AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2016GL069596

Key Points:
- Deepest observed convection in the Irminger Sea reached down to 1400 m in the winter of 2014–2015
- The local deep mixing was caused by strong atmospheric forcing equivalent to forcing during the early 1990s
- Low SST in the subpolar gyre can be explained through variability in surface cooling, not by reduced heat advection

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Citation:
de Jong, M. F., and L. de Steur (2016), Strong winter cooling over the Irminger Sea in winter 2014–2015, exceptional deep convection, and the emergence of anomalously low SST, *Geophys. Res. Lett.*, *43*, 7106–7113, doi:10.1002/2016GL069596.

Received 13 MAY 2016
Accepted 18 JUN 2016
Accepted article online 21 JUN 2016
Published online 8 JUL 2016

Strong winter cooling over the Irminger Sea in winter 2014–2015, exceptional deep convection, and the emergence of anomalously low SST

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Abstract Deep convection is presumed to be vital for the North Atlantic Meridional Overturning Circulation, even though observational evidence for the link remains inconclusive. Modeling studies have suggested that convection will weaken as a result of enhanced freshwater input. The emergence of anomalously low sea surface temperature in the subpolar North Atlantic has led to speculation that this process is already at work. Here we show that strong atmospheric forcing in the winter of 2014–2015, associated with a high North Atlantic Oscillation (NAO) index, produced record mixed layer depths in the Irminger Sea. Local mixing removed the stratification of the upper 1400 m and ventilated the basin to middepths resembling a state similar to the mid-1990s when a positive NAO also prevailed. We show that the strong local atmospheric forcing is predominantly responsible for the negative sea surface temperature anomalies observed in the subpolar North Atlantic in 2015 and that there is no evidence of permanently weakened deep convection.

1. Introduction

In a schematic sense the Atlantic Meridional Overturning Circulation (AMOC) consists of an upper branch in which warm waters flow northward and a lower branch in which cold, dense waters flow equatorward. In the North Atlantic and Nordic Seas deep convection is thought to form the vertical link by which these two branches connect. This idea spurred early box models of ocean circulation [*Stommel*, 1961]. It is therefore not surprising that models suggest a direct connection between deep convection and the AMOC strength [*Biastoch et al.*, 2008; *Danabasoglu et al.*, 2012]. However, to date observational evidence remains inconclusive [*Lozier*, 2012; *Rhein et al.*, 2013]. Paleo-oceanographic studies have concluded that the AMOC has weakened in the past [*Alley and Ágústsdóttir*, 2005] as a result of a sudden freshwater release into the subpolar gyre that would have inhibited convection. That situation bears resemblance to the reduced convection observed during the Great Salinity Anomaly in the 1960s [*Dickson et al.*, 1988; *Rudels*, 1995]. It is therefore hypothesized that in the future the AMOC may weaken as freshwater discharge from the Arctic Ocean or the Greenland Ice Sheet increases [*Hu et al.*, 2011]. This, in turn, may cause a reduction in atmospheric temperature in the Northern Hemisphere [*Vellinga and Wood*, 2008]. A decrease in ocean surface density as the result of a future warming climate is also predicted to lead to a decrease in AMOC strength [*Gregory et al.*, 2005; *Weaver et al.*, 2012]. However, such a change would occur much more gradual. Regardless of the cause, weakened deep convection would also impact the global carbon cycle as it would reduce the capacity of the North Atlantic as a carbon sink [*Gruber et al.*, 2002].

Some suggest that this process is already at work. The transport measurements at the Rapid Climate Change-Meridional Overturning Circulation and Heatflux Array (RAPID-MOCHA) at 26°N have shown a small yet steady decline in the AMOC since 1992 [*Frajka-Williams*, 2015]. This decline in overturning has been linked to the recent emergence of anomalously low sea surface temperatures (SSTs) in the North Atlantic. The cold anomaly stands out in the otherwise anomalously warm Earth in the Goddard Institute for Space Studies global temperature analysis (GISSTEMP) [*Hansen et al.*, 2010] and shows resemblance to the "warming hole" that appears in the North Atlantic in model predictions as a result of climate change and a weakened AMOC [*Drijfhout et al.*, 2012]. *Rahmstorf et al.* [2015] observed a similar warming hole in the twentieth century temperature trends and related this to enhanced freshwater input [*Bamber et al.*, 2012] and reduced AMOC strength. However, the suggested link between the low SSTs and a decline in AMOC strength ignores the role of local atmospheric forcing which is known to be important on interannual time scales [*Grist et al.*, 2015]. We

