

Surprising return of deep convection to the subpolar North Atlantic in winter 2007-08

Kjetil Våge^{1*}, Robert S. Pickart¹, Virginie Thierry², Gilles Reverdin³,
Craig M. Lee⁴, Brian Petrie⁵, Tom A. Agnew⁶, Amy Wong⁶ & Mads H. Ribergaard⁷

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¹*Woods Hole Oceanographic Institution, Woods Hole, USA*

²*Laboratoire de Physique des Océans, Plouzané, France*

³*Laboratoire d'Océanographie Dynamique et de Climatologie, Paris, France*

⁴*Applied Physics Laboratory, University of Washington, Seattle, USA*

⁵*Bedford Institute of Oceanography, Dartmouth, Canada*

⁶*Meteorological Service of Canada, Downsview, Canada*

⁷*Danish Meteorological Institute, Copenhagen, Denmark*

*Corresponding author, email address: kjetil@whoi.edu

The process of open-ocean convection in the subpolar North Atlantic Ocean forms a dense water mass that impacts the meridional overturning circulation and heat flux, and sequesters atmospheric carbon. In recent years the convection has been shallow or non-existent, which could be construed as a consequence of a warmer climate. However, in the winter of 2007-08 deep convection returned to the subpolar gyre in both the Labrador and Irminger Seas. Here we document this return and elucidate the reasons why it happened. Profiling float data from the Argo programme are used to document the deep mixing, and a variety of in-situ, satellite, and reanalysis products are analyzed to describe the conditions leading to the overturning. The transition to a convective state took place abruptly, without going through a preconditioning phase, which is contrary to general expectations. Changes in the hemispheric air temperature, tracks of storms, flux of freshwater to the Labrador Sea, and distribution of pack ice all conspired to enhance the air-sea heat flux, resulting in the deep overturning. This study illuminates the complexity of the North Atlantic convective system.

The subpolar North Atlantic Ocean is a critical component of the global climate system. Deep convection in the Labrador and Irminger Seas produces the water mass known as Labrador Sea Water (LSW)¹. This results in a net transfer of heat from the ocean to the atmosphere, which is balanced by northward advection of heat via the surface limb of the meridional overturning circulation (MOC). In response to global warming, most climate models predict a decline of the MOC, often due to a reduction of LSW formation (e.g. ref. 2). The ocean is also an important sink of atmospheric CO₂, and, as a result of dense water formation and transformation, more

anthropogenic carbon per unit area is stored in the subpolar North Atlantic than in any other ocean³. Furthermore, LSW is entrained by the dense waters overflowing the Greenland-Scotland Ridge⁴. The composite water mass product, known as North Atlantic Deep Water, is found throughout the World Ocean⁵ and forms the deep limb of the MOC. Through this pathway CO₂ can be sequestered in the abyssal ocean for centuries, but the pathway is only active as long as the depth of winter convection exceeds 1000 m⁶.

Since the mid-1990s, convection in the Labrador Sea has been shallow – and at times nearly absent⁶⁻⁸. The only major exception was the winter of 1999-00 (forming a water mass known as the “LSW 2000” class)^{6;9}. The last time convection occurred to depths of 2 km or more was during the late 1980s to early 1990s. This period was characterized by an extreme positive state of the North Atlantic Oscillation (NAO), which is the dominant pattern of climate variability in the North Atlantic¹⁰. A positive NAO index is associated with strong westerly winds, enhanced air-sea buoyancy fluxes, and is often linked to the onset of deep convection in the Labrador Sea¹¹ and Irminger Sea¹². However, there is not a one-to-one correspondence between convection and the NAO, since preconditioning plays an important role regulating the depth of convection⁶ and the NAO explains only some fraction of the atmospheric circulation variability¹³. A recent study¹⁴ has revealed a zonal shift of the Atlantic centers of action associated with changes in the NAO, making it more difficult to interpret the significance of the traditionally defined NAO index for oceanic convection. Here we show that convection returned unexpectedly to the subpolar gyre during the winter of 2007-08, with little evidence of preconditioning and in spite of the fact that the NAO index was lower than the previous winter.

