

RESEARCH LETTER

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Key Points:

- Increasing winter convection involving preconditioning since 2012 has resulted in a peak Labrador Sea mixed layer depth of 2100 m in 2016
- The resulting volume of newly ventilated relatively cool Labrador Sea Water is the largest since the modern deep convection record in 1994
- The density of newly formed Labrador Sea Water progressively increased during 2012–2016 to reach its highest value since the mid-1990s

Supporting Information:

- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Figure S6

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Further intensification of deep convection in the Labrador Sea in 2016

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Abstract There has been a progressive deepening of winter convection in the Labrador Sea since 2012, with the individual profile maximum depth exceeding 1800 m since 2014 and reaching 2100 m in 2016. This increase, during repeated positive phases of the winter North Atlantic Oscillation (NAO), resembles that during the formation of the record depth (2500 m) Labrador Sea Water (LSW) class in 1987–1994, attributed to repeated positive NAO forcing having provided critical preconditioning. The 2012–2016 LSW class is one of the deepest and most persistent ever observed (back to 1938). Year-round observations from profiling Argo floats since 2002 complemented by annual surveys are providing novel information on the seasonal-to-decadal evolution of LSW, such as its variable density, the recent multiyear preconditioning, and its 2016 density being the highest since the mid-1990s. These findings should help international observation programs and numerical model studies investigating LSW influences on the subpolar North Atlantic and Atlantic Meridional Overturning Circulation.

1. Introduction

The most common paradigms for potential anthropogenic climate changes involve an important role for the world ocean's thermohaline (or “overturning”) circulation [e.g., *Stocker et al.*, 2013; *Marshall et al.*, 2014], sometimes described as a “conveyor belt” [e.g., *Broecker*, 1991]. This role usually involves reductions in the strength and northward extent of the Atlantic Meridional Overturning Circulation (AMOC) which is a major regulator of the Earth's climate variability [e.g., *Broecker*, 1997; *Rahmstorf*, 2002]. The CMIP5 (Climate Model Intercomparison Project Phase 5) model simulations used as a primary basis for projections of future climate changes, as well as for hindcasts of the past century, in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change all include a reduction in the strength of the AMOC [*Collins et al.*, 2013]. This is generally considered to be related to the upper ocean density-stratifying influences of global surface warming and high-latitude freshening associated with ice melt and an intensified hydrological cycle. Substantial international scientific effort is presently focused on describing and understanding variability in the AMOC [*Ansorge et al.*, 2014; *McCarthy et al.*, 2015b; *Lozier et al.*, 2016], including in the North Atlantic (NA) where the only Northern Hemisphere deep convection regions are located.

The AMOC is complex and difficult to measure, and many key issues related to its historic as well as current and future changes remain unresolved [*Lozier*, 2012; *Buckley and Marshall*, 2016]. Two issues under present debate in the oceanographic research community are (i) whether the strength of the AMOC averaged over interannual-to-decadal timescales is actually decreasing [e.g., *Rahmstorf et al.*, 2015; *Parker and Ollier*, 2016] and (ii) whether interannual-to-decadal variations in deep convection in the Labrador Sea (LS)—the primary ventilation region for intermediate layer waters in the northern NA (Figure 1)—result in changes in the AMOC [e.g., *Lozier*, 2012]. In this paper, we report on recent hydrographic observations from the LS which are highly relevant to these issues and have high potential for being valuable contributions to broader community (observational and modeling) progress on regional and global climate variability.

The northern NA is widely recognized to be an area with strong atmosphere-ice-ocean coupling and decadal-scale variability and uncertainty in its long-term changes in temperature, salinity, and density over the past century [e.g., *Terry*, 2012; *Rhein et al.*, 2013]. The predominance of decadal variability over a longer term trend is particularly true below the seasonal surface layer in the LS [*Yashayaev and Loder*, 2016, hereinafter YL2016]. Here we report that the increasingly deep winter convection in the LS during 2012–2015 described by YL2016 was followed by even deeper convection in winter 2016, resulting in the latest Labrador Sea Water (LSW) pycnostad being the deepest, thickest, and densest since the modern record convection period of 1987–1994 and one of the deepest ever observed (since 1938). In view of the widespread changes in

