Influence of Meltwater from Labrador Sea ice and icebergs transported via Flemish Cap on the long-term North Atlantic Cold Anomaly

David Allan$^1$ and Richard Philip Allan$^2$

$^1$None
$^2$University of Reading

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Abstract

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The long-term North Atlantic Cold Anomaly (Cold Blob) was largely the consequence of three major episodes of low sea surface temperature (SST) in the subpolar North Atlantic in 1972-74, 1984-85 and 1991-94. Each of these episodes correlated with unusually low SST at Flemish Cap (a subsurface island of the Canadian continental shelf 600km east of Newfoundland) and with periods of high sea-ice cover over the deep basin of the Labrador Sea a year earlier. These cold periods at Flemish Cap and the Cold Blob were associated with the advance of sea-ice and icebergs to Flemish Cap, high iceberg counts off the coast of Newfoundland and the appearance of icebergs along the path of the North Atlantic Current (NAC) east of Flemish Cap. Studies of SST anomalies provided evidence for surface connections between Flemish Cap and the CB which utilize part of the NAC pathway. We propose that in the cold periods, residual meltwater from sea-ice and icebergs conveyed in the Labrador Current to Flemish Cap was relayed via the NAC to the subpolar North Atlantic to form the Cold Blob. After 1995, anomalous ice expansion in the Labrador Sea basin greatly diminished, sea-ice and icebergs did not reach Flemish Cap and cold meltwater was no longer transmitted to the subpolar North Atlantic to sustain the Cold Blob. This improved understanding of 20th-century meltwater pathways in the North Atlantic may relate to changes in the Atlantic Meridional Overturning Circulation and associated impacts on regional climate in the 21st century.

Plain language abstract

Over most of the world sea surface temperatures have risen by about 1°C over the last century but an area of the subpolar North Atlantic has cooled by about 1°C over the same period. This region (the Cold Blob) is largely explained by three major cold episodes around 1972-74, 1984-85 and 1991-94 which are experienced even more strongly near Flemish Cap, an underwater section of the continental shelf 600 km east of Newfoundland. Similar cold periods about a year earlier in the Labrador Sea between Greenland and Canada corresponded to three episodes of unusually thick sea-ice cover there. We link the development of the Cold Blob to three major episodes of ice and iceberg transport from the Labrador Sea to Flemish Cap from where icebergs entered the warm North Atlantic Current and cool meltwater moved northwards to form the Cold Blob. After 1995 the Cold Blob declined because the periods of increased ice in the Labrador Sea ended, ice and icebergs no longer reached Flemish Cap and cold meltwater was no longer transmitted to the subpolar North Atlantic. Knowledge of these long-term changes in North Atlantic temperatures can help us to understand the ocean currents that affect European and world climate.

Main Points

1. Three cold periods in the late 20th century dominated the temperature trend which defined the subpolar North Atlantic Cold Blob.

2. Three contemporaneous cold periods at Flemish Cap corresponded to three episodes of high ice formation in the Labrador Sea a year earlier.

3. The Cold Blob derives from meltwater of sea-ice and icebergs transported from the Labrador Sea via Flemish Cap to the subpolar North Atlantic.
Introduction

The nature of the long-term Cold Blob

It was first clearly shown by Drijfhout et al. (2012) that century-scale linear regression of North Atlantic sea surface temperature (SST) against global mean SST revealed a specific area of almost 1°C cooling in the subpolar North Atlantic (SPNA) which contrasted dramatically with the pervasive 1°C warming in the rest of the world ocean since 1900. Many authors have referred to it as a ‘warming hole’ which represents an area of relative cooling within a general warming trend (e.g. Gervais et al. 2018 and He et al. 2022) but the epicenter of this region (Figure 1, 2c) has undergone absolute cooling by about 1°C since 1900 (Allan and Allan 2019) so we prefer to use the description North Atlantic Cold Blob as suggested by Li et al. (2022). This is not elegant terminology but it does describe concisely the irregular area of long-term cooling in the SPNA seen on linear regression diagrams. This long-term (multidecadal) Cold Blob (CB) has been of particular interest because it has been linked to a decrease in Atlantic Meridional Overturning Circulation (AMOC) mooted as a possible indicator or driver of climate change (Drijfhout et al. 2012; Rahmstorf et al. 2015; Caesar et al. 2018, 2021; Gervais et al. 2018; Keil et al. 2020; Boers 2021; Rahmstorf, 2024).

Josey et al. (2018) and Sanders et al. (2022) considered the long-term CB (1900-2010) to be distinct from the short-term cold anomaly of 2014-16 because the long-term CB was clearly dominated by the large cold anomalies in the latter part of the 20th century. They concluded also that the former appeared to be driven primarily by ocean convection whereas the 2014-16 anomaly was mainly driven by surface energy flux forcing. There is also a marked difference in the geographical positions of the long-term CB (near 40°W) (Drijfhout et al. 2012; Allan and Allan 2019) and the short-term (2014-16) cold anomaly (near 30°W) (Josey et al. 2018). We agree that it is important to distinguish these two separate cold anomalies which in many cases have been conflated. In this work we deal only with the long-term cold anomaly (CB) based on data from 1900 onwards.

There have been a variety of suggestions to explain the existence of the long-term CB, with multiple drivers being implicated (Keil et al. 2020). Some of these suggestions have stressed the importance of advective influences (Caesar et al. 2021; Josey et al. 2018; Josey and Sinha 2022; Gervais et al. 2018) where cooling of the SPNA depends on delivery of cold surface water from a distant source whereas others have emphasised the role of ocean-atmosphere heat exchange such as reduced incoming sunlight or thermal infrared radiation or strong, cold winds which cool a specific region of the SPNA either by radiative heat, conduction or evaporation (Li et al. 2022; He et al. 2022). The present work provides evidence that horizontal advection of cold water, ice and icebergs from a distant source (proximally the Labrador Sea but ultimately the Arctic) appears to be the major driver of the CB although there might be essential roles for atmospheric influences in some aspects of the advective process, particularly in the formation and transport of extensive ice over the deep Labrador Sea basin. There is currently renewed interest in ice dynamics between the Arctic and North Atlantic because there appear to be statistical connections between enhanced Greenland ice melt and cooling episodes in the North Atlantic which are associated with episodes of warming in Europe (Oltmanns et al. 2024).

A large contribution to the CB appears to be made by three periods in the final decades of the 20th century when the sea surface temperature of the SPNA was markedly reduced (>1°C) compared with average conditions since 1900 (e.g. Deser et al. 2002; Hodson et al. 2014; Robson et al. 2016; Boers, 2021; Li et al. 2022). The relationship between these SPNA cool periods in the 1970s, 1980s and 1990s and expansion of sea ice in the Labrador Sea was first pointed out by Deser and Blackmon (1993) and Deser et al. (2002) and we have recently traced back these changes to three periods of ‘Odden’ ice expansion and melting in the Greenland Iceland Norway (GIN) Sea which in turn depended on three periods of Arctic ice expansion and transport through Fram Strait (Allan and Allan 2024). We have also linked the melting of Odden and Labrador Sea ice to the Great Salinity (and SST) Anomalies (Belkin et al. 1998 and Belkin 2004) in the Subpolar Gyre (SPG) formed between the Labrador, North Atlantic and East/West Greenland Currents (Allan and Allan 2024). Although the GSAs and the CB may both be consequences of three freezing periods
in the Labrador Sea basin in the late 20th century it is important to note that the cooling of the SPG which is
associated with the GSAs was seen in October-November as effluxes of meltwater from the Labrador Sea
(Allan and Allan 2024) whereas the CB is most prominent in January-February (Allan and Allan 2019).

Although the above evidence connects the cooling of the SPNA with meltwater from Labrador Sea ice, the
physical connection between the Labrador Sea and the apparently isolated cooling of the SPNA represented
by the CB has not been elucidated. In the present work we provide evidence from available observational
data to link the three major episodes of cooling in the SPNA to three specific periods between 1970 and
1995 when unusually high levels of winter sea-ice over the deep Labrador Sea basin melted in the summer,
increasing the survival of sea-ice and entrained icebergs in the Labrador Current as far as Flemish Cap (FC
in Figure 1) a crucial junction between the major warm and cold currents, from where cold meltwater was
transported northwards in the North Atlantic Current (NAC) to form the CB.