Mixed layers in the subpolar North Atlantic

Deep convection in the North Atlantic subpolar gyre is commonly thought to occur principally in the Labrador Sea (e.g. ref. 6). This view is based primarily on shipboard hydrographic surveys, which are typically carried out in late spring and summer after the convection has ceased. Float data from the Argo programme provide a means to sample throughout the convective season, though at more limited spatial resolution. During winter 2007-08, most of the Argo floats drifting in the northwestern part of the subpolar gyre measured deep mixed layers. This provides further direct evidence that deep convection occurs outside the Labrador Sea¹⁵ (see also figure 13 of ref. 16).

Three floats, documented for several years, are highlighted in Figure 1. These floats sampled the Labrador Sea, Irminger Sea, and the region south of Greenland. The deepest mixed layers in the records, measured in winter 2007-08, were approximately 1800 m in the Labrador Sea, 1000 m in the Irminger Sea, and 1600 m south of Greenland (see the Methods section below for details on the determination of the mixed layer depth). All of these were isolated mixed layers, where the float encountered a patch of convected water that had begun to re-stratify in the upper-layer since its last contact with the atmosphere. We examined the stratification in the central Labrador and Irminger Seas using the Argo data to verify that the very low values of buoyancy frequency (N) within the isolated mixed layers in Figure 1a could not have survived the previous summer. With the exception of a weakly stratified eddy encountered by float 4900500 in November 2006, the lowest values of N were observed in the winter mixed layers. Hence, in light of the weak advective speeds in these regions¹⁷, the overturning that caused the mixed layers in Figure 1a

occurred close to the point of observation. This is corroborated by recent shipboard observations in the Labrador Sea (showing convection to 1600 m)¹⁸ and moored time series in the Irminger Sea (revealing mixed layers to nearly 1000 m, Femke de Jong, personal communication). The deepest mixed layers reaching the surface that were observed by the profiling floats in winter 2007-08 were approximately 1600 m in the Labrador Sea (floats 4900494 and 4900677), 700 m in the Irminger Sea (float 6900240), and 1300 m south of Greenland (float 4900537). The properties of the LSW formed last winter are similar to the LSW 2000 class⁶. Interestingly, an 800 m deep mixed layer was measured by float 6900240 during winter 2006-07 in the northeastern Irminger Sea (Fig. 1c), in a region where deep mixed layers have previously been reported^{19;20}.

To put the winter of 2007-08 into perspective, a climatology of mixed layer depths was created for the period 2000-07, hereafter referred to as the base period (the Labrador and Irminger Seas were not well sampled before winter 2003). In particular, for each winter (Feb–Apr), and for each given float, only mixed layers deeper than 80% of the maximum recorded mixed layer depth were included. This was done to isolate the mixed layers recorded near the time and location of the peak convective activity, thereby avoiding a shallow bias associated with the non-uniform temporal and spatial character of convection. All of the profiles satisfying this criterion (28% of the total winter profiles) were combined into a single data set and interpolated onto a 1°x1° grid using a Laplacian-spline interpolator (Fig. 2, filled contours). The resulting spatial distribution of mixed layer depths for the base period indicates that the deepest mixing occurred in the western Labrador Sea, consistent with previous wintertime hydrographic surveys^{1;21} and PALACE and SOLO float observations²². A second region of enhanced convection is found south of Greenland. In general,