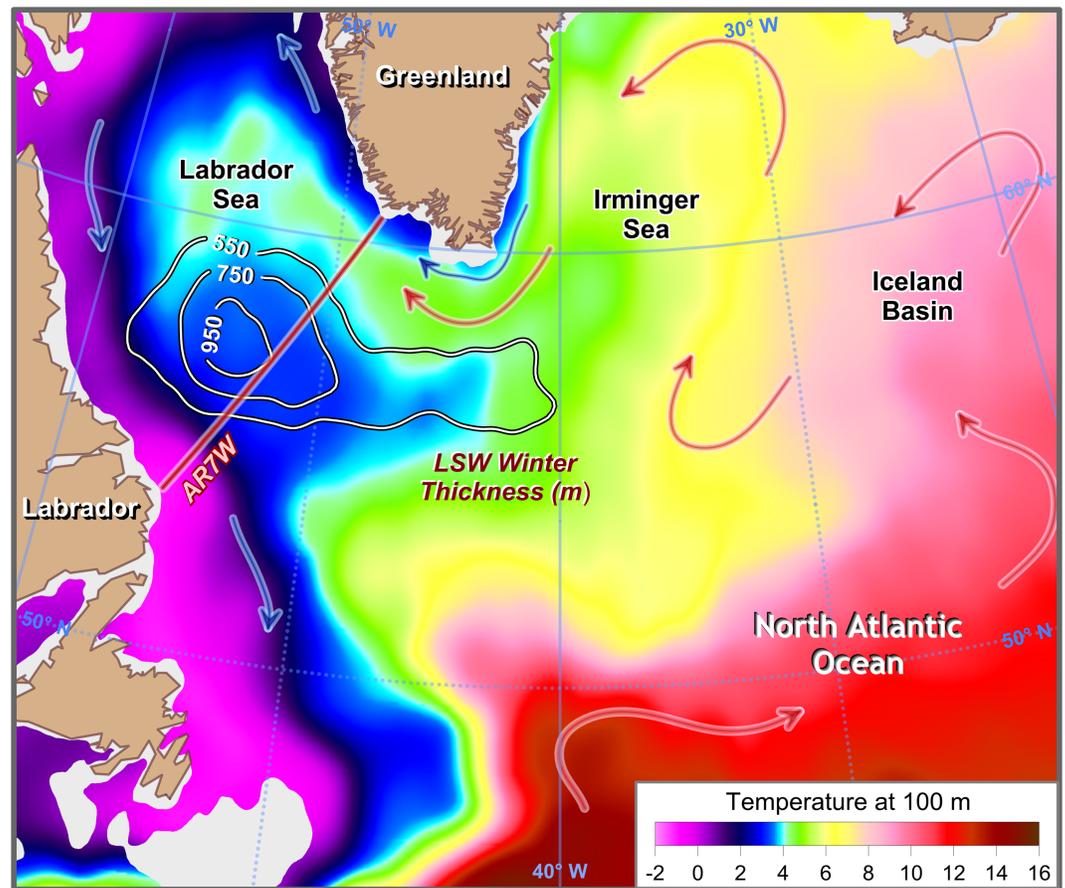


Figure 1. Map showing the locations of the AR7W line, the climatological ocean temperature ($^{\circ}\text{C}$) at 100 m (see Loder *et al.* [2015] for methodology), and the 2002–2016 winter thickness of LSW (white contours with black borders). The major upper ocean circulation features are indicated by arrows, with red indicating waters of subtropical origin and blue waters of subpolar origin.

NA circulation and heat content attributed to anomalous atmospheric forcing during the early 1990s [e.g., Polyakov *et al.*, 2010; van Sebille *et al.*, 2011], this recent return of strong convection signals further important decadal variability.

We build on recent papers describing the historical variability of LSW [Lazier *et al.*, 2002; Yashayaev, 2007, hereinafter Y2007] and enhanced deep convection in the region in 2008 [Yashayaev and Loder, 2009, hereinafter YL2009], 2014 [Kieke and Yashayaev, 2015, hereinafter KY2015], and 2015 (YL2016). We draw on an annual hydrographic survey across the LS (YL2016) and the unprecedented availability of year-round hydrographic observations since the 2002 start of the Argo float era [Riser *et al.*, 2016]. We point to observations of record-strong deep convection in the nearby Irminger Sea in 2015 [de Jong and de Steur, 2016; Fröb *et al.*, 2016] and a widespread cold anomaly in the subpolar NA in recent years [Duchez *et al.*, 2016] as reasons for climate community attention to recent anomalous conditions in the northern NA. The recurrence of strong deep convection in the subpolar NA also has implications for the global ocean sequestration of anthropogenic carbon [e.g., Li *et al.*, 2016] and potential implications for global warming hiatuses [e.g., Drijfhout *et al.*, 2014]. Regionally, it has potential implications for interannual-to-decadal variability in ocean heat content [e.g., Somavilla *et al.*, 2016], circulation [e.g., Yeager and Danabasoglu, 2014], sea level [e.g., McCarthy *et al.*, 2015a], sea ice [e.g., Yeager *et al.*, 2015], and biology [e.g., Hátún *et al.*, 2016] in and around the NA, including aspects of the AMOC [e.g., Rhein *et al.*, 2015], and for weather in adjoining continental regions [e.g., Gastineau and Frankignoul, 2015].

2. Data and Methods

Our primary data sources and methodology are temperature and salinity profiles from Fisheries and Oceans Canada (DFO) ship-based surveys and from Argo floats (YL2016) and a mix of standard and novel analyses.

The main data additions here are observations from Argo floats up to November 2016 and DFO's annual conductivity-temperature-depth (CTD) survey of the AR7W (Atlantic Repeat Hydrography Line 7 West) across the LS in May 2016 (Figure 1). We also draw on historical hydrographic data sets (KY2015), the winter (January-March) NAO index, and the U.S. National Centers for Environmental Prediction (NCEP) Reanalysis data available from various websites, as outlined in YL2016.