Figure 1. A bathymetric schematic diagram of the region east of Newfoundland (NF) showing the Grand
Banks (GB), Flemish Cap (FC) and the main ocean currents in this region including the North Atlantic
Current (NAC) and the Labrador Current (LC) based on the current velocity map of Solodoch et al. (2020)
but identifying the two branches LC-Arctic and LC-Atlantic as proposed by Florindo-López et al. (2020).
The merged LC current splits into the Deep Western Boundary Current (DWBC) traversing Flemish Pass
(FP) and the ‘leak’ DWBC (Solodoch et al. 2020) passing around Flemish Cap (dotted lines) and possibly
remerging with the DWBC along the eastern slope of the Grand Banks (Mertens et al. 2014). The main path
of the NAC is drawn to follow the 4000m contour as indicated by Carr and Rossby (2001) and Solodoch et
al. (2020). The eastward trajectory of the NAC is split into three branches (northern, middle and southern,
NB, MB and SB respectively) to reflect three main divisions of the NAC described by Stendardo et al. (2020)
and by Bower and von Appen (2008) who identified the northern and middle branches. The NB passes along
the line of the Charlie-Gibbs Fracture Zone (CGFZ) at 52°-53°N which is visible as a linear rift in the
contours in Figure 1. Also shown are the Tail of the Grand Banks (TGB), Northwest Corner (NWC) and the
position of CB epicentre centred on 54°N 43°W (dotted circle). The orange lines mark the locations of the
53°N mooring array of current meters which span the 1000m-3000m depth shelf break (A, (Fischer et al.
2004) and the Seal Island array (S) used by Florindo-López et al. (2020) to monitor ocean conditions across
the continental shelf and into the shelf break.
The Labrador Currents

Lazier and Wright (1993) showed that there are two major components of the Labrador Current north of 50°N, one of which mainly originates from the northern Labrador Sea and Baffin Bay and stays largely over the Labrador shelf in relatively shallow water (mostly <300m). The second component derives from the southern Labrador Sea and the Atlantic waters contributing to the West Greenland Current and occupies the deeper (1000-3000m) slope waters of the western Labrador Sea (Figure 1). These two components have been respectively labelled as Arctic Labrador Current (LC-Arctic) and Atlantic Labrador Current (LC-Atlantic) by Florindo-López et al. (2020) based on observations from the Seal Island transect (S in Figure 1) that crosses the Labrador Shelf at Hamilton Bank and reaches the deep LC-Atlantic. The shelf current (LC-Arctic) is likely to be the main transporter of icebergs from their major sites of origin in Baffin Bay and the northern Labrador Sea (Wilton et al. 2015) whereas LC-Atlantic is thought to carry ice and fresh water from the Labrador Sea basin and East Greenland but there is no evidence that it transports substantial numbers of icebergs. It appears that the two arms of the Labrador Current are distinct as far as Seal Island (53°N) (Florindo-López et al. 2020) but coalesce at a point to the west of Flemish Cap (Figure 1). This junction point is drawn at about 49°N 48°W to accord with the current-velocity maps shown by Han et al. (2008) based on data from the current meter array (A in Figure 1) between 53°N 52°W and 54°N 49°W in the LC-Atlantic and by Solodoch et al. (2020) who modelled current velocity around Newfoundland and found that the major arm of the combined Labrador Current followed the 1000m isobath through Flemish Pass and along the shelf of the Grand Banks to the TGB (Tail of the Grand Banks). The deep (slope) Labrador Current (LC-Atlantic) has often been identified as the main component of the Deep Western Boundary Current (DWBC) and this attribution applies also to the slope current adjacent to the eastern Grand Banks (Figure 1) (Fisher et al. 2004; Han et al. 2008; Xu et al. 2013; Zantopp et al. 2017; Handmann et al. (2018); Solodoch et al. 2020). The eastern branch of the DWBC circulates around Flemish Cap before possibly rejoining the main branch (Figure 1) and has been described by Solodoch et al. (2020) as the ‘leak’ of the DWBC around Flemish Cap.

The significance of Flemish Cap

Flemish Cap is a subsurface island extension of the Canadian continental shelf about 600km east of Newfoundland (Figure 1). It rises to within 125m of the surface at one point and presents an underwater barrier which bifurcates the merged Labrador Current (Colbourne and Foote 2000) to form the DWBC and the leak DWBC which passes along the deep slope to the north, east and south of Flemish Cap before possibly recombining with the DWBC. The combined Labrador Current (DWBC) partly retroflects near the TGB to interact with the Gulf Stream/NAC (Fratantoni and McCartney 2010) (Figure 1). The unusual stratification of waters over Flemish Cap is characteristic of the entire Labrador shelf region: there is a persisting cold (near 0°C) fresh layer 50-100m below the surface which is prominent in the summer and has been named as the Cold Intermediate Layer or CIL (Petrie et al. 1987; Colbourne and Foote 2000, Stein 2007; Colbourne et al. 2016; Florindo-López et al. 2020). The precise reason for the existence of this cold fresh subsurface layer is not well defined.

To the east, Flemish Cap borders on the warm salty NAC (Rossby 1996; Colbourne and Foote 2000, Mertens et al. 2014; Solodoch et al. 2020) so usually there are very considerable differences in temperature and salinity across Flemish Cap between the cold fresh leak DWBC and the NAC. Mertens et al. (2014) carried out a comprehensive ship and moorings-based study of the currents to the east of Flemish Cap along the 47°N latitude line including the leak DWBC moving south along the Flemish Cap continental slope between 44°W and 42°W and the NAC moving north along the continental rise between 42°W and 40°W (Figure 1) from 4000m depth to the surface. Solodoch et al. (2020) studied this region mainly employing a high resolution numerical model.

Although Flemish Cap is normally ice-free in winter, pack ice originating in Baffin Bay and the Labrador Sea can extend to Flemish Cap in February or March during particularly cold years (Colbourne and Foote 2000; Colbourne et al. 2016; Stein 2007) and this ice entrains icebergs which for many years have been routinely counted by the International Ice Patrol (see Open Research) by ship and aircraft observation over the period up to 2000 but more recently supplemented with data from Earth satellites.
The precise path of the NAC near Flemish Cap is of particular significance if we are to justify the hypothesis that icebergs and cold water can reach the NAC east of Flemish Cap. Rossby (1996) noticed that the northern and eastern boundary of the NAC (based on eddy kinetic energy at 50-100m) approximately follows the 4000m isobath east of the TGB and passes east of Flemish Cap at 43°W (Figure 1). This is supported by the work of Mertens et al. (2014) and Solodoch et al. (2020) and opens the possibility that sea-ice, icebergs and cold water from Flemish Cap might in some years overflow into the NAC, which is potentially capable of conveying this cold signal upstream to the SPNA via North West Corner (NWC in Figure 1). Our findings establish Flemish Cap as a crucial staging point in the transfer of cold meltwater derived from Labrador Sea ice and icebergs to the NAC and eventually to the SPNA on three major occasions during the 1970s, 1980s and 1990s. We propose that this transfer constitutes the advective component of the mechanism by which the CB evolved in the last decades of the 20th century.

Data and Methods

SST and sea ice cover data were obtained from the Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST: version 1.1 for SST and version 2.2 for sea ice) (Rayner et al. 2003; Titchner and Rayner 2014). The HadISST dataset was selected because its resolution was 1° whereas possible alternatives (ERSST, Extended Reconstructed Sea Surface Temperature or GISS, Global Sea-Ice and Sea Surface Temperature) had much lower resolution (2° and 5° respectively) and were not capable of capturing the detail of the CB shown by HadISST even though interpolation of sparse data for some areas is expected to reduce its effective resolution. Higher resolution, daily resolved SST was also utilised from the NOAA 1/4° Optimum Interpolation Sea Surface Temperature OISST V2 High Resolution Dataset (Huang et al. 2021). The Advanced Very High Resolution Radiometer (AVHRR)-only version is used to minimise effects from a changing observing system while anomalies are computed relative to a pre-compiled consistent long-term 1971-2000 climatology based on a range of datasets (Reynolds et al. 2007). Large-scale biases in the AVHRR SST are corrected using in situ data and the overall methodology is described in detail by Huang et al. (2021).

