., 2000). Knowledge on environmental and climate conditions and associated variability were proved crucial to understand changes in the ecosystem and recovery of fish stocks (Lehodey et al., 2006).

Most notably, however, the processes relevant for (both regional and planetary) climate variability originate or are modulated in the North Atlantic and have an impact on the regional and without overstatement global climate (e.g., Marshall et al., 2001; Vellinga and Wood, 2002). The subpolar North Atlantic, in particular, hosts a source of formation of its characteristic intermediate and deep water masses (e.g. Dickson et al., 2008). They constitute the northern loop of the Atlantic meridional overturning circulation (AMOC) and connect the warm and saline near-surface waters imported from the subtropics via the Gulf Stream and North Atlantic Current (NAC) to the cold and deep returning flow, known as the deep and abyssal limb of the AMOC. Water of subtropical origin advects heat and subsequently releases it to the atmosphere along its path toward the Polar Seas. This branch is often identified as Atlantic Water that crosses the Greenland-Scotland Ridge and enters the Nordic Seas (Greenland, Icelandic and Norwegian Seas) and eventually remote polar basins (e.g., Hansen et al., 2003; Yashayaev and Seidov, 2015). There (in the Nordic Seas), the

* Corresponding author.
E-mail address: dkieke@uni-bremen.de (D. Kieke).

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Atlantic Water feeds Nordic water mass formation regions (e.g., Mauritzen, 1996; Isachsen et al., 2007). Another branch originating from the NAC follows the given basin geometry of the subpolar North Atlantic and via the Irminger Sea enters the Labrador Sea, where it jointly with Arctic outflow and other local waters feeds the source of water mass formation in the Labrador and Irminger Seas. High oceanic heat losses between Labrador and Greenland, strongest during the winter period, reduce the density stratification and make the affected waters sink to greater depths (e.g., McCartney and Talley, 1982; McCartney, 1992), with the mean buoyancy-forced downwelling happening near the boundaries of the Labrador Sea (e.g. Pickart and Spall, 2007; Spall, 2010). Localized water mass formation regions act as windows to the deep ocean, as surface waters are transformed to intermediate and deep waters by a complex chain of physical processes, thus introducing characteristics previously imprinted at the surface into the deep ocean (like contents of high dissolved oxygen, transient tracers, and anthropogenic carbon). These deep waters are carried far into the southern hemisphere, ventilate the intermediate to deep ocean, and feed among others the formation of Circumpolar Deep Water, thus demonstrating the importance of North Atlantic water masses for the global ocean (e.g. Schmitz, 1996). Changes in the deep water formation have direct consequences for the ventilation of the deep ocean (e.g., Körtzinger et al., 2004; Stendardo and Gruber, 2012), the ocean's potential to store anthropogenic carbon (e.g., Sabine et al., 2004; Steinfeldt et al., 2009), and the strength of the AMOC and the associated heat transport (Srokosz et al., 2012).

The research efforts initiated and maintained in the North Atlantic for more than a century delivered many insights into the ocean circulation and both structure and variability of water masses and helped to identify processes that modulate ocean and climate variability in the western subpolar North Atlantic on a large range of time scales of ocean variability. While scientific motivation differed from cruise to cruise and project to project, data of the past 100 years of oceanographic observations in the subpolar North Atlantic constitutes an important legacy to today's society, as it is necessary and mandatory to describe observable changes in a world facing global warming and expected consequences (IPCC, 2013). Furthermore, available data is incorporated into numerical ocean and climate models that serve to better understand and improve prediction of ocean and climate variability and to assess past and future states of the ocean circulation.