The primary methodological addition here is a volumetric temperature-salinity census for the central portion of the AR7W line in the springs of 1994 and 2016, the culmination years of the two largest multiyear convection periods in the LS since at least the mid-1980s. In this analysis, we use temperature and salinity profiles from full-depth CTD casts along a 470 km segment of the AR7W line, weighted by the horizontal distance represented by each profile, and compute the layer thicknesses for overlapping 0.1°C temperature by 0.01 salinity bins. To obtain estimates of LSW volume, we perform a similar census for ~0.4°C by ~0.02 bins in each year and multiply the thickness of the LSW core by an estimate of the core's area during the Argo era of broad data coverage.

3. Results

3.1. LSW Extent and Extremes

The location of the LS convection zone can be seen in the distributions of climatological annual mean subsurface (100 m) temperature and 2002–2015 mean winter thickness of the LSW pycnostad (based on σ_1 values that are within $\pm 0.01 \text{ kg m}^{-3}$ of its core value) in Figure 1. Below the seasonal surface layer, the LS has the coldest off-shelf upper ocean waters of the entire open ocean NA south of Iceland. These waters extend southward in the Labrador Current along the continental margin and generally eastward toward the northeastern NA, as part of the subpolar gyre. The LSW pycnostad also extends eastward south of Greenland, in addition to its well-known equatorward exit pathway along the western margin [e.g., Talley and McCartney, 1982; Fischer *et al.*, 2010] (which is not apparent here because of reduced thickness in the boundary current). The important contribution of the generally westward advection of relatively warm (and, more importantly, relatively saline) water into the Irminger and Labrador Seas [e.g., Häkkinen *et al.*, 2011] can also be seen, consistent with contributions from both atmospheric cooling and advected salt to the wintertime upper ocean densification in these convection zones (YL2016).

The vertical and cross-basin extents of the LSW pycnostad in the spring of three contrasting convection years are shown in Figure 2, with the distributions of (potential) temperature, salinity, (potential) density, and dissolved oxygen. In winter 1994, after increasingly deep convection since 1987 [e.g., Dickson *et al.*, 1997; Y2007], the pycnostad extended to 2500 m in one profile and to 2400 m in an “aggregate” sense (see below), resulting in the record $LSW_{1987-1994}$ class with relatively uniform temperature, salinity, density, and dissolved oxygen extending across most of the basin. Note that by the time of these May surveys, a thin surface layer of relatively warm, fresh, and light water had developed.

In contrast to 1994, the pycnostad extended to only 800 m in 2011—the second shallowest of the Argo era (after 600 m in 2010)—with less uniform and warmer, more saline, lighter, and more oxygenated water in the 200–800 m depth range. Year 2011 was a near-record year at the other extreme, with annual temperature and salinity averaged over the 200–2000 m vertical interval in the central LS having some of their highest values ever observed (among those of years 1970, 1971, 2010, and 2013) and the corresponding densities having record low values (Figure 3). This (warming and increasing salinity) phase occurred somewhat gradually between 1994 and 2011, interrupted by weaker and shorter periods of intensified convection in 2000–2003 and 2008, respectively (and the $LSW_{2000-2003}$ and LSW_{2008} classes; see Figures S1–S3 in the supporting information for the AR7W property distributions in representative years).

The May 2016 distributions (Figure 2) indicate a substantial swing in LSW conditions back toward those of the early 1990s, in only a 5 year period (Figure 3). The pycnostad, henceforth $LSW_{2012-2016}$, was relatively broad and deep compared to that in 2011 (and prior years in the Argo era excepting 2002, 2003, and 2008) and relatively cool, fresh, dense, and well oxygenated to depths of 1500–2000 m. The aggregate maximum convection depth (taken as the 75th percentile of individual profile convection depths; YL2016) was 1900 m, with an individual profile maximum of 2100 m.