Annual and monthly iceberg numbers were obtained from the International Ice Patrol Annual Count of Icebergs South of 48 Degrees North, 1900 to Present, Version 1 (Figures 8a,b). From 1946-1982 iceberg counts were derived from ship reports supplemented with aircraft observations. From 1982 to the present, advanced airborne radar systems were the major source of observations but these were supplemented with mathematical models to predict iceberg drift and deterioration (from 1983) and by satellite reconnaissance (from 2017). These data cover a range of observing systems which change over time and therefore were primarily used to illustrate the spatial distribution of icebergs which were plotted as latitude-longitude points of new sightings. The data were also analysed by retaining only new sightings to avoid double-counting icebergs. However, since a focus was in determining numbers of icebergs reaching Flemish Cap and new sightings often were reported before icebergs reached this region, all iceberg sightings are displayed. The iceberg distribution is similar for both methodologies though very few are normally identified over Flemish Cap.

In this work we utilise part of the iceberg data but are aware of some of its deficiencies, particularly the difficulties of maintaining consistency in counts over a century of observation using changing techniques and observing systems, the tendency of icebergs to ground in shallower water, fragment and meander on their journey, the inability to distinguish small icebergs from large ones in standard counts and the possibility of double counting of the same icebergs. We are particularly interested in iceberg numbers between 1970 and 1995 prior to the satellite era and more uniform reporting procedures so we are aware of the possibilities for data ambiguities which have been pointed out by Marko et al. (1994).
The ocean bottom depth is provided by bathymetric mapping data from the General Bathymetric Chart of the Oceans; (GEBCO Compilation Group 2023) (doi:10.5285/f98b053b-0cbc-6c23-e053-6c86abc0af7b). This provides a continuous terrain model for oceans and land at 15 arc-second intervals which were smoothed for the purpose of plotting. Calculation of distance and area in the North Atlantic was derived from Google Earth Pro.

Results

1. The major contributor to the North Atlantic long-term Cold Blob was a series of three cold periods in the SPNA in the 1970s, 1980s and 1990s.

The long-term CB has generally been displayed in terms of the correlation of SST gridpoint time series with global mean SST as in Figure 2a,c,e which shows the CB as seen in in 1970 (a), 1995 (c) and 2020 (e) using a baseline starting in 1900 and employing Januaryuary values of HadSST. We have previously shown that the CB is maximal in winter and is scarcely visible in summer (Allan and Allan 2019). Only very small areas of weak cold anomaly were seen for the period 1900-1970 (a) but a prominent CB was seen for 1900-1995 (c) with a cold anomaly occupying a large area north of 50°N and particularly concentrated in a small area around 55°N 43°W which we describe as CB epicentre. This represents the obvious point on which to focus attention because of its prominence and persistent location and was evident in all such diagrams from 1980 to 2020 (not shown). The intensity waned after 1995 although the shape of the cold anomaly was maintained up to 2020. (e) Largely positive anomalies were seen throughout this period in the region of Flemish Cap (asterisk) The gradients of the SST time series data (b,d,f) broadly followed the intensity of the CB (a, c, e respectively). In 1970 when the CB was scarcely visible the gradient was -0.07°C/century, in 1995 when the CB was most intense it was -1.4°C/century and in 2020 it was -0.87°C/century. This implies that the major influences in the creation of the CB were the particularly cold periods between 1970 and 1995. Considering that between 1995 and 2020 there was a marked decrease in the intensity of the CB and in the corresponding SST gradient (Figures 2c-f) it appears that the post-1995 data (which is included in the 2020 CB) makes much less contribution to the CB than the 1970-1995 data. Thus the 2014-2016 (short-term) negative anomaly (see Introduction) which is visible in Figure 2f has little effect on the overall CB compared with large negative anomalies of 1970-1995. The mean SST between 1900 and 1969 was 5.2°C ±0.7(SD). Between 1996 and 2020 it was 4.9 °C ±0.6, statistically marginally less than 1900-1969. But between 1970 and 1995 it was 4.2°C ±0.6 a full degree cooler than the 1900-1969 series. This is a direct indicator of the major contribution of the 1970-95 period to the overall 1900-2020 cooling. Because of their relative prominence and significance for the intensity of the CB we decided to concentrate on these three cold periods between 1970 and 1995 and to determine the physical conditions which led to their appearance.
Figure 2. (a,c,e) The Cold Blob derived by linear correlation ($r$) of January grid point HadISST observations with global mean values over the same period for (a) 1900-1970, (c) 1900-1995 and (e) 1900-2020. The stippling shows where the linear fit between grid point SST and global mean SST is significant at the 90% confidence level allowing for autocorrelation. Positive correlations show where local temperatures vary in unison with global temperatures whereas negative correlations represent anticorrelations with global temperatures. The area displayed is from 40°-65°N and 55°-15°W and includes portions of the coastlines of Newfoundland, Greenland and Iceland. An asterisk marks the position of Flemish Cap in (a,c,e) Figures (b,d,f) show the January time series of HadSST at CB epicenter (54°N 43°W) corresponding to (a,c,e). Gradients of SST trend lines (red) for these three periods are shown as $dSST/dt$. 

(b) SST timeseries 54°N/43°W

(d) SST timeseries 54°N/43°W

(f) SST timeseries 54°N/43°W
2. Three major episodes of cooling at the CB correspond to three periods of cooling near Flemish Cap.

To relate the three major cooling periods at CB epicentre to other changes in the N. Atlantic we investigated the distribution of SST (Figure 3a) and SST anomalies (Figure 3b) in the wider area of the SPNA between Newfoundland and Greenland, adding a 1000m isobath overlay to identify the positions of Flemish Cap (oval feature centered on 47°N 45°W) and the TGB at 43°N 50°W, the most southerly region of the Grand Banks (see Figure 1). There is a clear division between cold polar waters associated with the Labrador Current and warmer waters to the south and east of the 1000m isobath. The interface between these contrasting bodies of water where the temperature gradient is greatest approximately traces the path of the Gulf Stream and NAC (Figure 1). In cold years at CB epicenter (1973, 1985 and 1991) the 1°C isotherm advanced as far as 45°W at Flemish Cap in Jan-March but in warm years the 1°C isotherm was close to 50°W west and the 3°C isotherm did not reach Flemish Cap. The relative cooling near Flemish Cap was confirmed from a study of the SST anomalies and this was particularly evident in 1973 and 1985 when a prominent cold spot was seen on or close to Flemish Cap (Figure 3b) with the cold anomaly stretching back along the path of the NAC towards the TGB. This cooling was less evident in 1991 (for reasons which will be referred to later) but there was a spread of cold anomaly northwards into the region of the CB which was also apparent in 1985 and to a lesser extent in 1973. In contrast, in the warm years (1967, 1978 and 1988) there was no evidence for anomalous cooling at Flemish Cap, CB epicenter or any other specific site. This evidence gives an initial indication that cold periods at Flemish Cap could be linked to the cold periods in the SPNA which are visualised as the CB.

We compared the time series of HadSST at CB epicenter in February between 1960 and 2020 with the corresponding time series for Flemish Cap (47°N 45°W) and the southern Labrador Sea (60°N 55°W). Figure 4a shows that there is a good agreement between temperatures at CB epicentre and Flemish Cap, with three main episodes of cooling which are greatest in 1973, 1985 and 1991/1994, similar to the findings of Colbourne and Foote (2000) for Flemish Cap. Although there is a cool period in the CB trace in 2015-17 (not shown) it does not correspond with a marked change at Flemish Cap or in the Labrador Sea (compare 1973 and 1985) and seems more likely to correspond to the short-term 2014-2016 cooling and freshening event mentioned in the Introduction.

