Deep-Sea Research I 101 (2015) 98–109

Contents lists available at ScienceDirect

Deep-Sea Research I

journal homepage: www.elsevier.com/locate/dsri

# Water mass transformation in the Iceland Sea

Kjetil Våge [a,*], G.W.K. Moore [b], Steingrímur Jónsson [c,d], Héðinn Valdimarsson [d]

[a] Geophysical Institute, University of Bergen and Bjerknes Centre for Climate Research, Bergen, Norway
[b] University of Toronto, Toronto, Canada
[c] University of Akureyri, Akureyri, Iceland
[d] Marine Research Institute, Reykjavik, Iceland

ARTICLE INFO

*Article history:*
Received 7 October 2014
Received in revised form
12 February 2015
Accepted 3 April 2015
Available online 13 April 2015

*Keywords:*
Iceland Sea
Open-ocean convection
North Icelandic Jet
Denmark Strait Overflow Water
Atlantic Meridional Overturning Circulation
Cold air outbreak

ABSTRACT

The water mass transformation that takes place in the Iceland Sea during winter is investigated using historical hydrographic data and atmospheric reanalysis fields. Surface densities exceeding $\sigma_\theta = 27.8$ kg/m$^3$, and hence of sufficient density to contribute to the lower limb of the Atlantic Meridional Overturning Circulation via the overflows across the Greenland-Scotland Ridge, exist throughout the interior Iceland Sea east of the Kolbeinsey Ridge at the end of winter. The deepest and densest mixed layers are found in the northwest Iceland Sea on the outskirts of the basin's cyclonic gyre, largely determined by stronger atmospheric forcing near the ice edge. Much of the accumulated wintertime heat loss in that region takes place during a few extreme cold air outbreak events. Only a small number of hydrographic profiles (2%) recorded mixed layers sufficiently dense to supply the deepest part of the North Icelandic Jet, a current along the slope off northern Iceland that advects overflow water into the Denmark Strait. However, low values of potential vorticity at depth indicate that waters of this density class may be ventilated more regularly than the direct observations of dense mixed layers in the sparse data set indicate. A sudden increase in the depth of this deep isopycnal around 1995 suggests that the supply of dense water to the North Icelandic Jet, and hence to the densest component of the Atlantic Meridional Overturning Circulation, may have diminished over the past 20 years. Concurrent reductions in the turbulent heat fluxes and wind stress curl over the Iceland Sea are consistent with a decrease in convective activity and a weakening of the cyclonic gyre, both of which could have caused the increase in depth of these dense waters.



## 1. Introduction

The water mass transformation that takes place within the Nordic Seas, at the northern extremity of the Atlantic Meridional Overturning Circulation (AMOC), impacts the world ocean and is of key importance for the North Atlantic climate system (e.g. Gebbie and Huybers, 2010; Rhines et al., 2008). Warm, saline Atlantic waters flow northward across the Greenland-Scotland Ridge into the Nordic Seas, release heat to the atmosphere, and the resulting densified waters return southward through gaps in the ridge as overflow plumes. While the overflow transport is about evenly divided east and west of Iceland, the largest overflow plume and the densest contribution to the lower limb of the AMOC passes through the Denmark Strait between Greenland and Iceland (Fig. 1, Jochumsen et al., 2013).

The winter mean climate of the subpolar North Atlantic is dominated by a large-scale pressure dipole known as the North Atlantic Oscillation (NAO) with the Icelandic Low and Azores High being its centers of action (Hurrell, 1995; Hurrell and Deser, 2009). The NAO is considered to be in its positive state when the sea level pressure is anomalously high (low) in the southern (northern) center of action. In its positive state, there is enhanced westerly flow across the mid-latitudes of the North Atlantic. The Iceland Sea is situated in the trailing trough that extends north-eastwards from the Icelandic Low towards the Barents Sea (Serreze et al., 1997). Along this trough there is a secondary low-pressure center known as the Lofoten Low that has a climatological center to the west of northern Norway near 72°N, 14°E (Jahnke-Bornemann and Bruemmer, 2009). The pressure dipole consisting of the Icelandic and Lofoten Lows is known as the Icelandic Lofoten Dipole (ILD). In addition to being important features in the winter mean flow, these two locations are also the primary (Icelandic Low) and secondary (Lofoten Low) maxima in cyclone frequency over the subpolar North Atlantic (Wernli and Schwierz, 2006). Although the NAO and ILD share a common center of action, the Icelandic Low, Jahnke-Bornemann and Bruemmer (2009) have shown that since the 1980s the two pressure dipoles are only weakly correlated.

* Corresponding author.
*E-mail address:* kjetil.vage@gfi.uib.no (K. Våge).

http://dx.doi.org/10.1016/j.dsr.2015.04.001
0967-0637/© 2015 Published by Elsevier Ltd.