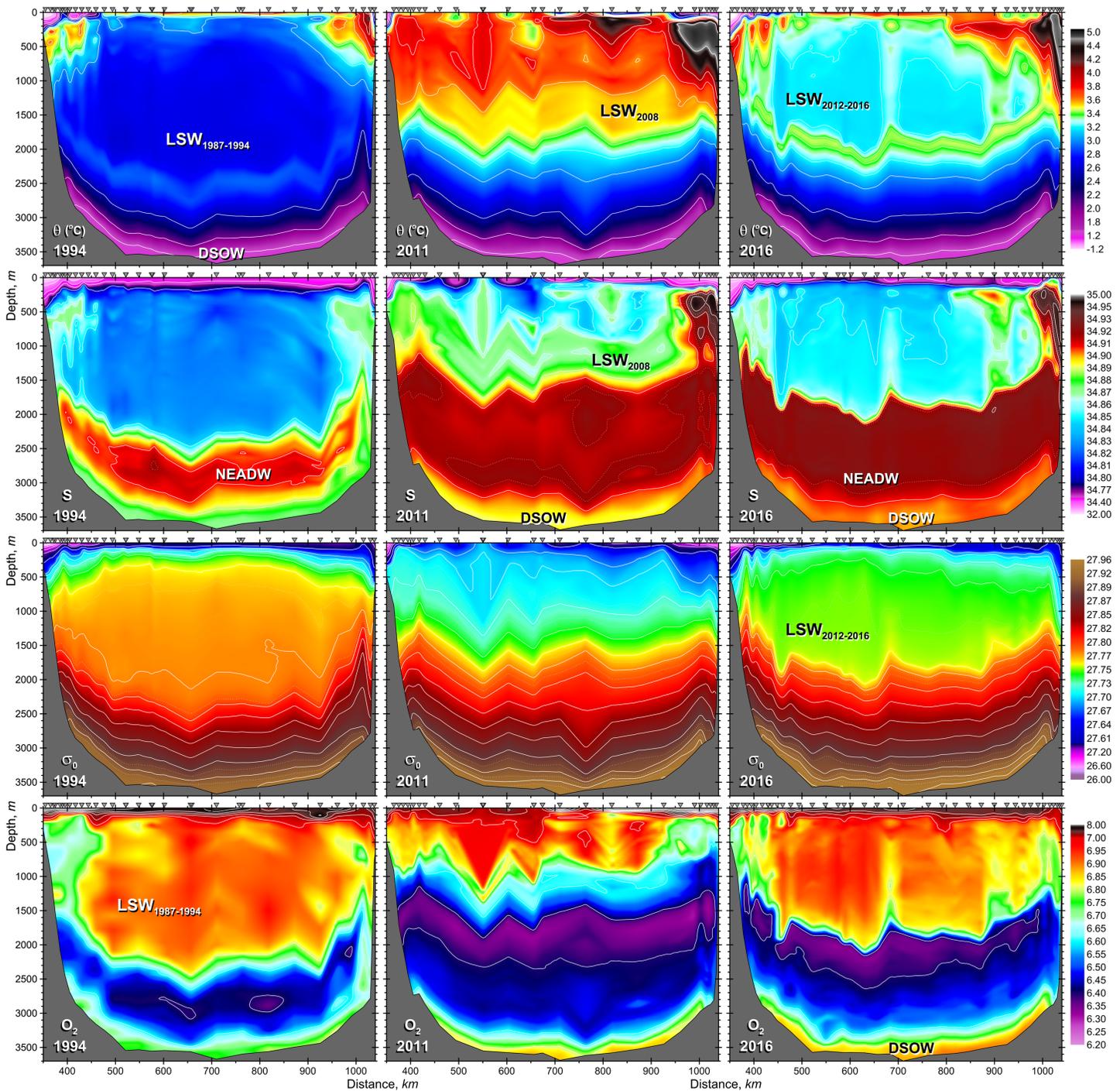


Figure 2. Distributions of potential temperature (θ), salinity (S), potential density (σ_0 , referenced to the surface), and dissolved oxygen (O_2) on the AR7W line in the springs of 1994, 2011, and 2016. Major classes of LSW, as well as the deeper underlying limbs (Northeast Atlantic Deep Water (NEADW) and Denmark Strait Overflow Water (DSOW)) of the AMOC, are indicated.

3.2. Time Evolution of LSW_{2012–2016}

The development of LSW_{2012–2016} can be seen in more detail in the combination of time-depth plots of the spatially averaged properties in the central LS (Figure 4), the distribution of properties on AR7W in the annual surveys (Figures 2 and S1–S3), and temperature-salinity (θ - S) plots for the central LS from these surveys (Figure 5). To place the 5.5 year time-depth plots (Figure 4) in a longer-term perspective, the reader is referred