The low temperature extremes at Flemish Cap in 1973 (1.3°C), 1985 (0.7°C) and 1990 (1.9°C) were not seen at any other point between 1930 (not shown) and 2020 over which period the mean February temperature was 3.7° ± 0.9°C (range denotes standard deviation). Correlation between temperatures at Flemish Cap and CB epicentre from 1964-1990 was high (r=0.79) but between 1995 and 2010 it was low (r=0.29) (r is the Pearson correlation coefficient). This change in correlation was associated with an approximately 1°C step increase in temperatures at Flemish Cap after 1990 compared with temperatures in the Labrador Sea and at the CB. Such a systemic warming at Flemish Cap in the early 1990s can explain why cooling near Flemish Cap in the 1990s was less evident than in 1985 and 1973 (Figure 3b). A similar step change in the warming of the subpolar gyre in the mid-1990s was reported by Robson et al. (2012) but not specifically at Flemish Cap.

There were three main troughs in the HadISST time series for the southern Labrador Sea (Figure 4a) but these were in 1972, 1983-84 and 1993, leading the minima at Flemish Cap and CB epicentre by about a year, consistent with the observations of Deser et al. (2002) who calculated a lag of about a year between temperatures in the Labrador Sea and the North Atlantic. This is confirmed for the period 1960 to 1990 which shows that the maximum correlation between Flemish Cap and Labrador Sea time series is reached when the Flemish Cap data is shifted backwards by a year (Figure 4b). On the other hand, there is no significant lag between the Flemish Cap time series and that for CB epicenter. These results suggest that it takes about a year for surface water (and ice) in the Labrador Sea to reach Flemish Cap but that there is a relatively rapid equilibration of surface water SST between Flemish Cap and CB epicenter. It should be noted that the 1991-94 episode of cooling in the CB is made up of two separate periods centred on 1991 and
1993-4 and this is true also for Flemish Cap. The Labrador Sea time series shows a similar biphasic event in the 1990s but again leading the Flemish Cap time series by about a year (Figure 4a).

**Figure 3.** Latitude-longitude plots from 40°-60°N 60°-30°W of (a) HadSST SST (contours every 1°C) and (b) HadSST SST anomaly relative to the 1960-2010 climatology for January-March mean for 1973, 1985 and 1991 (cold years at Flemish Cap) and 1967, 1978 and 1988 (warm years at Flemish Cap). The black line overlay is the 1000m isobath which shows the positions of Flemish Cap (centered on 47°N 45°W) and the Tail of the Grand Banks (43°N 50°W for the 1000m and 100m isobath on this scale).
Figure 4. (a) HadISST SST time series for February from 1960-2010 comparing Flemish Cap (47°N 45°W) with CB epicentre (54°N 43°W) and the southern Labrador Sea (60°N 55°W). (b) Variation in the correlation between the HadSST time series (1960-1990) for Flemish Cap and those for the Labrador Sea and CB epicenter when the latter two time series are shifted forwards or backwards in time relative to Flemish Cap.

3. Do cold anomalies at Flemish Cap reach the NAC?

The high correlation between surface temperatures at Flemish Cap and those at the CB (Figure 4) and the apparent cold surface water connection between these two locations which are about 800km apart (Figure 3b) suggests the possibility that cold anomalies at Flemish Cap might be carried to the CB via the NAC which is close to the eastern edge of Flemish Cap (Figure 1 and Mertens et al. 2014). This possibility was investigated by plotting anomalies of OISST (Optimum Interpolation Sea Surface Temperature (see Open Research) which offers much higher resolution data (0.25° x 0.25° instead of 1° x 1° for HadISST data) although OISST data only goes back to September 1981. Figure 5a shows that in the cold years 1985, 1991 and 1994, cold anomalies extended from close to the TGB to east of Flemish Cap (along the path of the NAC, Figure 1), then northwards to the region near Northwest Corner (53°N) and along the line of the CGFZ (52°-53°N) which represents the path of the northern branch of the NAC (Stendardo et al. 2020, Bower and von Appen 2008; Figure 1). Cold anomalies were also observed to reach as far north as 54°N, the latitude of CB epicentre. These results resemble those for HadISST anomaly shown in Figure 3 and raise the possibility that in certain years cold anomalies extended from Flemish Cap in a pattern which resembled the split of the path of the NAC into three major segments as it traverses the Mid Ocean Ridge (Stendardo et al. 2020).

In the warmer years, 1982, 1988 and 1996, warm anomalies replaced the cold anomalies but were seen in similar locations corresponding to the path of the NAC but slightly to the south and east of the cold anomalies. We conclude that in both the cold and warm years, OISST anomalies (negative and positive respectively) represent a guide to the path of the NAC. Because the negative OISST anomalies extend at least as far as NWC and the CGFZ (around 53°N, Figure 1) they may also contribute to the relatively cold surface water which defines the CB whose epicenter is at 54°N 43°W (Figure 1, 2a).
The results shown in Figure 5a are for individual weeks in early spring but it is important to emphasise that they represent typical SST trends for cold years and warm years during the entire period between 1981 and 2000. We have confirmed this with the Hovmoeller plots shown in Figure 5b (time v latitude at 47^oN) and Figure 5c (time v longitude at 44^oW). Figure 5b covers longitudes between the Newfoundland coast and the path of the NAC east of Flemish Cap and demonstrates well-defined cold periods in the spring of the years around 1985 and 1990-1994 centered on 44^oW on the eastern side of the Flemish Cap plateau. The subsidiary cool region near 47^oW seems likely to correspond to the deep fissure between the Grand Banks and Flemish Cap known as Flemish Pass which is a major route for icebergs carried in the Labrador Current (Figure 1).

Figure 5c covers longitudes between the south of Flemish Cap and the coast of Greenland at 44^oW and shows that in addition to the strong cold signals in the spring of years in the mid-1980s and early 1990s corresponding to the latitude of Flemish Cap (47^oN) it also shows a cold signal centred on 52^o-56^oN corresponding to the cool regions shown in Figures 2, 3b, 4a and 5a which would contribute to the CB.

There is an apparent lateral correspondence between the cooling periods at Flemish Cap and those in the region associated with the CB but little evidence for a significant time difference between cold anomalies at the two sites, consistent with a relatively rapid transit between Flemish Cap and the CB (see also Figure 4a).

The bathymetry section at 47^oN between 50^oW and 40^oW (Figure 5d) illustrates the position of Flemish Pass (near 48^oW), the plateau of Flemish Cap (46^o-44^oW) and the steep slope between 44^oW and 43^oW descending to 4500m at 41^oW. We compared the OISST SST anomaly data for 1983 and 1985 (respectively warm and cold years at Flemish cap) along this section to determine if cold anomalies moving east from Flemish Cap could reach as far as the NAC. In May 1985, the greatest surface negative anomaly (-5.5^oC) was observed at 43^oW where surface waters of the NAC reached their most westerly mean position (mean of 47 years of observations, Mertens et al. 2014). A similar but less marked result was seen for March 1985 where the maximum negative anomaly was at 44^oW on the edge of the Flemish Cap plateau.

In contrast, in 1983 when there were marked positive anomalies in the NAC region (Figure 4a) there was no evidence for cold anomalies at Flemish Cap (45^oW). In 1983 and other years (1980, 1988 Figure 4a) when there was no cold anomaly at Flemish Cap, there was still a small cold anomaly in the slope region (44^o-43^oW) (Figure 4d) so that even in warmer years the slope waters were relatively cold. Thus, waters from Flemish Cap always cooled the NAC in this period but the effect was much stronger in the cold years such as 1985. We chose to examine 1985 and 1983 as years of respectively large and small cold anomaly (Figure 4a) and March and May as months of respectively, maximum sea-ice cover and maximum iceberg numbers.

In the next sections we investigate the relative importance of these two factors in cooling of Flemish Cap and the NAC.
Figure 5. (a) The distribution of OISST SST anomalies relative to a 1971-2000 long-term climatology east of Newfoundland in selected weeks of the cold years 1985, 1991 and 1994 and the warm years 1983, 1988 and 1996. The black line marks the position of the 1000m isobath and indicates the positions of Flemish Cap and the TGB as in Figure 3. (b) Time-longitude plot of SST anomalies at 47°N between 50°W and 40°W. (c) Time-latitude plot of SST anomalies at 44°W between 45°N and 60°N. Scale -3°C-+3°C for (b) and (c). The period covered by (b) and (c) was 1982-1996. (d) Comparison of OISST SST anomalies with bathymetry in March and May 1983 and 1985 on a transect line at 47°N between 50°W and 40°W.
4. The three major cold periods at Flemish Cap and the CB are each associated with expansion of sea-ice eastwards as far as Flemish Cap.

