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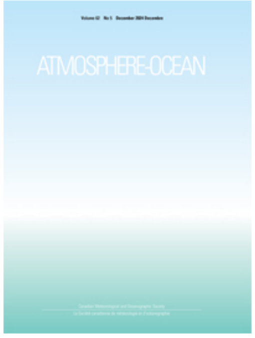

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Influence of Meltwater from Labrador Sea Ice and Icebergs Transported Via the Flemish Cap on the Long-Term North Atlantic Cold Anomaly

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ABSTRACT *The long-term North Atlantic Cold Anomaly (Cold Blob, CB) was largely defined by three major episodes of low sea surface temperature (SST) in the subpolar North Atlantic in 1972–1974, 1984–1985 and 1991–1994. Without these cold periods, there would have been no CB. Each of these episodes correlated with unusually low SST at the Flemish Cap (a subsurface island of the Canadian continental shelf) and with periods of high sea ice cover over the deep basin of the Labrador Sea a year earlier. These cold periods at the Flemish Cap and the CB were associated with the advance of sea ice and icebergs to the Flemish Cap, high iceberg counts off the coast of Newfoundland and the encroachment of icebergs on the path of the North Atlantic Current (NAC). Studies of SST anomalies in high iceberg years provided evidence for surface connections between the Flemish Cap and the CB utilizing 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 the Flemish Cap was relayed via the NAC to the subpolar North Atlantic to form the CB. After 1995, anomalous ice expansion in the Labrador Sea basin greatly diminished, sea ice and icebergs did not reach the Flemish Cap and cold meltwater was no longer transmitted to the subpolar North Atlantic to sustain the CB. These observations make it difficult to see how the CB could be relevant to mooted changes in the Atlantic Meridional Overturning Circulation and associated impacts on regional climate in the twenty-first century.*

RÉSUMÉ *[Traduit par la rédaction] L'anomalie froide à long terme de l'Atlantique Nord (« Cold Blob », CB) a été largement définie par trois épisodes majeurs de basses températures de surface de la mer (TSM) dans l'Atlantique Nord subpolaire en 1972–1974, 1984–1985 et 1991–1994. 1.0 94. Sans ces périodes froides, le CB n'aurait pas existé. Chacun de ces épisodes a été corrélé avec des TSM anormalement basses au bonnet Flamand (une île souterraine du plateau continental canadien) et avec des périodes de forte couverture de glace de mer dans le bassin profond de la mer du Labrador un an plus tôt. Ces périodes froides au bonnet Flamand et le CB ont été associés à l'avancée de la glace de mer et des icebergs au bonnet Flamand, à des nombres élevés d'icebergs au large de la côte de Terre-Neuve et à l'empiètement des icebergs sur la trajectoire du courant de l'Atlantique Nord (CAN). L'étude des anomalies de la TSM au cours des années à forte concentration d'icebergs a fourni des preuves de l'existence de connexions de surface entre le bonnet Flamand et le CB utilisant une partie du trajet du CAN. Nous proposons qu'au cours des périodes froides, l'eau de fonte résiduelle de la glace de mer et des icebergs transportés par le courant du Labrador jusqu'au bonnet Flamand soit relayée par le CAN jusqu'à l'Atlantique Nord subpolaire pour former le CB. Après 1995, l'expansion anormale de la glace dans le bassin de la mer du Labrador a fortement diminué, la glace de mer et les icebergs n'ont pas atteint le bonnet Flamand et l'eau de fonte froide n'a plus été transmise à l'Atlantique Nord subpolaire pour soutenir le CB. Ces observations font qu'il est difficile de voir comment le CB pourrait être pertinent pour les changements envisagés dans la circulation méridienne de retournement de l'Atlantique et les impacts associés sur le climat régional au cours du XXI^{e} siècle.*

KEYWORDS Cold Blob; the Flemish Cap; sea ice; icebergs; North Atlantic Current; Labrador Current

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1 Introduction

a *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 epicentre of this region (Figs. 1 and 2c) has undergone *absolute* cooling by about 1°C since 1900 (Allan & Allan, 2019) so we prefer to use the description North Atlantic Cold Blob as suggested by Li et al. (2022). This is not elegant nomenclature 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 (Boers, 2021; Caesar et al., 2018, 2021; Drijfhout et al., 2012; Gervais et al., 2018; Keil et al., 2020; Rahmstorf, 2024; Rahmstorf et al., 2015).