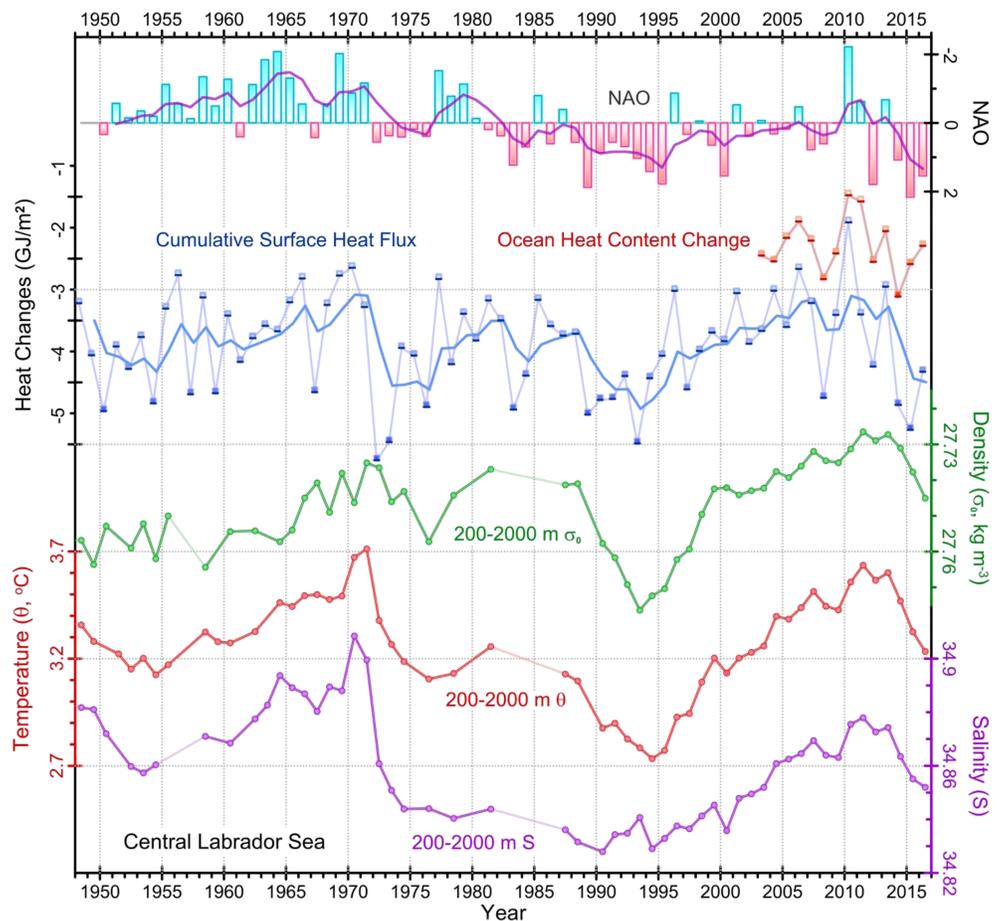


Figure 3. Key annual forcing and hydrographic indices for the central LS since 1948. The upper bar graph shows the normalized winter NAO index (inverted scale). The next two time series represent heat changes in the central LS during each yearly cooling season; first (in red), the change in ocean heat content during each ocean cooling season of the Argo era based on profile data and, second (in blue), the change inferred from the cumulative surface heat flux computed from NCEP R2 data (with the color intensity of each yearly square indicating the relative magnitude within each series). For the NAO and surface flux, a low-frequency curve has been included to reflect the cumulative effect of preconditioning, using a five-point filter (with value plotted at the last year of each period). The lower three curves are estimates of the annual mean temperature (θ), salinity (S), and density (σ_n , referenced to the surface; inverted scale) averaged over the 200–2000 m interval in the central LS.

to the corresponding monthly resolution plots for the 13 year 2002–2015 period and the time-depth plots of annual temperature, salinity, and density for 1938–2015 in YL2016.

In addition to showing the seasonal evolution of properties and density layer thicknesses in individual years, Figure 4 provides an unprecedented view of their evolution during the multiyear preconditioning period leading to the formation of the major LSW_{2012–2016} class. There was limited connectivity between the shallow pycnostads that developed during the winters of 2009 to 2011 (YL2016). However, starting in winter 2012 when the aggregate maximum convection depth was 1300 m, there was increased year-to-year persistence of newly ventilated water at intermediate depths, as particularly apparent in temperature and density layer thickness.

In 2012 the winter NAO returned to a relatively strong positive value, comparable to its peak values in 1989, 1995, and 2000 (Figure 3). After a weak negative value in 2013, the index had moderate-to-strong positive values in 2014, 2015, and 2016, with the 2015 peak value being the largest since the nineteenth century. The time-depth plots (Figure 4) and θ - S plots during the AR7W surveys (Figure 5) indicate that the slightly reduced convection (to 1200 m) in 2013 did not significantly intensify or expand the remnant 2012 pycnostad. However, starting with the strong convection in 2014, there has been a clear deepening of the pycnostad and intensification of its anomalous (cool and dense) properties in subsequent winters (Figure 5b) while the