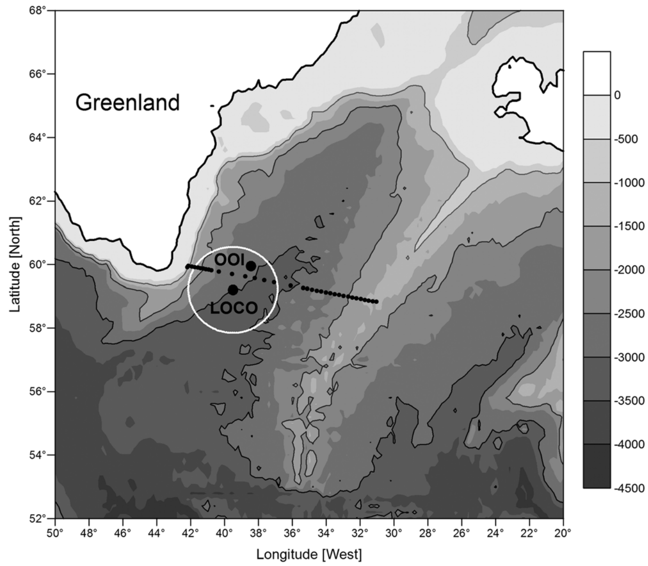

Figure 1. Bathymetry of the Irminger Sea and locations of observations. The bathymetry of the Irminger Sea is illustrated by the grey shading, with the 1 km, 2 km, and 3 km isobaths as darker grey contours. The LOCO mooring (marked by the black dot) is located in the center of the Irminger gyre and south of the AR7E section. The OOI profiling mooring (black dot) is located slightly north of AR7E. Argo profiles within 150 km (white circle) of the LOCO mooring were used to fill gaps in the mooring record and to extend the time series into 2016. The small black dots mark the CTD section carried out in July 2015 (see Figure 3).

will show that the low SSTs are indeed the result of strong local winter cooling in the winter of 2014–2015, which resulted in exceptionally deep convection in the subpolar gyre.

2. Data

2.1. In Situ Data

The LOCO (long-term ocean circulation observations) moorings is located in the central Irminger Sea (Figure 1) [*de Jong et al.*, 2012]. This mooring is located right in the area of interest, namely, the center of the SST anomaly. The mooring is outfitted with a McLane Moored Profiler measuring conductivity-temperature-depth (CTD). The time series of daily hydrographic profiles from the LOCO mooring, covering September 2003 to July 2015, is presented here (Figure 2). Temperature and salinity data are binned into 1 dbar averages and are calibrated using shipboard CTDs at deployment and recovery. Dissolved oxygen profiles were obtained from a similar McLane Moored Profiler in the Ocean Observatories Initiative (OOI) Irminger Sea array, which is located near LOCO (Figure 1) and was deployed in summer 2014. The convection strength is determined using mixed layers observed in the LOCO profiles. The mixed layer depth is defined as the bottom of the homogenously mixed layer, above the gradient that indicates the transition from the unstratified mixed layer to the undisturbed stratified profile. Mixed layers had to be evident in temperature, salinity, and density to be included into the mixed layer depth time series. The method is described in more detail in *de Jong et al.* [2012]. Planetary potential vorticity, or PV, was calculated over 25 dbar windows after applying a 50 dbar running mean filter. Two observational gaps (between September 2011 and August 2012 and between January 2013 and September 2014) were filled using Argo profiles within 150 km of the LOCO mooring (Figure 1). This range excludes profiles from the boundary currents and provides a sufficient number of profiles from the gyre. The Argo profiles of temperature and salinity were vertically interpolated to 10 dbar intervals. Mixed layer depths and PV were derived for the interpolated profiles [*de Jong et al.*, 2012].

Data from a hydrographic survey spanning the Irminger Basin in July 2015 are included. CTD stations were taking along the AR7E section, with station spacing of 9 km near the boundaries widening to 45 km in the interior. Salinity and dissolved oxygen measurements from the hydrographic survey were calibrated using in situ salinity and oxygen samples.