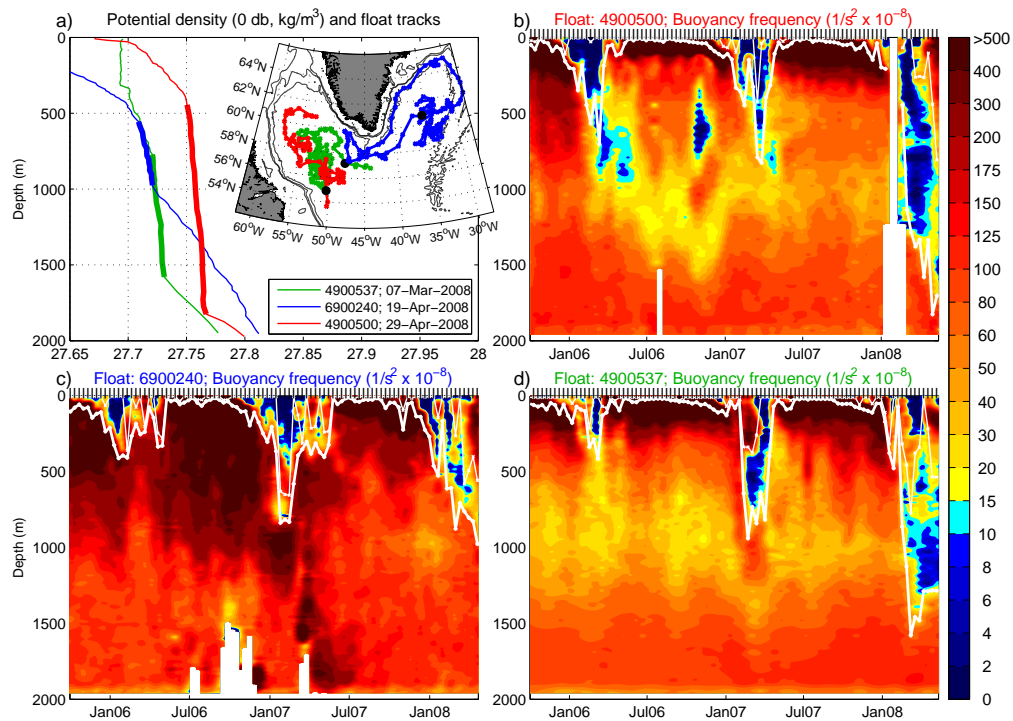


Figure 1: Potential density and buoyancy frequency squared for three selected Argo floats drifting in the Labrador and Irminger Seas from 2006-08. (a) Profiles showing the deepest recorded mixed layer in the Labrador Sea (red), in the Irminger Sea (blue), and south of Greenland (green). The inset shows the trajectories of each float and the locations of the highlighted profiles (black dots). (b-d) Temporal evolution of buoyancy frequency along the trajectories of floats 4900500 (b), 6900240 (c), and 4900537 (d). The white lines indicate the extent of the deepest mixed layer, and the vertical bars along the top denote the time of each profile along the trajectory.

the overturning throughout the 8-year base period was shallow (less than 1000m). By contrast, the mixed layers observed during winter 2007-08 (Fig. 2, triangles) were significantly deeper (by more than 1000 m in some instances). One sees enhanced mixing in the western Labrador Sea, in the region south of Greenland, and in the southern Irminger Sea east of Cape Farewell. It is clear that deep convection returned to a broad area of the western North Atlantic subpolar gyre in 2007-08; the obvious question is, why.