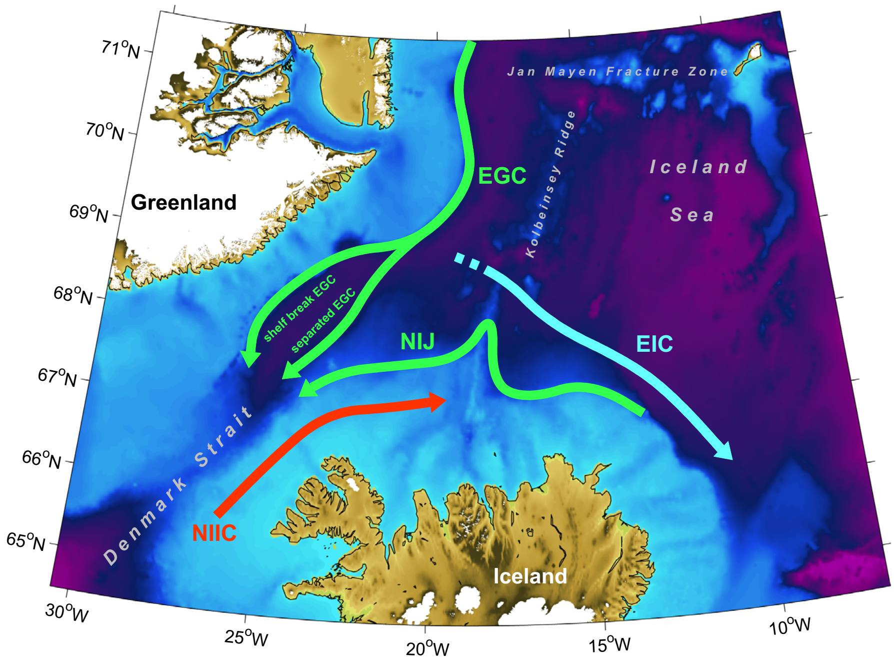


**Fig. 1.** Bathymetry and schematic circulation in the Iceland Sea. The acronyms are EGC=East Greenland Current; NIJ=North Icelandic Jet; EIC=East Icelandic Current; NIIC=North Icelandic Irminger Current.

The winter mean atmospheric circulation over the subpolar North Atlantic is therefore the result of a complex interplay between these two quasi-independent pressure dipoles. With regard to the Iceland Sea, it appears that the ILD is the primary mode of inter-annual variability (Kelly et al., 1987; Jahnke-Bornemann and Bruemmer, 2009; Moore et al., 2012, 2014). During periods when the Icelandic Low is anomalously deep, southerly flow is established over the Iceland Sea resulting in the advection of warm air and a concomitant reduction in the magnitude of the air–sea heat fluxes (Moore et al., 2012). In contrast, when the Lofoten Low is anomalously deep, the Iceland Sea is under the influence of northerly flow that advects cold air into the region leading to an increase in the magnitude of the sea to air heat fluxes. As a result of this sea-level pressure distribution, the Iceland Sea is situated in a saddle point between the two lows and this leads to a local minimum in air–sea total turbulent heat flux (Moore et al., 2012).

Despite relatively weak atmospheric forcing, oceanic convection takes place in the central Iceland Sea east of the Kolbeinsey Ridge (Fig. 1) and results in the formation of Arctic Intermediate Water (Swift and Aagaard, 1981). Doming isopycnals associated with the presence of a cyclonic gyre (Stefánsson, 1962; Swift and Aagaard, 1981; Voet et al., 2010) facilitate the water mass transformation. Typical late-winter mixed-layer depths are on the order of 200 m (Swift and Aagaard, 1981). The remnants of this convective product are observed during the rest of the year as a cold layer near this depth (e.g. Jónsson, 2007).

The depth of convection in the Iceland Sea is to some extent regulated by the magnitude of the wind stress curl, which has a pronounced influence on the surface salinity (Jónsson, 1992). Fresh conditions during the so-called "ice years" of the late 1960s may have caused a temporary cessation of convection (Malmberg and Jónsson, 1997). At that time the East Icelandic Current, usually an ice free current, transported a larger amount of cold, fresh water of polar origin as well as a substantial amount of drift ice, perhaps brought about by a period of northerly winds and reduced wind stress curl (Dickson et al., 1975; Jónsson, 1992). Over the past three decades a pronounced decline in sea ice concentration in the western Nordic Seas has led to a retreat of the ice edge from the cyclonic gyre in the central Iceland Sea. Simulations with a one-dimensional mixed-layer model predict that the ensuing trend of diminished wintertime atmospheric forcing will reduce the depth and density of the convective product (Moore et al., 2015).

While earlier studies claimed significant contributions from the Iceland Sea to the Denmark Strait overflow plume (e.g. Swift et al., 1980; Livingston et al., 1985; Smethie and Swift, 1989), the current consensus is that the transformation of Atlantic inflow into Denmark Strait Overflow Water (DSOW) occurs primarily within the cyclonic circulation around the margins of the Nordic Seas (Mauritzen, 1996; Eldevik et al., 2009). In this scenario interior convection in the western basins contributes only to a minor extent. It is generally thought that DSOW is mainly advected to the Denmark Strait by the East Greenland Current (e.g. Rudels et al., 2002), but that it contains to various extents an admixture of water formed within the Iceland Sea (Olsson et al., 2005; Tanhua et al., 2005, 2008; Jeansson et al., 2008). The variability among these studies may be related in part to a temporal switching between sources of DSOW (Rudels et al., 2003; Holfort and Albrecht, 2007; Köhl, 2010).

The emphasis on the Iceland Sea as a source of DSOW was renewed with the discovery of a current flowing along the slope north of Iceland in the direction of the Denmark Strait, later called the North Icelandic Jet (NIJ), by Jónsson (1999) and Jónsson and Valdimarsson (2004). They found that the NIJ was potentially of sufficient strength to account for the bulk of the overflow water if some entrainment of ambient water is assumed. Extensive hydrographic/velocity surveys along the slope west and north of Iceland indicate that the NIJ advects both the densest overflow water and a major fraction of the total overflow transport (1.4–1.5 Sv, 1 Sv$=10^6$ $m^3/s$) into the Denmark Strait (Våge et al., 2011, 2013). Observations and numerical simulations suggest that the NIJ originates along the northern coast of Iceland (Våge et al., 2011; Logemann et al., 2013; Yang and Pratt, 2014). In particular, Våge et al. (2011) hypothesize that it is the deep limb of an overturning loop that involves the boundary current system north of Iceland and water mass transformation in the central Iceland Sea.

Several studies indicate that waters ventilated in the Iceland Sea also take part in the overflows east of Iceland. The Faroe Bank