The results described above in sections 1-3 extends previous findings of a relationship between cold periods in the Labrador Sea and low temperatures in the SPNA (Deser and Blackmon 1993 and Deser et al. 2002). These authors showed that periodic increases in winter Labrador Sea ice followed by the dissolution of this ice as it moved southwards were linked to later reductions in SST in the SPNA. 1972, 1983 and 1993 were notable as years when unusually large quantities of ice formed in the deep basin of the Labrador Sea (Figures 6a,b). In each case, in subsequent years (1973-74, 1984-85, 1994) this anomalous Labrador Sea ice greatly diminished, and was presumed to be carried south together with meltwater by the LC-Atlantic Current initially (Figure 1). Concurrently, increases in SIC were seen in 1984-85 and 1994 (but not in 1973-74) in the Newfoundland Sea south of 55°N and extending as far as Flemish Cap in 1973-74, 1985 and 1994 .Figure 6a,b shows marked expansions of SIC as far as the middle of Flemish Cap in 1973-74, 1985 and 1993-94 and these same three periods corresponded to the coldest years at Flemish Cap (Figures 3, 4, 5a). At no point in this series did sea-ice extend south of 45°N between 50°W and 45°W so sea-ice was never observed over the Grand Banks (see Figure 1).

It is plausible that in high anomalous ice years there was a physical transfer of ice from the Labrador Sea basin to the region corresponding to the LC-Arctic west of the 1000m isobath but the mechanism of such a transfer is obscure. An alternative possibility is that much of the ice east of the 1000m isobath (i.e. in the LC-Atlantic) melted before reaching 55°N but survived long enough to shield ice and icebergs in the LC-Arctic from the warmer Atlantic waters to the east and from wave-related attrition, so that the SIC anomaly in the LC-Arctic would have increased, more ice reached Flemish Cap and more icebergs survived to reach Flemish Cap.

In Figure 6a we illustrate the position (broken rectangle) of the Labrador Sea region of deep convection region (RCD) corresponding to the highest thickness of Labrador Sea Water in winter 1996-1997 as reported by Lavender et al. (2002). This is very similar to the RCD defined by Lab Sea Group (1998) for 1997 and Yashaev and Loder (2016, 2017) for 2002-2016 which had highest thickness at 57°N 54°W. Clearly, there were some years (1972, 1983-1984 and 1993) when anomalous ice expansion in the Labrador Sea basin encroached on the RCD but still left it mostly as open water which would have allowed deep convection to occur in response to rapid surface cooling. Moreover, the proximity of labile ice would have lowered the surface temperature and contributed cold, low salinity meltwater which may have undergone deep convection in response to periods of strong ocean cooling in winter.

Figure 6b compares the time series of mean annual SIC in the Labrador Sea basin (box 1 in figure 6a) with that in the Newfoundland basin (box 2) and near Flemish Cap (box 3) and shows that there is a 1-2 year lag between major peaks of SIC in the Labrador Sea (1972, 1983-84, 1990-91, 1993) and Flemish Cap (1993-94, 1985, 1993, 1994), similar to the lag for temperature shown in Figure 4a. The low temperature periods at Flemish Cap and the CB (Figure 4a) were therefore related to the progress of sea-ice eastwards across Flemish Cap although the maximum extent was only 45°W, far short of the NAC. Although there were subsidiary Labrador Sea SIC peaks in 2009-2012 and thereafter, there was little evidence for corresponding peaks in ice near Flemish Cap, consistent with the small changes in SST at Flemish Cap over this period (Figure 4a). In contrast to these results for Flemish Cap, there was an unshifted correlation (r=0.6) between mean SIC in the Labrador basin (box 1) and in the Newfoundland basin (box 2) with only slight indication of a year lag for the 1985 SIC peak (Fig 6c). There were prominent examples of post-2000 SIC peaks for the Newfoundland basin (box 2) some of which coincided with those in the Labrador Sea basin although it is notable that these were not reflected in corresponding peaks near Flemish Cap. Thus, the ice which reaches Flemish Cap is not only restricted to the coldest years but appears to take a year longer to reach Flemish Cap compared with ice in the Newfoundland basin.
Figure 6. (a) Sea ice fractional cover (SIC, HadISST2 dataset) in March of 1971-74, 1982-85 and 1991-1994 in the area between 45°-65°N and 65°-40°W. The position of the 1000m isobath is shown in black and defines the Labrador Sea basin (area deeper than 1000m) and the position of Flemish Cap (elliptical region east of Newfoundland). The position of the Labrador Sea deep convection region (RCD) is shown as a rectangle between 55°-59°N 56°-51°W (Lavender et al. 2002) in selected panels. Boxes 1, 2, 3 shown for 1983 refer respectively to areas corresponding to the Labrador Sea basin, (55°-65°N 60°-50°W), the Newfoundland basin (45°-55°N 55°-50°W) and the area close to Flemish Cap (45°-50°N 50°-45°W). (b) Mean SIC time series from 1960-2020 comparing boxes 1, 2 and 3.)
5. Drainage of anomalous Labrador Sea ice meltwater into the SPG follows the LC-Atlantic path.

Although it appears from Figure 6 that sea-ice is largely carried in the LC-Arctic south of 55°N, it is important to establish how meltwater released from the southern Labrador Sea might be drained. Allan & Allan (2024) showed that sea-ice accumulated in the southern Labrador Sea during the 1983-1984 winter melted in the summer of 1984 and the accumulated cold water drained into the SPG in the fall of 1984, marking the end of the 1980s Great Salinity Anomaly. It should be noted that in summer/fall there are no icebergs or sea-ice to complicate interpretation of SST data. We examined the route of the initial drainage in September-November 1984 using daily data for SST anomaly and the results are shown in Figure 7. On September 8, 1984 there was a large area of negative SST anomalies in the Labrador Sea while the region south of 52°N including the SPG was occupied mainly by positive anomalies. A week later, there was evidence for the appearance of cold anomalies near Flemish Cap and south of the TGB and this became stronger by September 19 when a clear line of negative anomalies extended southwestwards along the 1000m isobath. This suggested that the initial drainage of the Labrador Sea meltwater was through the LC-Atlantic (slope) current (Figure 1) and not the LC-Arctic (shelf) current which carries ice (Figure 6) and icebergs. This is seen particularly from September 19-21 when cold water extended from the Labrador Current into the path of the NAC and back towards the Labrador Sea, plausibly recycling around the SPG as envisaged for the Great Salinity Anomalies (Belkin et al. 1998; Allan and Allan 2024). After September 21, negative SST anomalies continued to spread around the SPG until by November 1 most of the cold anomalies had departed from the Labrador Sea and the majority were circulating in the SPG before dispersing to the southeast and west by November 15.

Figure 7. Drainage of cold water from the southern Labrador Sea into the SPG in the fall of 1984. Changes in OISST SST anomaly are shown from September 8 to November 15 1984 during the final efflux of cold water from the southern Labrador Sea after melting of the ice accumulated in the 1983-84 winter. The black line is the 1000m isobath which represents part of the steep slope down to deep water (>3000m) and is distinct from the Labrador shelf region (generally <400m deep in this region).
These results support the hypothesis that Atlantic-derived waters including the particularly cold waters resulting from melting of anomalous ice in the Labrador Sea basin are carried in the LC-Atlantic (Deep Western Boundary Current) while a large proportion of sea-ice and icebergs is carried southwards in the LC-Arctic along the Labrador Shelf (Figure 6).

6. Did icebergs reach Flemish Cap and did they enter the NAC?

Although sea-ice reached Flemish Cap in certain years between 1970 and 1995 there is no evidence from Figures 5 or 6 that ice reached as far as the NAC whose path runs close to the eastern margin of Flemish Cap (Figure 1). Icebergs have a similar transit time to sea-ice between the Labrador Sea and Newfoundland, (from 0.5 to 1.5 years according to Wilton et al. 2015) but it is not certain if icebergs reached as far as Flemish Cap before melting. Recent modelling data suggests that only the very largest (>4x10⁸ tonnes) icebergs calved in West Greenland could reach Flemish Cap (Parayil et al. 2022) and they took about a year to make the journey.