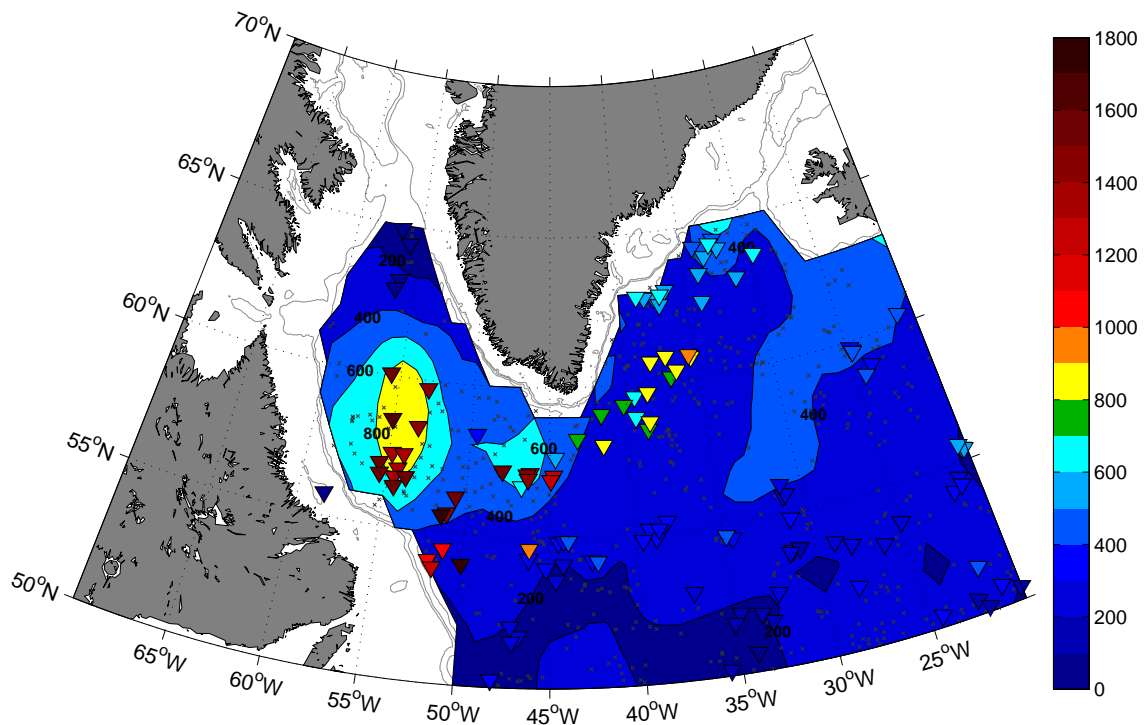


Figure 2: Changes in wintertime mixed layer depth distribution. The February - April mixed layer depths from winter 2007-08 (triangles) are contrasted to the average mixed layer depths for the period 2000-07 (filled contours). Only mixed layers deeper than 80% of the maximum mixed layer depth recorded by each float were included. The black crosses indicate the locations of the data points. The depth contours are 500, 1000, and 2000 m.

Atmospheric forcing

Applying a bulk formula, as described in the Methods section, we computed winter-averaged (Dec–Feb) heat flux anomalies for each of the winters of this decade, relative to the base period (Fig. 3). It is immediately obvious that the winter of 2007-08 was much more severe than the previous winters in terms of heat removal from the ocean. In particular, a band of strong heat flux anomalies exceeding 100 W/m^2 extends from the ice edge in the Labrador Sea, around southern Greenland into the Irminger Sea. Diagnosis of the heat flux components reveals that the main cause of the enhanced heat flux was unusually cold air temperatures (and associated low humidities) during this past winter. Figure 4 shows the 2 m North American Regional Reanalysis (NARR) air temperature anomalies for the individual months of December 2007 through February 2008, relative to monthly climatologies of the base period. The temperature over the northwestern part of the subpolar gyre was several degrees colder than the corresponding temperature of the base period for each of the months. Consistent with this, the air temperature recorded at the Prins Christian Sund meteorological station near Cape Farewell was 2.8°C colder in winter 2007-08 than the corresponding mean of the base period.

As seen in Figure 4, there is a clear relationship between the air temperature anomalies in the Labrador Sea in winter 2007-08 and the location of the ice edge. Here we define the ice edge as the location of 50% ice concentration (the results are not sensitive to this definition). In 2007-08 the edge of the pack-ice extended significantly farther into the Labrador Basin compared to the base period (compare the grey and brown lines in Figure 4). The largest air temperature anomalies,