SSTs from the Extended Reconstructed Sea Surface Temperature data set version 4 (ERSSTv4) were obtained from NOAA. The ERSST data set consists of monthly mean values on a 2° by 2° grid extending from 1854 to present. The ERSST ocean data are used in the Goddard Institute for Space Studies global temperature analysis (GISSTEMP) [*Hansen et al.*, 2010]. A time series for SST in the central Irminger Sea was derived by averaging SSTs over a box extending 1° latitude north and south and 2° longitude east and west of LOCO. This time series has a high correlation ($R = 0.88$) with the time series of the mean SST over the subpolar gyre east of Greenland (taken here as 52 to 60°N and 40 to 10°W).

2.2. Atmospheric Forcing

Local mesoscale atmospheric features dominate the regional forcing over the western subpolar gyre and the Irminger Sea, in particular, [*Moore and Renfrew*, 2005; *Våge et al.*, 2009; *Oltmanns et al.*, 2015]. Therefore, we

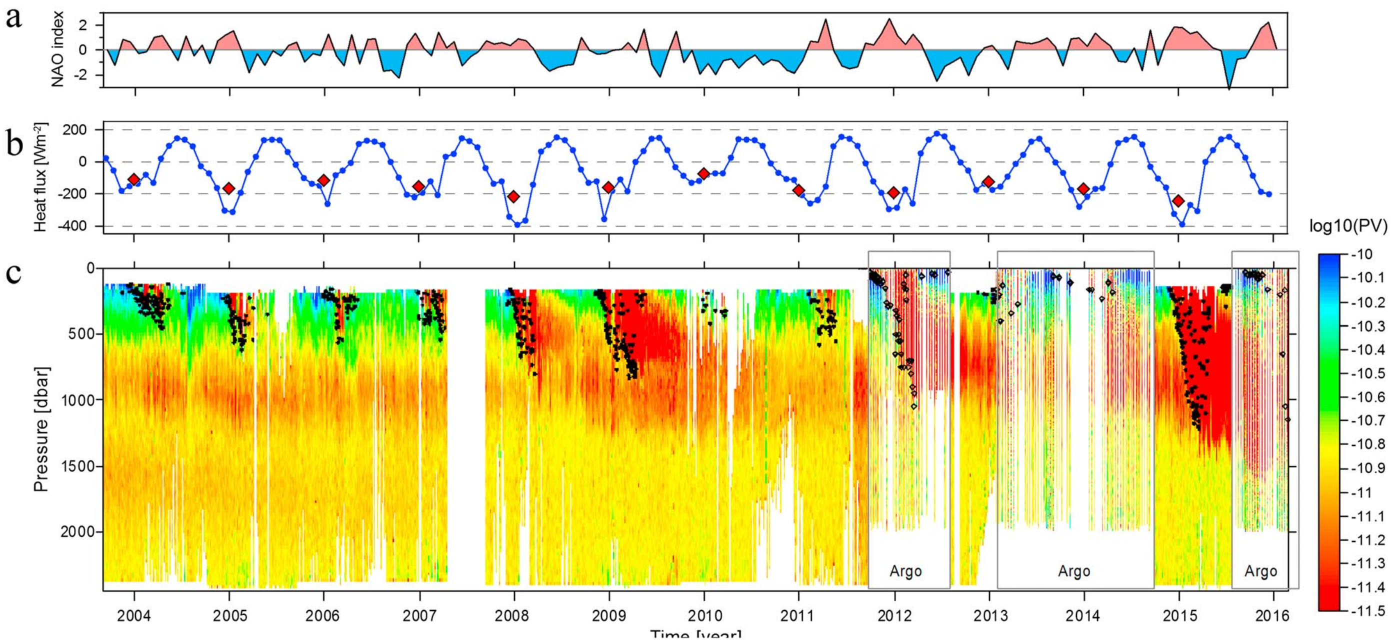

Figure 2. Time series of stratification and surface forcing at the LOCO mooring. (a) The monthly NAO index. (b) The surface heat flux over the mooring is drawn with monthly mean fluxes (blue dots) from NARR and the winter means (November–April, red diamonds). (c) The vertical stratification. Colors indicate planetary potential vorticity (in $m^{-1}\ s^{-1}$) (plotted on a logarithmic scale to highlight the mixed layers). The mixed layer depths are indicated with the black dots. The periods when Argo data are used to fill gaps are marked with the light gray boxes.