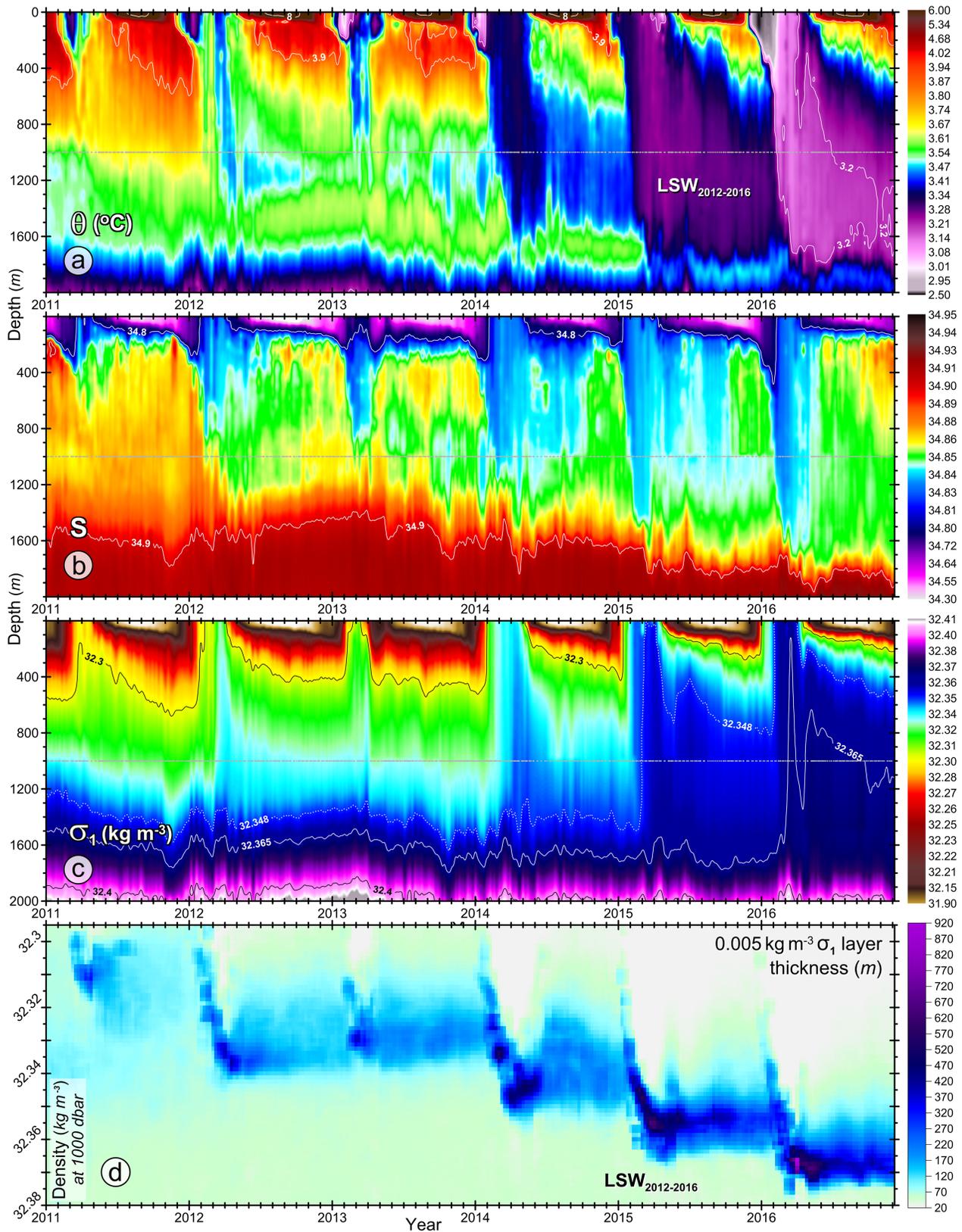


Figure 4. Time-depth plots of (a) potential temperature, (b) salinity, and (c) potential density (σ_1 , referenced to 1000 dbar), and (d) time- σ_1 plot of σ_1 layer thickness in the upper 2000 m of a 60,000 km³ core area of the central LS during 2011–2016, showing the evolution of LSW_{2012–2016}. The white dots at 1000 m in Figures 4a–4c indicate the profile times, and selected isolines are also included in these figures.