There is extensive data for the distribution of iceberg sightings from the International Ice Patrol (Open Research) and this information for May (corresponding to maximum iceberg numbers) in the period 1960-1995 is illustrated in Figure 8a. This diagram makes it clear that icebergs north of 50°N were largely confined to the shelf region corresponding to LC-Arctic although data north of 52°N were not available during 1980-1994 so this observation relates only to 1965-1980. Further south, icebergs were observed over Flemish Cap and as far as the path of the NAC as judged from the 4000m isobath and the work of Mertens et al. (2014) and Solodoch et al. (2020) (Figure 1). The data in Figure 8b shows that in the colder years 1972, 1985 and 1994 (Figure 2a, 5a), iceberg numbers were high and many not only reached Flemish Cap but progressed as far east as 42°W whereas in the warmer years 1970, 1980 and 1988, there were many fewer icebergs overall and very small numbers reached as far as Flemish Cap (Figure 8b).

In the coldest years icebergs also reached the area to the south of Flemish Cap where the 4000m isobath and the NAC come closest to Flemish Cap (Figure 8b). Indeed, the largest cold anomalies appear to be south of Flemish Cap (Figures 3b, 5a) so icebergs reaching this region could have the largest effect on cooling the NAC. It is notable that the years when the highest iceberg counts were registered over the whole area south of 50°N were also those when ice reached Flemish Cap (1972-74, 1983-85 and 1990-94, Figure 6b). This is consistent with the conclusion of Marko et al. (1994) who noted that ‘the critical role of the sea-ice was to assure the survival of a very small fraction of the iceberg population created each year’.

In the cold years, some icebergs also progressed through Flemish Pass, and east of the Grand Banks along the path of the DWBC, before meeting the NAC near the TGB (Figure 8a). The Grand Banks appears to exclude most icebergs probably because it is relatively shallow (<100m) and any relatively small icebergs which reached the Grand Banks would soon melt. Much of Flemish Cap is deeper than 250m and can accommodate larger icebergs. Exclusion of icebergs from the Grand Banks implies that most icebergs reaching 50°N have a draft larger than 100m and thus exceed about 4x10⁶ tonnes according to the classification of Parayil et al. (2022). Icebergs would only be excluded from Flemish Cap if they had drafts larger than about 200m (4x10⁶ tonnes). From a modelling study of trajectories of icebergs calved from Jakobshaven (Ilulissat) in West Greenland, Paravil et al. (2022) showed that only the very largest icebergs (initial mass >4x10⁶ tonnes and calving draft >230m) would survive as far as 47°N 43°W (east of Flemish Cap and within the NAC region).

From the moorings data of Mertens et al. (2014) the fast (20-30cm/s) northward current characteristic of the NAC at the surface extends westwards as far as 43°W so icebergs which reached 43°W could be drawn into the NAC. This is further evidence that in some years, introduction of sea-ice, icebergs and cold meltwater from Flemish Cap into the adjacent NAC might allow the cold signal to be carried via the NAC into the SPNA, potentially contributing to the CB. It should be noted that the excursion of the NAC path known as Northwest Corner (NWC, Figure 1) (Lazier 1994, Rossby 1996) passes near 53°N 45°W, not far from CB epicentre at 54°N 43°W (Figure 1) so it is possible that delivery of cold water to the SPNA from Flemish
Cap via the NAC could generate the CB. If buoys released into the NAC can be trapped in the recirculating gyre at Northwest Corner (Rossby 1996) then so also could cold surface water which could potentially contribute to the CB. Lazier and Wright (1993) envisaged elements of the NAC reaching as far as 54°N.

Figure 8. (a) New icebergs plotted at their first sighting latitude and longitude between 1965 and 1995. (b) Observed icebergs in May 1972, 1985 and 1991 when temperatures at Flemish Cap were unusually low and in 1970, 1980 and 1988 when temperatures were relatively high (see Figure 4a). These International Ice Patrol observations were limited to 52°N from 1980-1994 so do not show icebergs along the Labrador coast during this period. The dense line near 52°N is therefore believed to be an observation artifact. The 1000m isobath (gray line) is included in (a) and (b) to show the positions of the TGB(43°N 50°W) and Flemish Cap (FC) (see Figure 1) and the 4000m isobath (dashed line) gives an indication of the path of the NAC around Flemish Cap.
If icebergs can reach Flemish Cap and enter the NAC, then equally, icebergs reaching the TGB are likely to enter the Gulf Stream/NAC a short distance south of the TGB and contribute to the cooling of the NAC which is subsequently transferred to the CB. One major difference between these two modes of iceberg entry into the NAC is that in high ice years significant amounts of sea-ice reach Flemish Cap as well as icebergs whereas no sea-ice appears to get further south than 46°N (Figure 6a). This would mean that icebergs transferred via Flemish Cap to the NAC are more likely to survive than those entering via Flemish Pass and the TGB. Icebergs progressing east of Flemish Cap would initially enter the DWBC and might be carried southwards but could reach the NAC as a result of eddy interactions of the DWBC with the NAC. However, the main conclusion to be derived from Figure 8 is that in particularly cold periods, some icebergs reached as far as the NAC east of Flemish Cap whereas in warmer years, not only were there many fewer icebergs in total but very few reached Flemish Cap and none reached the NAC.

**Discussion**

It was noticed thirty years ago that there was an apparent correlation between fluctuations in sea-ice cover in the Labrador Sea and SST values 1-2 years later in the SPNA (Deser and Blackmon 1993, Deser et al. 2002). Consistent with this evidence, we show here that the three major periods of Labrador Sea ice expansion in the late 20th century (Figure 6a) were each associated with corresponding cold periods in the Labrador Sea which were followed about a year later by corresponding cold periods in the SPNA centered on 54°N 43°W (Figure 4a), the epicenter of a region of long-term cooling, the North Atlantic Cold Blob (CB; Figure 2, see Introduction). Without these three cold periods between 1970 and 1995 there would have been no significant CB (Figure 2). Our evidence for the essential role of these limited major cold periods for the appearance of the CB is difficult to reconcile with the concept that the CB was the result of a century-long cooling trend in the subpolar North Atlantic (Li et al 2022). Most of the cooling occurred between 1970 and 1995 and even the 1900-2020 CB was mainly due to the continuing influence of these 20th century cold periods in the data.

We observed also that temperatures at CB epicenter were well correlated and in phase with three similar but colder periods at Flemish Cap (Figures 3,4a, 5b,c) which occupies a crucial intermediate position on the route of the Labrador Current bringing ice, icebergs and cold water from the Labrador Sea to meet the North Atlantic Current. It is initially surprising that there should be such a close link between temperature at Flemish Cap and CB epicentre which are separated by 800km of ocean but there is evidence for a physical connection between cool surface water at Flemish Cap and the CB in the three cold periods in the 1970s, 1980s and 1990s (Figures 3b, 5a). We propose that the link between the cold anomalies at Flemish Cap and the CB is provided by the normal northward pathway of the NAC east of Flemish Cap, via the gyre known as Northwest Corner. Surface currents associated with the NAC east of Flemish Cap have a velocity of about 30cm/sec (Flatau et al. 2003, Mertens et al.2014) so the time taken to traverse 800km would be about one month. Comparing the SST time series at Flemish Cap with that at CB epicenter (Figure 4a,5c) a lag of one month would be difficult to detect.

The crucial role of Flemish Cap in transmission of cold water from the Labrador Sea to the SPNA is evident from our studies of SST, sea-ice and iceberg numbers in the late 20th century. It was only in the coldest years at Flemish Cap and the CB that the 1°C isotherm (Figure 3a), sea ice (Figure 6) and icebergs (Figure 8) reached Flemish Cap and icebergs were observed east of Flemish Cap in the path of the NAC close to 43°W (Figure 8). This last observation is the basis of our suggestion that in the coldest years between 1970 and 1995, cold meltwater from ice and icebergs traversing Flemish Cap was carried in the NAC towards the CB. It is difficult otherwise to explain the close correspondence between the time series of temperature at Flemish Cap and the CB (Figure 4) and for indications of continuity between cold regions near Flemish Cap and those in the CB region (Figure 3b, 4c).