use the North Atlantic Regional Reanalysis (NARR) [*Mesinger et al.*, 2006] to quantify the atmospheric forcing. This regional reanalysis has higher resolution (0.3° or about 32 km), which enables it to capture small-scale features more accurately. A time series representative for the forcing over the LOCO mooring was obtained by averaging daily values of radiative and turbulent heat fluxes over the same area as the ERSST. The local atmospheric forcing is known to be strongly linked to the North Atlantic Oscillation (NAO) [*Yashayaev*, 2007; *van Aken et al.*, 2011]. The time series of the monthly mean NAO index [*Hurrell*, 1995] was obtained from NOAA.

3. Results

3.1. Strong Surface Cooling in the Winter of 2014–2015 and Resulting Deep Convection

NARR surface heat fluxes over the Irminger Sea show that the annual buoyancy in the winter of 2014–2015 was substantially larger than the 2003 to 2015 mean (Figure 2). The annual (June to July) mean for 2014–2015 was −91.5 compared to $-47.4\ W\ m^{-2}$ (2003–2015), and the winter (November to April) mean was −242.9 compared to $-158.5\ W\ m^{-2}$ (2003–2015). This makes the 2014–2015 heat flux comparable to the strong surface forcing in the winters of 1993 and 1994, which were −265.0 and $-257.9\ W\ m^{-2}$, respectively, for the November–April mean. The strong surface forcing in the winter of 2014–2015 was both due to high peak values and the persistence of winter through April, 1 month longer than usual. The long, cold winter was associated with a positive state of the North Atlantic Oscillation (NAO) that lasted throughout the winter (Figure 2). High NAO conditions also prevailed in the early 1990s and were associated with the well-documented large amount of classical Labrador Sea Water (LSW) produced in the Labrador Sea [*Yashayaev et al.*, 2007].

In preconditioned areas such as the Irminger Sea strong surface cooling results in deep convective mixing. Both the PV and mixed layer depth of the time series since 2003 reveal unprecedented convection in the winter of 2014–2015 (Figure 2). Active mixed layers were observed to go down to 1225 m, while the stratification of the upper layers was completely removed down to 1400 m. This is considerably deeper than mixing observed in previous years. Mixing seen in 2007–2008 (to 800 m), in 2008–2009 (to 1000 m) [*de Jong et al.*, 2012] and in 2011–2012 (1000 m) [*Piron et al.*, 2015]. Convection in the winter of 2014–2015 was not limited to the mooring location but extended throughout the basin. The volume of Labrador Sea Water (LSW) present in the basin was completely replaced by a new convective water mass (Figure 3). We denote this