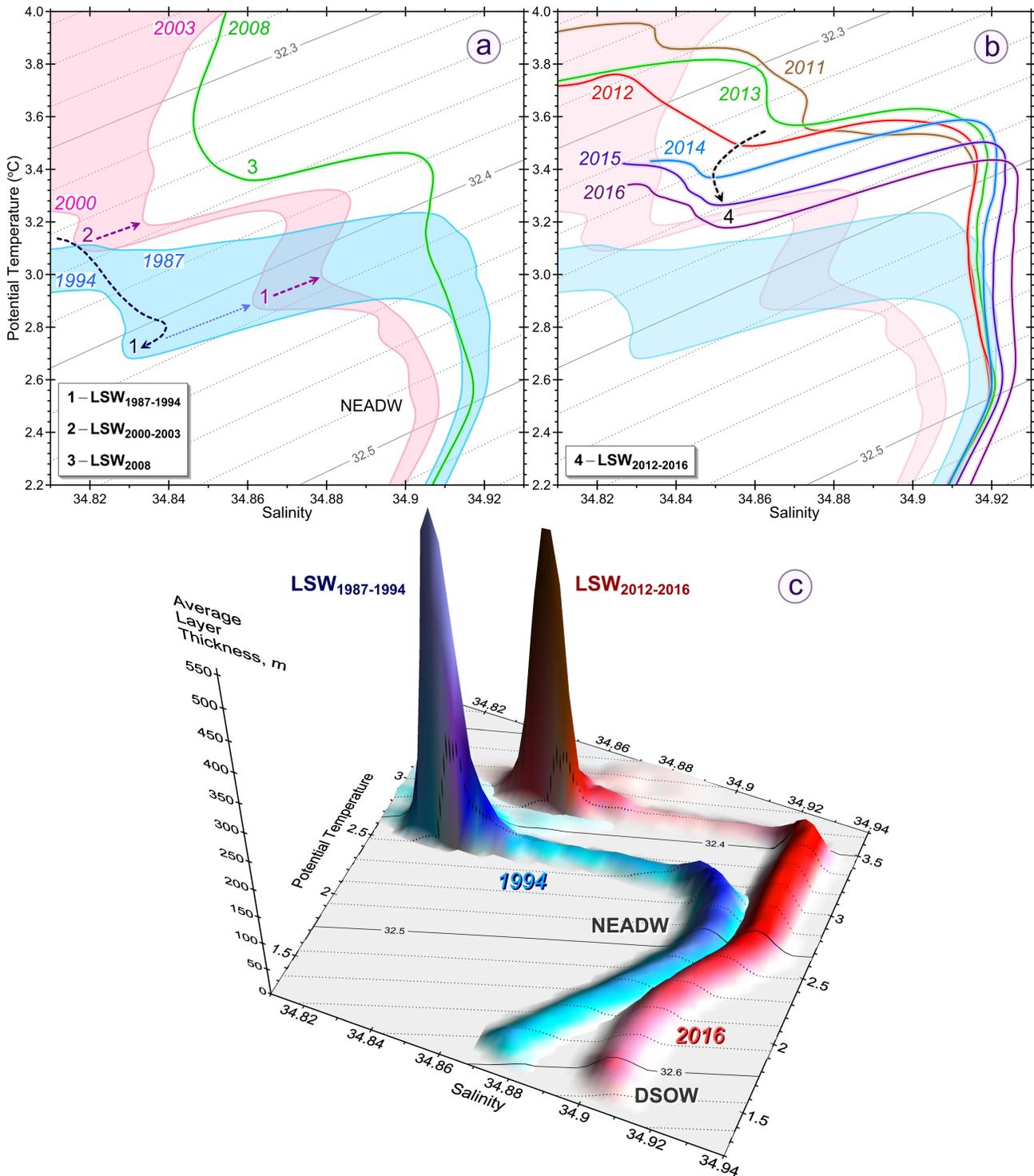


Figure 5. Temperature-salinity (θ - S) plots for the central LSW for (a) the moderately strong convection year 2008 and (b) individual years between 2011 and 2016 showing the evolution of the recent strong LSW_{2012–2016} class, with the envelope of θ - S properties during the record-strong 1987–1994 and moderately strong 2000–2003 convection periods in the background. Each annual profile is an average (in σ_1 space) of observations over a 470 km segment along the AR7W line, for the approximate depth range 300–3600 m. The core θ - S values of the four largest LSW classes since the late 1970s are labeled using numbers reflecting their chronological sequence, and the interannual progressions of core θ - S within the multiyear LSW_{1987–1994}, LSW_{2000–2003}, and LSW_{2012–2016} classes are indicated using dashed arrows. The deeper NEADW and DSOW are notated and the σ_1 isopycnals indicated by the grey background curves. (c) Volumetric θ - S plot of the 1994 and 2016 profiles from Figures 5a and 5b, showing the (spring) postformation states of LSW_{1987–1994} and LSW_{2012–2016}. Average layer thicknesses are shown for 0.1°C θ by 0.01 S bins which results in no single bin entirely capturing the slightly varying core θ - S values of each pycnostad.

positive winter NAO phase continued, analogous to that which occurred during 1987–1994 (Figure 5a). Aggregate maximum convection depths were 1500 and 1700 m in 2014 and 2015, respectively (YL2016), before increasing to 1900 m in 2016 (Figures 2 and 4). These have been the largest since the record 1994 depth (excepting the 1550 m depth in 2008) and among the largest in the modern observation record outside the 1987–1994 period (e.g., Y2007). Their nearly progressive increase since 2011 can be viewed as a reinforcement of the 2012 pycnostad and preconditioning for the peak (to date) 2016 state.

3.3. Longer-Term Variability

YL2016 have described how the intermittent recurrence of enhanced deep convection periods in the Labrador Sea, and the associated formation of major LSW classes, are contributing to a predominant decadal-scale variation in hydrographic properties which makes it difficult to determine whether anthropogenic changes are occurring. This is illustrated in the updated (to 2016) time series of 200–2000 m temperature, salinity, density in Figure 3. The added 2016 values continue the recent (since 2011) trends in these properties which are reversals of those which had been occurring since the 1994 penultimate state of LSW_{1987–1994}. Somewhat analogously, there was a reversal in the early 1970s of the trends over the previous two decades to those of the increasingly positive NAO period from 1972 to 1994 (see *van Aken et al.* [2011] for further discussion concerning historical decadal-scale variability). Clear century-scale trends are not yet apparent in these integral properties of one of the potential driving and/or buffering regions of Earth climate variability. There is a hint of a possible long-term decrease in LSW density which is in the expected sense for global warming contributing to a reduction in deep convection and reduction in the AMOC, but this is disappearing with the recent recurrence of strong convection.