Each of the three main cold periods near Flemish Cap (Figure 4a) can be largely explained as a consequence of the dissolution of unusually extensive sea ice cover over the deep basin of the Labrador Sea about a 1-2 years earlier (Figure 6a,b). It is a normal annual event for sea-ice from Baffin Bay, Hudson Bay and the
northern Labrador Sea to be carried in the (shelf) LC-Arctic towards Newfoundland but in the 1970s, 1980s and 1990s there were periods of high SIC over the Labrador Sea basin which is not usually ice-covered (Figure 5a,b). Marko et al. (1994) showed that iceberg counts at 48°N were strongly related to the extent of sea ice in the southern Labrador Sea and Newfoundland, particularly in those years (1972, 1983-84 and 1993) with the highest SIC in the Labrador Sea basin (Figure 6a). Most icebergs in this region appear to have come from Baffin Bay or West Greenland, carried in the LC-Arctic (Wilton et al. 2015; Figure 8a) but dissolution of the enhanced sea-ice in the Labrador Sea basin in the 1970s, 1980s and 1990s appears to be linked to an increase of ice in the LC-Arctic and subsequently at Flemish Cap (Figure 6a,b). Based on the changes in SIC anomalies (Figure 6a) it appears that south of 55°N, little ice remained east of the 1000m isobath (i.e. in the LC-Atlantic) but there were increases in sea-ice in the LC-Arctic west of the 1000m isobath and this extra ice would make it more likely that icebergs in the LC-Arctic would survive as far as Flemish Cap and the NAC. We conceive that it was the dissolution of this temporary icy reservoir in the Labrador Sea basin in 1973, 1985 and 1991/1994 which released ice and cold water into the LC-Atlantic and this facilitated the survival of ice and icebergs in the LC-Arctic as far as Flemish Cap.

Evidence has recently been presented that meltwater and ice from the southern Labrador Sea is likely to be incorporated into LC-Atlantic (Florindo-López et al. 2020) and this is supported by Figure 7. These authors made the important observation that the content anomaly of LC-Atlantic waters was greatest in the early 1970s, mid 1980s and early 1990s, plausibly due to melting of the anomalous ice in the Labrador Sea basin during the same periods. Although little ice was seen east of the 1000m isobath (i.e. LC-Atlantic) south of 55°N (Figure 6a) unusually cold meltwater carried in the LC-Atlantic would have helped to preserve icebergs and sea-ice in the LC-Arctic especially when the two currents combined near 49°N 48°W (Han et al. 2008) so more icebergs would have progressed as far as Flemish Cap and the NAC.

Due to their great size, icebergs are likely to survive longer than sea-ice and thus more likely to reach Flemish Cap, consistent with observations of large numbers of icebergs between 1960 and 1998 reaching further east than Flemish Cap (Figure 8a) while sea-ice reached no further than the centre of Flemish Cap (Figure 6a). The critical role of Flemish Cap in the origin of the CB could thus be due to its unique geographical position at the interface between the major cold and warm currents when in three periods between 1960 and 1995 the Labrador Current brought sea-ice and icebergs over Flemish Cap and icebergs reached the path of the NAC. Given its pivotal position at the interface between the Labrador Current and the NAC, temperature changes at or near Flemish Cap might reflect critical climate adjustments in the wider North Atlantic. No sea-ice in the Labrador Current reached the Gulf Stream/NAC junction near the TGB (Figure 6) but some icebergs did reach the path of the NAC between the TGB and Flemish Cap (Figure 8a,b). However, in the cold years 1974, 1985 and 1994 (Figure 8b) most of the icebergs appeared to be routed over and around Flemish Cap so that the most important influences cooling and freshening the NAC would have been sea-ice reaching Flemish Cap and icebergs passing east of Flemish Cap into the NAC. Icebergs reaching so far east would have been of the largest size with a calving draft approaching 250m (Paravil et al. 2022) so would have been more likely to become grounded at some points on their journey south. This would delay them and could help to explain why there was a year’s delay between temperature changes in the Labrador Sea and those at Flemish Cap (Figure 4a).

The connections between SST anomalies at the CB and sea ice and icebergs reaching Flemish Cap may have been missed in the past because many previous studies have combined SST data over very wide areas of the Atlantic, often conflating local warm and cold anomalies. For example, Hodson et al. (2014), Robson et al. (2016), Boers (2021) and Li et al. (2022) saw the same three troughs of North Atlantic SST (1970s, 1980s, 1990s) as we have done but they sampled wider areas of the North Atlantic which included many positive anomalies (see Figure 2a) so the negative anomalies registered were considerably less those we have measured at Flemish Cap and the CB epicentre.

The three episodes of sea-ice expansion in the Labrador Sea basin which preceded the development of the CB appear to have been caused by three expansions and dissolutions of the Odden ice in the Greenland-Iceland-Norway Sea which may be in turn related to three periods of increased export of Arctic ice through Fram Strait (Allan and Allan 2024). Thus, a continuous chain of events links ice expansion in the Arctic to ice expansion in the GIN Sea to ice expansion in the Labrador Sea to transport of ice and icebergs to the
NAC via Flemish Cap and transport of residual cold water to the CB. This complex route achieved the transfer of meltwater from Arctic ice to the SPNA in three periods at the end of the 20th century resulting in the phenomenon of the CB. The process appears to have come to a halt in 1995 as temperatures rose in the North Atlantic and particularly at Flemish Cap (Figure 4a) which is a pivotal point between the Labrador and North Atlantic Currents. Only in the special circumstances of 1970-1995 where icebergs and cold meltwater reached past Flemish Cap and as far as the NAC could their cold influence be seen to be transferred to the CB via the NAC. We emphasise however, that sea-ice reaching Flemish Cap and icebergs reaching the NAC are largely significant insofar as they indicate the main path of cold meltwater which represents far more sea-ice and icebergs than the few percent which are visible near Flemish Cap.

The Flemish Cap cold periods are more intense than those at the CB (Figure 4a) so it might be anticipated that there would be a CB centered on Flemish Cap. The reason for the absence of such a feature is that warmer periods at Flemish Cap dominate the long-term trend there and render it positive (Figure 2). This is consistent with the increasingly positive trends in this region after 1995 (Figure 3b, 4b,c) and may be associated with the reduction in sea-ice and icebergs reaching Flemish Cap after 1995 (Figures 6, 8). A more fundamental reason for the cessation of the cold periods at Flemish Cap and the CB is that the anomalous periods of ice expansion in the Labrador Sea no longer occurred (Figure 6) because the precursor Odden ice ceased to form, probably associated with reductions in Arctic ice expansion after 1990 (Allan and Allan 2024).

We note also that the mysterious Cold Intermediate Layer (CIL; e.g. Florindo-López et al. 2020) is particularly prominent in the spring, is observed to occupy the same regions of the Canadian continental shelf as the LC-Arctic which represents the main route of iceberg movement southwards (see Introduction) and is a major region of iceberg melt (Marko et al. 1994). We speculate that that the CIL represents spring and summer iceberg meltwater, particularly because Moon et al. (2020) showed that iceberg meltwater tends to gather not at the surface but in a layer about 50-150m below the surface which may be sustained into the fall. This behaviour is typical of the CIL which is a cold fresh layer 50-100m below the surface often remaining through the summer. The existence of the CIL over Flemish Cap is consistent with our demonstration here that icebergs reach Flemish Cap in high ice periods and many may have grounded and decayed there.