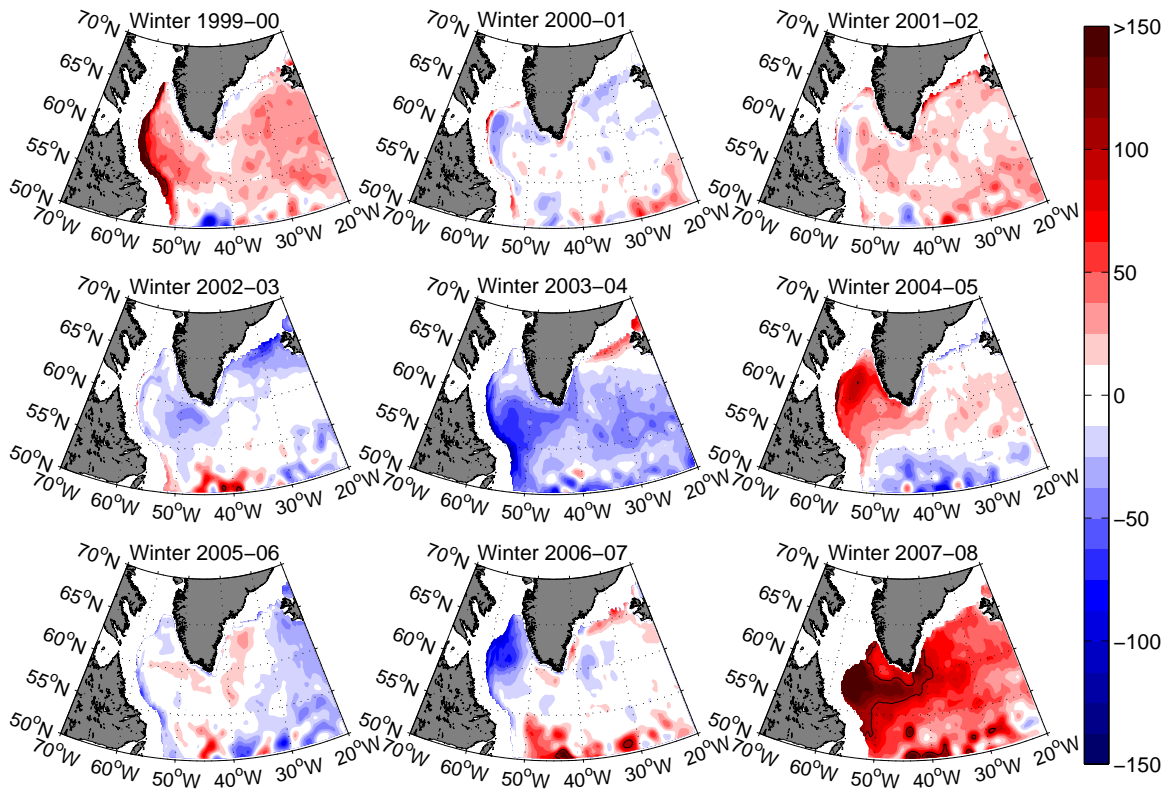


Figure 3: Interannual variability of wintertime air-sea heat flux. Each panel shows the mean December through February bulk heat flux anomaly field (W/m^2) for the given winter relative to the 2000-07 base period. The 100 W/m^2 isoline is contoured.

those exceeding -6°C , are found where the ice edge from winter 2007-08 extended past the ice edge from the base period. However, low air temperatures extended well beyond the ice edge across the basin into the southwest Irminger Sea. As seen below, this is because the anomalously large amounts of ice allowed the cold air emanating from the North American continent to remain largely unmodified by air-sea exchange as it passed eastward to the interior basin where convection occurred.

During most of the base period (the winters 2001-06) the NAO index was close to zero or

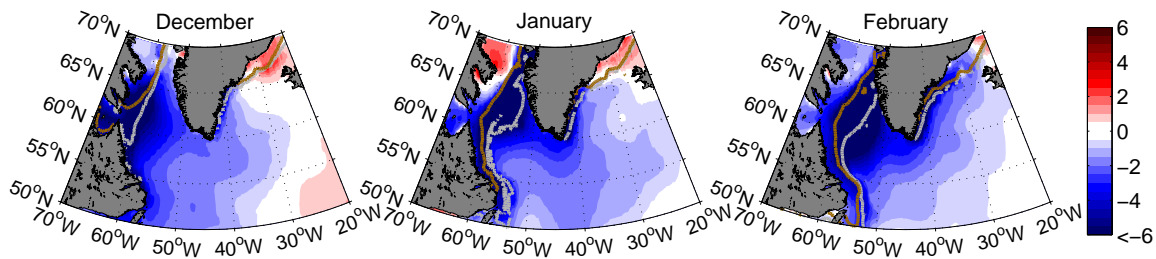


Figure 4: Relationship between air temperature and ice concentration in winter 2007-08. Monthly mean air temperature anomalies (colour) relative to the 2000-07 base period are shown, overlain by the 50% ice concentration limits from 2007-08 (grey contours), and mean 50% ice concentration limits for the base period (brown contours)

negative, which is consistent with the fact that deep convection did not take place in the subpolar gyre during this time. By contrast, during the last two winters (2006-07 and 2007-08) the NAO index was above +2, and, as is typical for such states, there were westerly winds throughout much of the western subpolar gyre. However, deep convection occurred only during the latter winter (the mixed layer depths recorded during winter 2006-07 were similar to the climatological values in Figure 2). Consideration of the winter-averaged surface wind field anomalies, relative to the base period, suggests why. As seen in Figure 5a, the wind vector anomalies in 2006-07 were generally from the east throughout most of the Labrador Sea. Furthermore, the anomaly pattern in the vicinity of southern Greenland for that winter is consistent with an atmospheric flow regime known as the reverse Greenland tip jet²³, which typically does not lead to deep mixing²⁴.