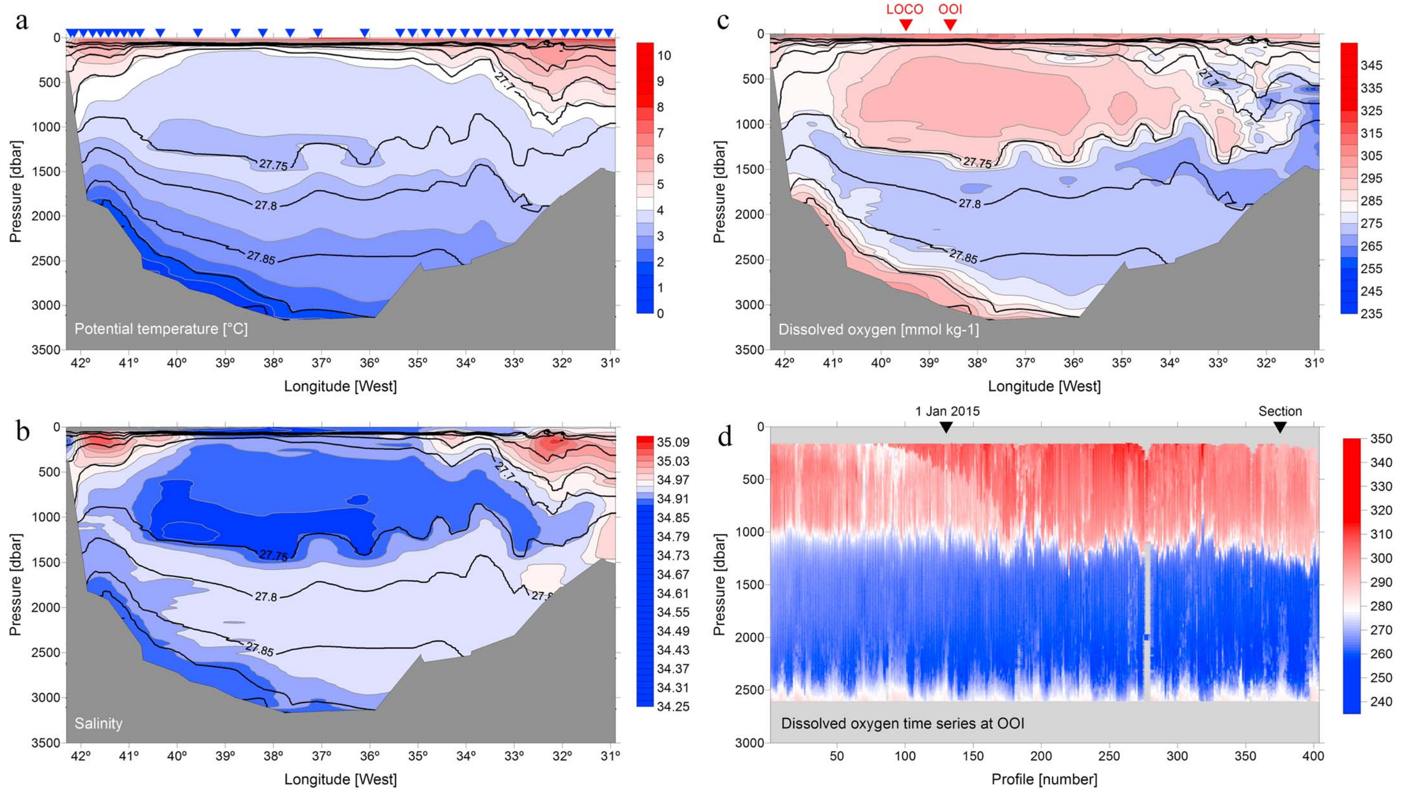

Figure 3. Hydrographic sections of the Irminger Sea surveyed in July 2015 and the time series of dissolved oxygen at OOI. Shown are the (a) potential temperature, (b) salinity, and (c) dissolved oxygen hydrographic sections. Blue triangles on the top of Figure 3a denote the CTD station locations, see also Figure 1. The positions of LOCO and OOI are indicated by the red triangles in Figure 3c. Isopycnals are drawn in Figures 3a–3c in black with an interval of 0.05 kg m^{-3}. The 27.75 isopycnal is located nearly at the bottom of the high oxygen waters at roughly 1250 m in the central basin. Figure 3d shows the time series of dissolved oxygen at OOI.

water mass as iLSW, to indicate its origin in the Irminger Sea (i) while acknowledging its similarity to LSW formed in the Labrador Sea. The fresh and cool iLSW, containing a high dissolved oxygen signature, was seen in the cross-basin hydrographic section of July 2015 (Figure 3). Dissolved oxygen profiles from the OOI array also confirm that this ventilation was taking place locally as deepening mixed layers from December 2014 through April 2015 showed the increase in oxygen. For the Irminger Sea, the new situation in 2015 (Figure 4) was reminiscent of the hydrographic conditions as seen in the 1990s [*Våge et al.*, 2011].

3.2. Ocean Temperature Variability

The Irminger and Labrador Seas are basins of net annual heat loss to the atmosphere, even in years with weak winters. The heat lost to the atmosphere is resupplied by radiative surface fluxes in summer as well as lateral input of heat through restratification (advection) with warmer water from the boundary currents (Figure 3). The radiative fluxes, which are mostly a function of the time of year and latitude, show very little interannual variability. The advective fluxes can have significant variability, potentially related to the northward heat transport by the AMOC. The appearance of negative SST anomalies in the North Atlantic (Figure 4) concurrent with a negative trend of the AMOC observed at the RAPID-MOCHA array has led to speculation that this process is already at work and that a weakened northward transport of heat is responsible for the low temperatures.