Here, we review important milestones of the past 100 years of North Atlantic observational hydrography and focus on the historic developments that have shaped our knowledge on the cold and dense water masses forming the deep return branch of the AMOC, collectively known as the North Atlantic Deep Water (NADW). NADW consists of an upper and lighter and a lower and denser component. The upper component originates in the Labrador Sea located between Canada and Greenland, as reflected in its name – Labrador Sea Water (LSW). It is produced by deep wintertime ocean convection and is injected into the large-scale mid-depth to deep circulation system via various pathways as, for example, those revealed in parameter maps and float trajectories (e.g. Talley and McCartney, 1982; Sy et al., 1997; Fischer and Schott, 2002; Yashayaev et al., 2007; Bower et al., 2009; Kieke et al., 2009), removing it from the formation region. The lower component of NADW originates from the Nordic Seas source waters spilling over the Denmark Strait (Denmark Strait Overflow Water, DSOW) and the Iceland-Scotland Ridge (Iceland-Scotland Overflow

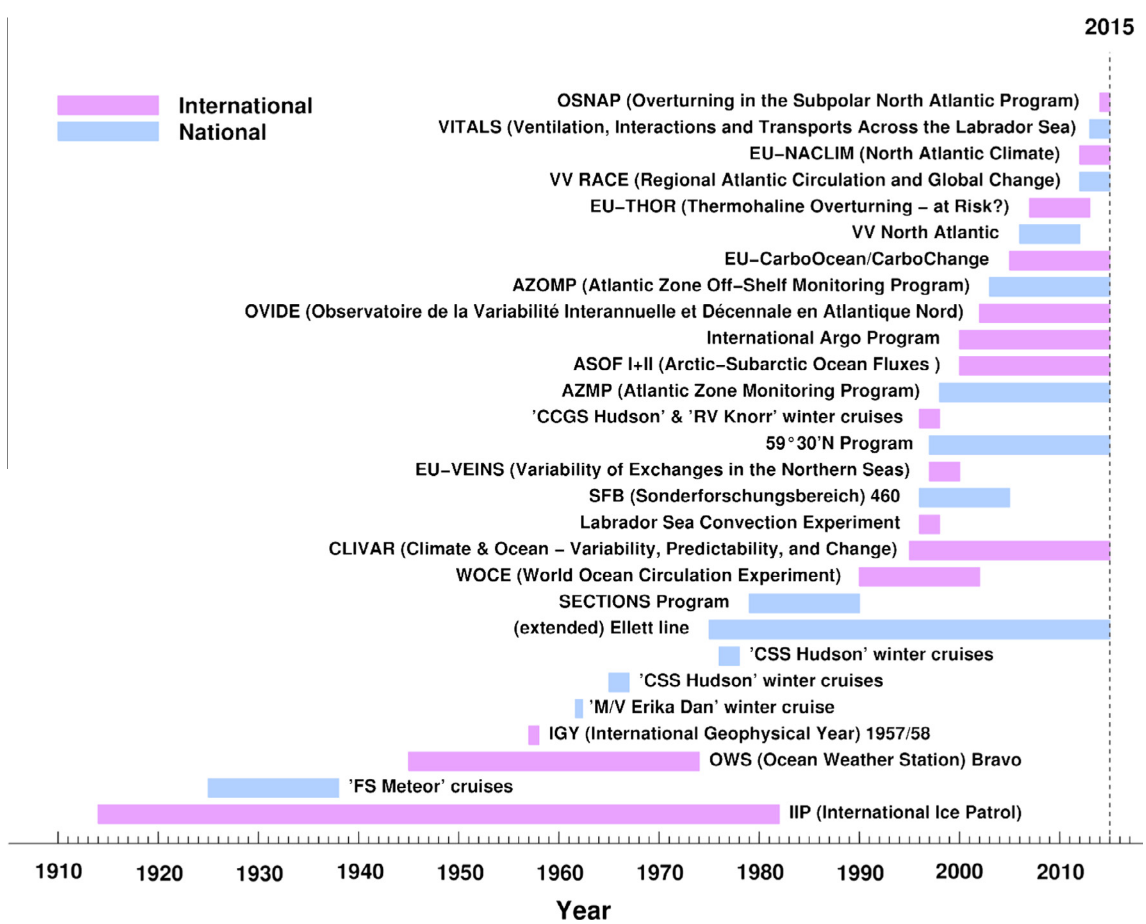

Fig. 1. Overview on major oceanographic observational programs conducted in the subpolar North Atlantic over the past 100 years, with relevance for the formation of Labrador Sea Water.