In contrast, the surface wind field anomaly for winter 2007-08 shows very strong westerly winds off the Labrador ice edge (Fig. 5b), which, in light of Figure 4, boosted the advection of cold air toward the region of deep convection. In addition, the anomalously strong westerly

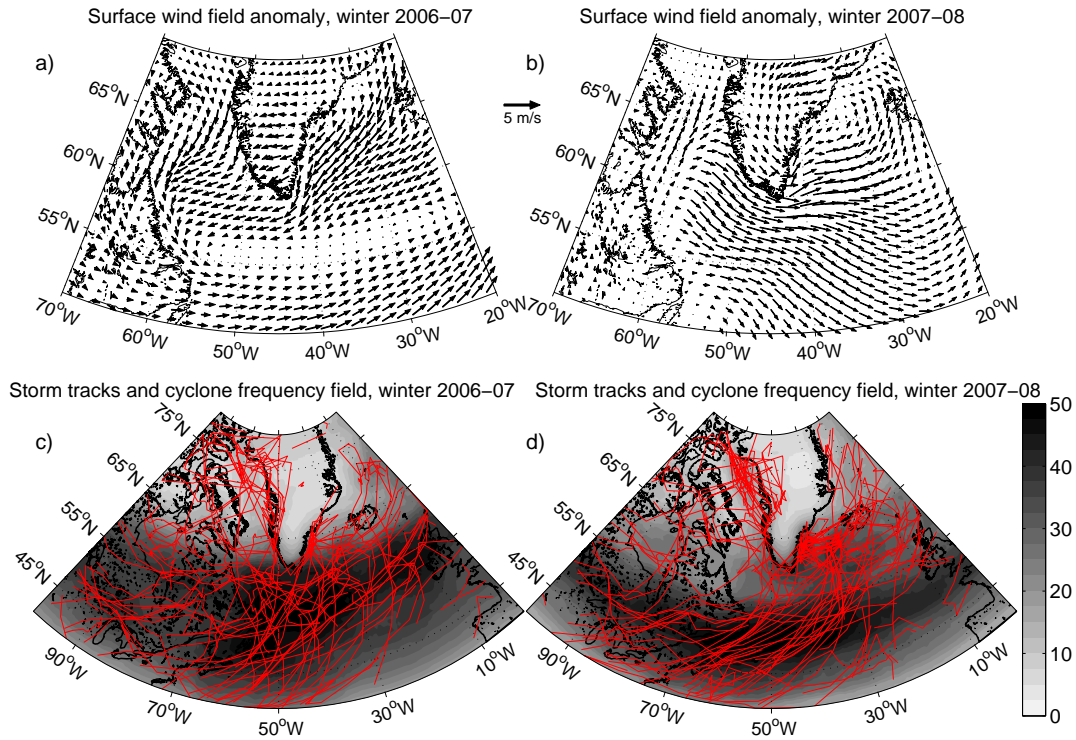


Figure 5: Wind anomalies and storm properties for the two high NAO winters of 2006-07 and 2007-08. Top row: NARR surface wind vector anomalies (m/s, every 21st vector) relative to the 2000-07 base period. Bottom row: Storm tracks (red lines) and cyclone frequency field (grey shading).

winds south and east of Cape Farewell suggest that a larger number of forward Greenland tip jet events²³ took place during this winter. Tip jets are intense, small-scale wind phenomena that occur near the southern tip of Greenland²⁵ and arise due to interaction between cyclones and the high local orography²³. The forward tip jet is known to force convection in the Irminger Sea^{26;27}. Indeed, using an objective empirical orthogonal function (EOF) method²⁶, we verified that more forward tip jets occurred during winter 2007-08 than in winter 2006-07. While the exact number of tip jets is sensitive to the chosen threshold wind speed, for the threshold used

previously in the literature²⁶ there were 17 and 27 events for the extended winters (Nov–Apr) of 2006-07 and 2007-08, respectively. This is part of the reason why deep mixed layers were observed not only in the western Labrador Sea this past winter, but also south of Greenland and east of Cape Farewell (Fig. 2).

Storm patterns

In order to examine the relationship between the convective activity taking place on both sides of Greenland, we performed a statistical analysis of various metrics for each of the winters during this decade (2000-08). It was found that a significant correlation (-0.41 to -0.64) exists between the air temperature anomaly in the central Labrador Sea and the value of the forward tip jet EOF, with a time lag of 6-9 hours. This implies that tip jet events in the Irminger Sea often follow cold air outbreaks over the Labrador Sea. Inspection of the NARR fields reveals that the same storms that pull cold air off of eastern Canada into the Labrador Sea, tend to cause high winds in the lee of Cape Farewell as the low pressure systems progress eastward along the storm track. Therefore, conditions that favour deep convection in both basins often arise due to the same set of storms.