The recently observed recurrence of widespread deep convection in winter 2014–2015 disputes the suggested relation between increased freshwater input and consequent reduced convection in the subpolar gyre. Moreover, the hydrographic observations from the central Irminger Sea in summer 2015 show no evidence of any freshening relative to hydrographic sections of previous years. We propose that these negative SST anomalies must be investigated in light of the decadal variability and local surface forcing. Figure 4b presents the time series of ERSST temperature in the Irminger Sea from 1880 to present. Unlike the Northern Hemisphere mean temperature, which shows a clear upward trend, the Irminger Sea SST shows considerable

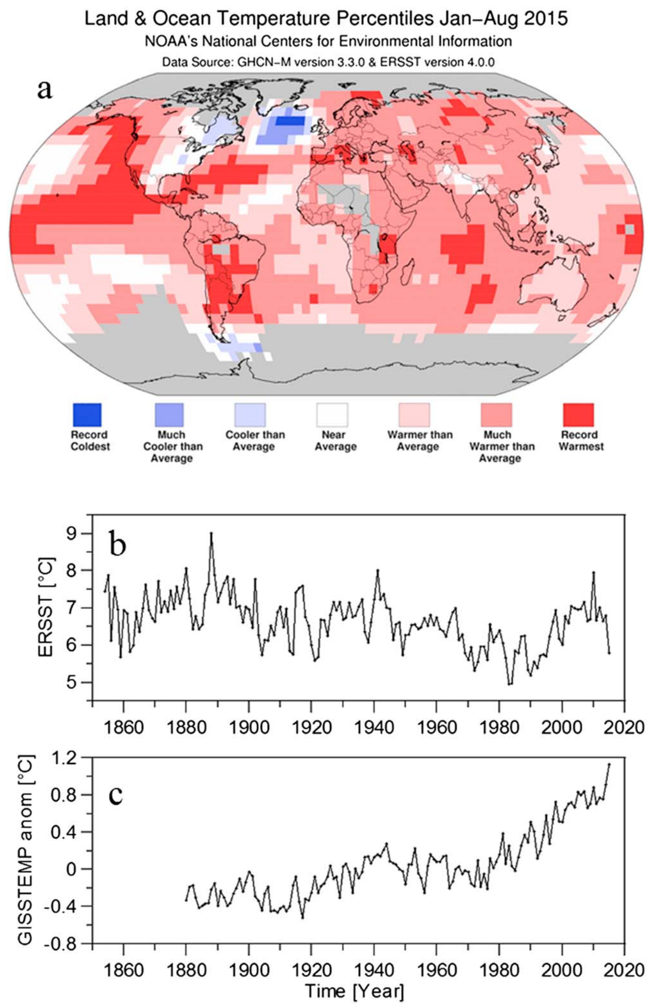

Figure 4. (a) NOAA map of temperature percentiles from September 2015. The map was obtained from http://www.ncdc.noaa.gov/temp-and-precip/global-maps/. On NOAA maps from early to mid-2015 the cold anomaly in the eastern subpolar gyre stood out. On later maps more cold anomalies appeared. (b) Annual (January to December) mean SST in the Irminger Sea from ERSST. (c) Annual mean Northern Hemisphere temperature anomaly from GISSTEMP.

interannual and interdecadal variability (Figure 4c versus Figure 4b). In addition, while the temperature in the Irminger Sea dropped significantly in 2015, it is not unprecedented (Figure 4b). Temperatures were at a minimum in the 1980s–1990s after a prolonged period of cooling. *Van Aken et al.* [2011] related this decadal decrease in temperature directly to strong surface forcing during a positive NAO and the repeated strong occurrence of convection. The cessation of strong cooling after the NAO switched to a negative state in 1995 resulted in a gradual increase in temperature in the basin, which lasted until 2010. Since then the basin has been cooling, with much stronger cooling in temperature in the winter of 2014–2015 which dropped the temperature below the reference temperature used to derive GISSTEMP SST anomalies.