Following YL2009, YL2016 also showed how there has been a close correspondence between the variations in the heat content decrease in the central LS during each fall-winter cooling season of the Argo era and the cumulative (seasonal) surface heat loss to the atmosphere based on the NCEP data. These time series are updated in Figure 3, together with the addition of a lagged low-pass-filtered curve to the surface flux and NAO time series (back to 1950). The filter was chosen to represent the cumulative (multi-year, reflecting preconditioning) effects of successive fall-winter surface heat extraction (from the ocean) and successive positive NAO winters, using a linear-forward weighted average over 5 years (relative weights of 0.2, 0.4, 0.6, 0.8, and 1.0). There is a remarkable correspondence in the pentadal-to-decadal variability in these multi-year cumulative atmospheric forcing indices and the unfiltered spatially averaged annual density and temperature time series averaged over most of the upper intermediate waters in the central LS (the upper 200 m was not included because of lack of information on the seasonal cycle prior to the Argo era). This agreement, which includes 2016 having the most extreme multi-year cumulative NAO and surface flux forcing but not the most extreme individual-year forcing, provides strong support for an important preconditioning role of cumulative atmospheric forcing in the recurrent major deep convection periods in the Labrador Sea [e.g., *Dickson et al.*, 1996]. On the other hand, it does not preclude important roles of variable sea ice [e.g., *Våge et al.*, 2009], surface meltwater [e.g., *Yang et al.*, 2016], and ocean advection [e.g., *Häkkinen et al.*, 2011] in convection variability, nor does it pinpoint the origin of the variable atmospheric forcing [e.g., *Grist et al.*, 2016; *Kim et al.*, 2016].

Figure 5c has a comparison of the properties and thickness of the major LSW_{2012–2016} and LSW_{1987–1994} classes in temperature-salinity space, using 0.1°C θ by 0.02 S bins. The most recent class was warmer (~3.2°C versus ~2.7°C), slightly more saline (~32.85 versus ~32.83), and lighter (core σ_1 value of ~32.37 versus ~32.41). Note from Figure 3 that these 2016 values are closer to their corresponding long-term averages than to extreme values, reflecting the predominance of decadal-scale variability over a long-term trend. The average thickness of the spring 2016 pycnostad along the AR7W line based on a volumetric analysis similar to that in Figure 5c (but with the θ and S bins broadened to 0.4°C and 0.02, respectively, to capture the entire pycnostads; Figure S4) is 1400 m, compared to 1800 m in 1994. Making the crude assumption that the area of each pycnostad is similar to that in winter averaged over 2002–2015 (310,000 km², approximated as the area inside the 550 m thickness contour in Figure 1 which has an extent of 425 km along the AR7W line compared to the 1994 and 2016 pycnostads' extent of 470 km), estimates of the spring pycnostad volumes are 430,000 and 560,000 km³ for LSW_{2012–2016} and LSW_{1987–1994}, respectively. These are of comparable magnitude to the 380,000 and 630,000 km³ estimates in YL2016 for the late winter pycnostad volumes in year groups of relatively weak and relatively strong convection during the Argo era up to 2015. However, they are only rough estimates since information on the actual area of the pycnostads in 1994 and 2016 is not available and contributions from

convection in the western boundary current [e.g., *Pickart et al.*, 2002] are not included. Further, these estimated areas and volumes include the eastward extension of the pycnostad south of Greenland which probably needs further consideration of whether it should be included in LSW [e.g., *Fröb et al.*, 2016].

Finally, we note significant changes since 1994 in the underlying Northeast Atlantic Deep Water (NEADW) and Denmark Strait Overflow Water (DSOW) in Figure 5, such as a reversal in the freshening over the previous four decades [*Dickson et al.*, 2002; *Yashayaev and Dickson*, 2008; *Sarafanov et al.*, 2010] which will be discussed elsewhere.

4. Concluding Points

The above average surface heat extraction from the central LS in four of the past five winters, associated with positive NAO anomalies, has reversed the trends in maximum convection depths and vertically averaged temperature, salinity, and density that had occurred over the preceding 16 years. This and previous reversals in the early 1950s, early 1970s, and early 1990s have resulted in a predominant bidecadal variation in the formation of major classes of LSW and associated ventilation of the intermediate-depth waters of the Northwest Atlantic. The resulting LSW_{2012–2016} class, involving preconditioning due to successive cool (destratifying) winters, is the largest since the record LSW_{1987–1994} class and a strong candidate for the second largest (in combined depth and duration) in the modern record (since 1938), with an average thickness (and volume) in the central LS in spring 2016 approximately 78% of that in spring 1994. This strong, apparently natural, decadal-scale variability makes it very difficult to determine whether significant anthropogenic changes in LSW formation and properties have occurred.

Nevertheless, considering the various references cited in section 1, the occurrence of relatively strong deep convection in the Labrador and Irminger Seas in recent years has potentially important implications for oceanographic variability across the subpolar North Atlantic and possibly in the AMOC. However, further analyses are needed, in particular drawing on observations and model interpretations from various regional programs, the ongoing Argo and other international programs [e.g., *McCarthy et al.*, 2015b; *Srokosz and Bryden*, 2015], and the new internationally coordinated Overturning in the Subpolar North Atlantic Program [*Lozier et al.*, 2016]. It remains to be seen whether this recent intensification of intermediate-depth ocean ventilation in a key part of the Earth climate system has reached its peak or will continue and what its impacts will be.

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