It still remains to be determined why there were such big differences in the wind field anomalies between the winters of 2006-07 and 2007-08, despite the fact that the NAO index was comparable for both years (stronger, in fact, for winter 2006-07). Analysis of the National Centers for Environmental Prediction (NCEP) sea level pressure data and calculated storm trajectories

sheds light on this. Figure 5c,d (grey shading) show the cyclone frequency field for the two winters, where cyclone frequency denotes how often a given grid point in the domain is contained within a cyclone (as defined in the Methods section) relative to the full period. In terms of the number and strength of low pressure systems passing through the domain, the two winters were similar. However, the tracks of the storms during winter 2007-08 tended to be shifted more to the south (Fig. 5, red lines). In particular, the cyclones followed a more well-defined track from the east coast of North America toward the Irminger Sea. While it is well known that changes in the North Atlantic storm track associated with positive versus negative states of the NAO index can have an impact on convection in the Labrador Sea¹¹, the results presented here indicate that even moderate shifts in the storm track – within a high NAO regime – can have profound consequences.

Preconditioning

It is generally believed that preconditioning of the water column is conducive for the onset of deep convection, whether it be strengthening of the cyclonic circulation or the presence of remnant convected water from previous winters. In this regard, the return of deep convection to the Labrador and Irminger Seas in winter 2007-08 was a surprise. As seen in Figure 3, the air-sea heat flux in both seas was anomalously weak during the preceding winter, and the Argo floats showed relatively shallow mixed layer depths that winter. Furthermore, examination of the summer (May–Oct) Argo density data gives no indication of an enhanced gyre circulation. In particular, gridded lateral

fields of isopycnal depth indicate that the density surfaces which eventually outcropped during winter 2007-08 in the Labrador and Irminger Seas were anomalously deep relative to the base period. This is consistent with the elevated sea surface height field compared to the period of deep convection in the early 1990s (ref. 28, updated through winter 2007-08, Sirpa Häkkinen, personal communication).

As detailed above, the large amount of pack ice in the northwest Labrador Sea this past winter played a major role in the onset of convection. Animations of sea ice motion using high resolution data from the Advanced Microwave Scanning Radiometer (AMSR-E) suggest that both local formation and export from Baffin Bay²⁹ contributed to the heavy Labrador Sea ice cover. Values of liquid freshwater flux from 2004 to 2007, calculated using hydrographic data from the Davis Strait/Arctic Gateways project, show a trend of enhanced net freshwater flux into the Labrador Sea, with values of 96, 107, 133, and 136 $10^3\text{m}^3/\text{s}$, respectively, relative to a salinity of 34.8. (The trend is statistically significant at the 95% confidence level.) Consistent with this, gridded Argo salinities in the upper 20 m reveal that the northern Labrador Sea was anomalously fresh in summer 2007 relative to the base period. By inhibiting mixed layer deepening through the fall, therefore causing increased cooling of the near-surface water column, this surplus of freshwater undoubtedly contributed to the enhanced local ice formation during winter 2007-08. We note that the increased liquid and frozen freshwater flux into the Labrador Sea was likely tied to the large export of sea ice from the Arctic Ocean that contributed to the record minimum in sea ice extent observed in summer 2007³⁰. Ironically, this disappearance of Arctic sea ice, which has been linked to global warming, may have helped trigger the return of deep wintertime convection to the North

Atlantic.

A similar sudden onset of deep convection in the Labrador Sea occurred during the extraordinarily cold winter of 1971-72³¹, also associated with an increased flux of freshwater to the sea (the Great Salinity Anomaly³²). However, the main source of freshwater at that time was the West Greenland Current, which is believed to be the dominant pathway of freshwater into the interior basin³³. Hence the entire Labrador Sea (not just the northern part) was capped by low salinity water in 1971-72. By contrast, in summer 2007 the surface waters of the central basin were in fact salty compared to the base period. We note, however, that the 2007-08 AMSR-E animation indicated significant equatorward ice flux in the East Greenland Current all the way to Cape Farewell, which is likely the downstream response of the recent enhanced ice export through Fram Strait³⁴. As this pathway from the Arctic Ocean to the Labrador Sea is longer, it could be expected that freshening of the interior Labrador basin will occur in the near future. This means that next winter there may be the competing effects of a broad surface salinity cap (inhibiting deep convection) versus a preconditioned water column due to last year's remnant LSW (which is conducive for deep overturning).