Similarly, we can show that this cooling of the Irminger Sea is primarily due to surface forcing. We do this using a simple one-dimensional model, which assumes a balance between temperature changes (dT/dt) at LOCO, surface heat fluxes (Q_{sfc}), and lateral advection of heat (Q_{adv}).

$$H\rho C_p \frac{dT}{dt} = Q_{sfc} + Q_{adv}. \quad (1)$$

where H is the layer thickness, ρ is density, and C_p is the specific heat. The initial temperature at time $t = 0$ is chosen to be equal to the observed mean temperature over the layer at the start of the LOCO record. Daily surface fluxes (Q_{sfc}) are available from the NARR reanalysis. We chose the layer thickness H to be 1000 m, which is the approximate mean mixed layer depth, typo at LOCO. Since we want to study the effect of interannual variability in the surface forcing, we chose Q_{adv} to be constant throughout the record. This constant value for Q_{adv} was obtained by a fit of the model to the SST time series, with a stronger weight on the winter temperatures, and was found to be 46.1 W m^{-2} or 95% of the long-term mean Q_{sfc}.

The temperature evolution obtained from equation (1) and temperature at LOCO are compared in Figure 5. To obtain a mean temperature over the upper 1000 m, the upper part (~150 m) of the LOCO temperature profiles was extended to the surface using daily interpolated ERSST values using a cubic fit of the profiles. These obtained profiles agreed well with Argo profiles, which do extend to the surface. Argo profiles within 120 km of LOCO are used from mid-2011 to mid-2014 to fill the data gap in the moored profiler series. The Argo range was limited to 120 km here in order to reduce noise in the time series. The temperature record (Figure 5) shows that significant drops in temperature occur in years of deep convection (2008, 2012, and 2015). The temperature evolution derived from the simple model follows the observed temperature well. The strong winters of 2008, 2012, and 2015 result in the observed temperature drops, and similarly, the limited seasonal

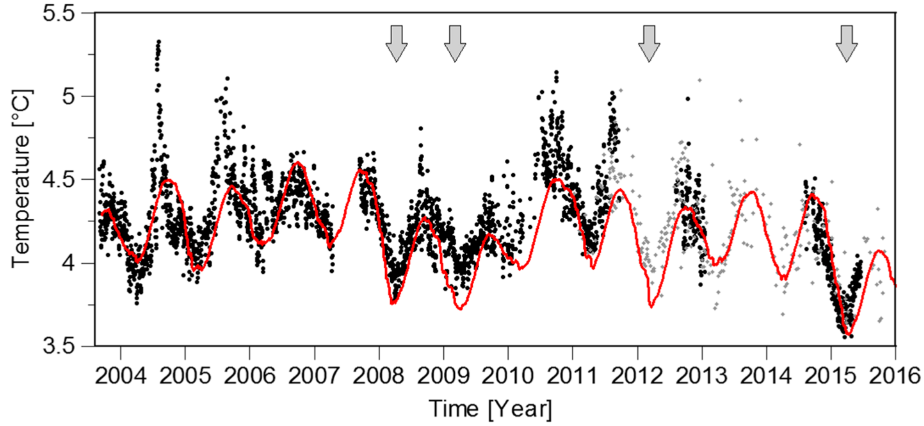

Figure 5. Temperature evolution of the upper 1 km in the central Irminger Sea. Mean temperatures from extended daily LOCO profiles are plotted in black. Mean temperatures from Argo profiles within 120 km are used between mid-2011 and mid-2014. The temperature evolution of the one-dimensional model using NARR surface fluxes is shown in red. Years with strong convection are indicated by the arrows at the top.

range observed in 2010 corresponds to a particularly weak winter (Figure 5). We conclude that the most recent cooling in the winter of 2014–2015 resulted in the low SST anomalies in the North Atlantic. Although this model is admittedly a crude representation of the local thermodynamics, we find that the observed temperature variability is explained without invoking a trend in the lateral heat transport that would be representative of an AMOC slow down. In fact, when the model is run reversely, extracting a time record of Q_{adv} out of the observed temperature changes and know surface forcing, the resulting time series of Q_{adv} is noisy and does not show a trend.