Returning to the question regarding the relative importance of advective and atmospheric influences on the development of the CB, the present work argues that advection of ice, icebergs and cold meltwater from the Labrador Sea to the North Atlantic via Flemish Cap and the NAC is the major factor. It is difficult to explain the observed close relationship between three cold periods in the Labrador Sea, Flemish Cap and CB epicentre other than by an advective process involving the transport of sea ice, icebergs and cold water in the Labrador Current to Flemish Cap and thence probably via the NAC, to the CB. This is a special case of a perfectly normal process which occurs every year but does not usually involve transport of icebergs as far as Flemish Cap and beyond. Finally, it seems unlikely that a primary cooling of the SPNA due to atmospheric influences could on three separate occasions in the late 20th century transmit cold water to an even colder and more restricted area at Flemish Cap (Figure 3,4,5). We note that even recent proponents of the idea that atmospheric cooling is primary only ascribe 62% or 50% to this source (Li et al. 2022; He et al. 2022). While air-sea heat fluxes certainly contribute to the SST changes in some months and years (e.g. Sanders et a. 2022), our previous work indicates that this is a factor secondary to horizontal advective surface heat transfers (Allan and Allan 2024).

Notwithstanding these considerations, the three episodes of freezing in the Labrador Sea in 1972, 1983-1984 and 1993 would have required unusual periods of strong cold winds probably blowing from Greenland in winter (Allan and Allan 2024) in order to form extensive ice over the deep basin of the Labrador Sea. Also, iceberg and sea ice drift are very susceptible to wind strength and direction so the numbers of icebergs together with associated meltwater which reach Flemish Cap and the NAC are likely to be subject to these very variable atmospheric factors. Furthermore, the cold surface signals carried by the NAC to CB epicentre...
are likely to have been dispersed into the wider CB by the strong winds common in the North Atlantic in spring. Finally, there is good evidence that northerly winds through Fram Strait assisted the exit of Arctic ice which began the process eventually leading to the evolution of the CB (Allan and Allan 2024). For these reasons, atmospheric influences would still have had a substantial role in the development of the CB as many studies have suggested previously (Li et al. 2022; He et al. 2022).

Besides pointing out the link between unusual ice expansion in the Labrador Sea and the CB we have also argued that Labrador Sea ice has a role in the development of the three Great Salinity Anomalies or GSAs (Allan and Allan 2024). The development of the cold anomaly in the SPG which is characteristic of the GSAs is evident over a period of a few weeks in September 1984 (Figure 7) and the initial distribution of the cold anomaly resembles the classical pattern of the GSA (Belkin et al. 1998). We note that the CB is particularly evident early in the year (January-March, Allan and Allan 2019) when it is defined by cold water, ice and icebergs reaching Flemish Cap and beyond to the NAC whereas the GSAs appear to be related to the release of meltwater from the Labrador Sea basin into the SPG in the fall when there is no sea-ice or icebergs (Figure 7). Thus, the CB and the GSAs are separate manifestations of the dynamics of ice formation and dissolution in the Labrador Sea.

We can therefore extend the ‘wider perspective’ referred to in our recent work (Allan and Allan 2024) to follow a sequence of events from ice expansions in the Arctic, in the Odden (Greenland-Iceland-Norwegian Sea basin) and then in the Labrador Sea basin, leading to the GSAs and to ice and iceberg expansion at Flemish Cap from where meltwater was directed by the NAC to form the CB. This work has possible implications for deep convection in the Labrador Sea because the ice expansion which occurred in the deep basin of the Labrador Sea in the 1970s, 1980s and 1990s encroached on the region of deep convection (RDC) in the Labrador Sea (Figure 6a). While pack ice over the whole of this region might be expected to inhibit deep convection by insulating the surface waters from atmospheric forcing, ice adjacent to the RDC might augment surface cooling driven by cold winds and could potentially increase the likelihood of deep convection of surface water freshened by melting ice. Oceanic deep convection involves a complex interplay between cold, dry winds from adjacent land and ice cover driving rapid heat and moisture loss from the open ocean, dynamically-driven doming of density surfaces and a combination of inflows from ocean circulation and ice melt as well as pre-conditioning of ocean column stratification (Lab Sea Group, 1998).

Strong deep convection in the winter of 1972 occurred suddenly after a long period of shallow convection over the preceding decade (Lazier 1993) and coincided with a marked increase in SIC close to the RDC (figure 6a). A very large deep convection event (>2000m) took place in the 1990s when again SIC had increased in the Labrador Sea basin but this link between deep convection and SIC over the RDC was less convincing for the 1980s event (Yashayaev and Loder 2016). Any possible effects on deep convection of ice formation close to the RDC would have disappeared after 2000 when SIC in the Labrador Sea basin largely reverted to normal low levels, perhaps associated with warming sea temperatures. Deep convection in the Labrador Sea after 2000 initially reverted to more normal levels (Yashayaev and Loder 2016,2017) but there was a further large episode of deep convection from 2015-2020 (Yashayaev 2024) which was also associated with rises in SIC in the Labrador Sea, Newfoundland Basin and Flemish Cap, although not on the scale of the 1990s event (Figure 6b).

Deep convection at the RDC is an important component of the Atlantic Meridional Overturning circulation (AMOC) which exchanges cold fresh water in the Deep Western Boundary Current (DWBC,) for warmer saltier water in the NAC. The DWBC, the major southward limb of AMOC, appears to be largely represented by the western component of the Labrador Current through Flemish Pass (Figure 1; Solodoch et al. 2020). These authors have described the ‘leak’ of the DWBC north of Flemish Cap (Figure 1) which would reduce the normal flow of the DWBC through Flemish Pass and putatively reduce the AMOC. We show here that in the late 20th century there were episodes when large amounts of sea ice reached Flemish Cap and icebergs were routed into the path of the NAC, the northward limb of the AMOC. Such a ‘short-circuiting’ of the ‘normal’ (Flemish Pass) pathway as a result the Flemish Cap ‘leak’ may have reduced the AMOC. If the CB is largely the product of the cold periods between 1970 and 1995 which sent icebergs and associated meltwater into the NAC via the Flemish Cap ‘leak’ current, this may have been the origin of the apparent reciprocal links between the CB intensity and AMOC strength which have been suggested by
others (Rahmstorf et al. 2015; Keil et al. 2020; Boers 2021). Drijfhout et al. (2012) speculated that the ‘warming hole’ (CB) ‘may be involved in an ocean adjustment which precedes the AMOC decline’. The mechanism giving rise to the cooling of the SPNA which was manifest as the CB largely disappeared after 2000 (Figures 2, 4a, 6) so is difficult to see a role for the long-term CB in modulation of the AMOC up to present. The 1900-2020 long-term CB obviously still includes the large 20th century cold periods (Figure 2) and although it also includes the 2014-16 cold period, this is a relatively small contributor to the overall negative gradient (Figure 2f), besides probably representing a different cooling mechanism (e.g., Sanders et al. 2022).

Because the CB has been proposed to have a significant involvement in modulation of AMOC and wider aspects of Atlantic climate, the origin of this cold feature has long been of interest. Our demonstration here of the connection between the CB and accumulation of ice and icebergs at Flemish Cap raises the possibility that the CB has its origin in ice and iceberg meltwater carried to the SPNA via the NAC. This mechanism appears to be largely confined to the last decades of the 20th century and should be considered in the interpretation of links between long-term cooling of the North Atlantic, changes in AMOC and implications for regional climate.

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Open research
In the preparation of this manuscript we downloaded and analysed some data from Climate Explorer (https://climexp.knmi.nl) which is part of the WMO Regional Climate Centre at KNMI (Koninklijk Nederlands Meteorologisch Instituut).

Sea surface temperature and sea ice cover data were obtained respectively from https://www.metoffice.gov.uk/hadobs/hadisst/ and https://www.metoffice.gov.uk/hadobs/hadisst2/.

OISST (Optimum Interpolation Sea Surface Temperature) V2 data from the Advanced Very High Resolution Radiometer (AVHRR) infrared satellite were obtained from https://www.psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html.

Annual and monthly iceberg counts were obtained from the International Ice Patrol Annual Count of Icebergs South of 48 Degrees North, 1900 to Present, Version 1. 2020, https://doi.org/10.7265/z6e8-3027.

Calculation of distance and area in the North Atlantic was from Google Earth Pro, kh.google.com.

Ocean bottom depth is provided by bathymetric mapping data from the General Bathymetric Chart of the Oceans (GEBCO Compilation Group 2023) (doi.org/10.5285/f98b053b-0cbe-6c23-e053-6c86abc0af7b).

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