The myriad of factors involving the atmosphere-ocean-ice system that led to the return of deep convection in winter 2007-08 highlights the complexity of the convective system in the North Atlantic, making it difficult to predict when deep mixing is likely to occur. A final notable aspect from last year was that the anomalously cold air temperatures over the subpolar North Atlantic in winter were not a local phenomenon. According to the Goddard Institute for Space Studies

temperature anomaly timeseries³⁵, the global temperature dropped 0.45°C between the winters 2006-07 and 2007-08. This decrease was particularly strong across northern North America, where the mean winter temperature was more than 3°C colder this past winter (Fig. 6). It is possible that the strong La Niña during winter 2007-08 may have contributed to this, suggesting that global atmospheric modes need to be considered as well when diagnosing convection in the North Atlantic.

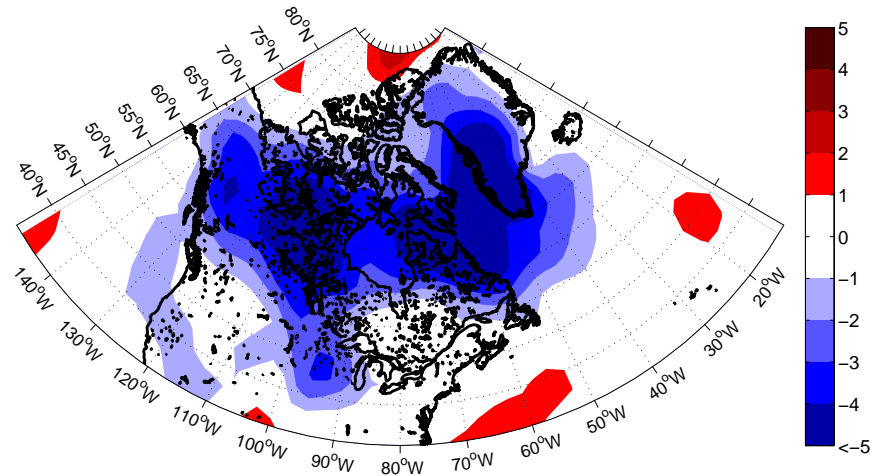


Figure 6: Hemispheric air temperature decrease in winter 2007-08. The difference in NCEP 2 m air temperature (°C) over North America and Greenland between winters 2007-08 and 2006-07 is contoured.

Methods

The global program of profiling floats known as Argo has been in operation since 2000. The floats typically drift at a depth of 1000 m, and, every 10 days, profile between a depth of 2000 m and

the surface providing measurements of temperature and salinity. Rudimentary quality control is performed before the data become public. For this analysis we used a combination of real-time and delayed-mode data, the latter having been corrected for drift in the conductivity and pressure sensors³⁶. Only profiles assigned a quality flag of 1 or 2 (indicating “good” or “probably good” data) were used, and a subset of profiles known to have been mis-calibrated³⁷ were excluded. Measurement uncertainties are expected to be less than 0.01°C and 0.03 for temperature and salinity, respectively. Late winter (Feb–Apr) mixed layer depths for the 2,023 profiles obtained between 2000-08 in the western subpolar gyre were estimated following a routine²¹ that involved manual inspection of each profile. An advantage of this procedure is that identification of mixed layers that have become isolated from the sea surface is possible. Both in the Labrador and Irminger Seas such isolated mixed layers are often observed during active convection^{21;26}, either in the form of stacked multiple mixed layers or as early stages of restratification. Through inspection of the temporal evolution of the regional mixed layers and trends in stratification, we are confident that the isolated mixed layers were formed by local convection during a given winter.

Air-sea turbulent heat fluxes were computed using a bulk algorithm³⁸ with the inputs of wind speed, humidity, air temperature and sea surface temperature (SST). For the wind data we used the multiple-satellite blended Sea Winds product³⁹, which has a space and time resolution of 0.25° and 6 hours, respectively. SST and ice concentration were acquired from an optimum interpolated, blended analysis of satellite and in-situ data provided once per day at 0.25° spatial resolution⁴⁰. Humidity and air temperature were obtained from the high-resolution (32 km and 3 hours) NARR project⁴¹. The bulk heat fluxes computed as such compare well with a newly released heat flux

product⁴² for the period of overlap (2000-06). Finally, storm tracks and cyclone field (defined as the area within the outermost closed 2 hPa pressure contour of a low pressure system)⁴³ were computed, with global NCEP⁴⁴ reanalysis sea level pressure data used as input.

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Correspondence

Correspondence and requests for materials should be addressed to Kjetil Våge (kjetil@whoi.edu).

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Competing interests statement

The authors declare that they have no competing financial interests.