4. Conclusions and Discussion

A 12 year time series from a profiling mooring in the Irminger Sea shows record deep mixing in the winter of 2014–2015. The local mixing removed the stratification of the upper 1400 m of the water column and thereby all traces of the intermediate water mass which is commonly identified as Labrador Sea Water. The suitability of the Irminger Sea as convective area was proposed earlier by *Pickart et al.* [2003], but deep water formation with the same density of LSW was never directly observed. The hydrographic section from July 2015 reveals the basin wide extent of the mixing, with a large volume of recently ventilated water, high in dissolved oxygen concentration, filling the interior. The deep mixed layers were caused by prolonged strong surface cooling. The surface heat flux was comparable to that of the early 1990s, which was also associated with a positive phase of the North Atlantic Oscillation.

The Irminger Sea has recently gained attention as a region of negative SST anomaly over the North Atlantic. Low SSTs are thought to be indicative of enhanced freshwater input, which may weaken convection [*Yang et al.*, 2015]. As our observations demonstrate, deep convection in the subpolar gyre has intensified rather than declined over recent years. The observed increase in convection after 2008 fits the frequency of periods with large convection events recurring every 10 years [*van Aken et al.*, 2011]. We also showed that the negative temperature anomalies can be explained nearly entirely by interannual variability in surface buoyancy forcing.

In the subpolar gyre the SST record is characterized by strong interannual variability. *Henson et al.* [2016] showed that time series in this region must be particularly long (on the order of 40 years, compared to ~10 years in subtropical regions) before a climate change driven trend with statistical significance emerges out of the time series. This period might even be longer if we consider that the Atlantic multidecadal variability in subpolar SST is also on the order of 50 years [*Häkkinen et al.*, 2011]. On even longer time scales, the impact of surface warming on convection may be stronger than that of freshwater forcing. In general, care must be taken in associating processes identified in long (multidecadal or multicentury) model runs with shorter observational time series even though they may show the same spatial “fingerprint.” On these shorter, interannual time scales, the variability in the subpolar gyre is exceptionally large, and local forcing processes are likely to be more relevant than the processes associated with multidecadal change.

At present it is unclear how exactly, and on which time scale, deep convection in the Irminger and Labrador basins influence the properties and strength of the overturning circulation in the subpolar North Atlantic. Also, the interconnectivity with the AMOC as presently measured in the subtropical gyre has yet to be identified [*Lozier*, 2012; *Rhein et al.*, 2013]. A recently initiated international observational project, Overturning of the Subpolar North Atlantic Program (OSNAP, www.o-snap.org), aims to increase our understanding of the subpolar gyre through simultaneous measurements obtained by mooring arrays in all boundary currents, basin-wide hydrographic sections, floats, and gliders. The deep convection that occurred in 2014–2015 is extremely timely as it took place, while this new observing system was installed. Hence, it will for the first time allow to quantify the either direct or indirect effect of deep convection on the Overturning of the Subpolar North Atlantic, and, more importantly, how that overturning relates to the AMOC as measured at 26°N [*Cunningham et al.*, 2007; *Srokosz and Bryden*, 2015].

Acknowledgments

The research leading to these results has received funding from the European Union 7th Framework Programme (FP7 2007–2013) under grant agreement n.308299 NACLIM Project. LOCO data are submitted to the OceanSITES database (http://www.oceansites.org/). We thank H.M. van Aken for initiating the Irminger LOCO program. Argo data were collected and made freely available by the International Argo Program and the national programs that contribute to it (http://www.argo.ucsd.edu, http://argo.jcommops.org). SSTs from the Extended Reconstructed Sea Surface Temperature data set version 4 (ERSSTv4) were obtained from NOAA. GISTEMP Team, 2016: *GISS Surface Temperature Analysis (GISTEMP)*. NASA Goddard Institute for Space Studies. Data set accessed 1 April 2016 at http://data.giss.nasa.gov/gistemp/. *NARR data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at* http://www.esrl.noaa.gov/psd/. NAO index were obtained from NOAA Climate Prediction Center http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml. *Ocean Observatories Initiative* [2015]. Irminger Sea (Node). GI02HYPM. Apex Profiler Mooring. CTDPF. 6 May 2016/. V.0_01. Raw data. [dynamic data set, 12 September 2014 to 8 August 2015]. Retrieved from OOI website serving raw data.

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