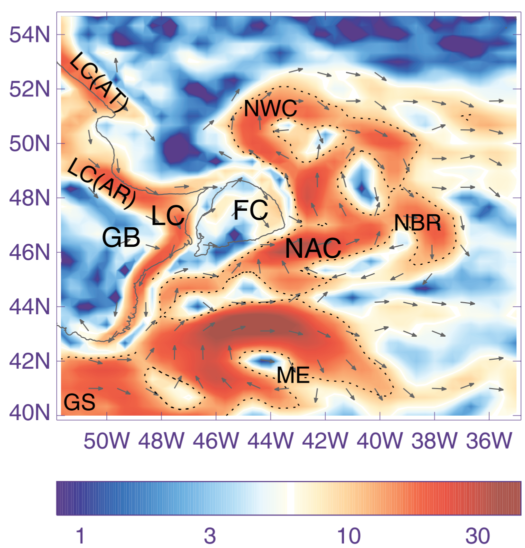

Fig. 1 A mean current velocity map of the major ocean currents east of Newfoundland for the years 1993–2003. The path of the North Atlantic Current (NAC) is enclosed by a dotted line following the 13 cm s^{-1} isovelocity line which is used later in the manuscript to define the position of the NAC. The Mann Eddy (ME), Northwest Corner (NWC) and the Newfoundland Basin Return Current (NBR) are labelled. The main path of the combined Labrador Current (LC) passes southwards close to the Grand Banks (GB) to meet the Gulf Stream (GS) near 42°N 50°W. Also shown are the Atlantic origin Labrador Current (LC[AT]) and the Arctic origin Labrador Current (LC[AR]). These currents are separated by the 1000 m isobath (solid gray line) which also defines the position of the Flemish Cap (FC). Arrows mark direction of currents with velocity >6 cm s^{-1}. Colour bar shows current velocity in cm s^{-1} on a log10 scale.

Josey and Sinha (2022) and Sanders et al. (2022) considered the long-term CB (1900–2010) to be distinct from the short-term cold anomaly of 2014–2016 because the long-term CB was clearly dominated by the large cold anomalies in the latter part of the twentieth century. They concluded also that these cold anomalies appeared to be driven primarily by ocean convection whereas the 2014–2016 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) (Allan & Allan, 2019; Drijfhout et al., 2012) and the short-term (2014–2016) cold anomaly (near 30°W) (Josey & Sinha, 2022). 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; Gervais et al., 2018; Josey & Sinha, 2022; Josey & Sinha, 2022) where cooling of the SPNA depends on the delivery of cold surface water from a distant source, whereas others have emphasized the role of ocean-atmosphere heat exchange such as reduced incoming solar radiation or strong, cold winds which cool a specific region of the SPNA either by radiative heat transfer, conduction or evaporation (He et al., 2022; Li 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 the dynamics of ice movements 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 twentieth century when the sea surface temperature of the SPNA was markedly reduced (>1°C) compared with average conditions since 1900 (e.g. Boers, 2021; Deser et al., 2002; Hodson et al., 2014; Li et al., 2022; Robson et al., 2016). 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 & 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 & Allan, 2024). We have also linked the melting of Odden and Labrador Sea ice to the Great Salinity (and SST) Anomalies (GSAs, Belkin et al., 1998) in the Subpolar Gyre (SPG) formed between the Labrador, North

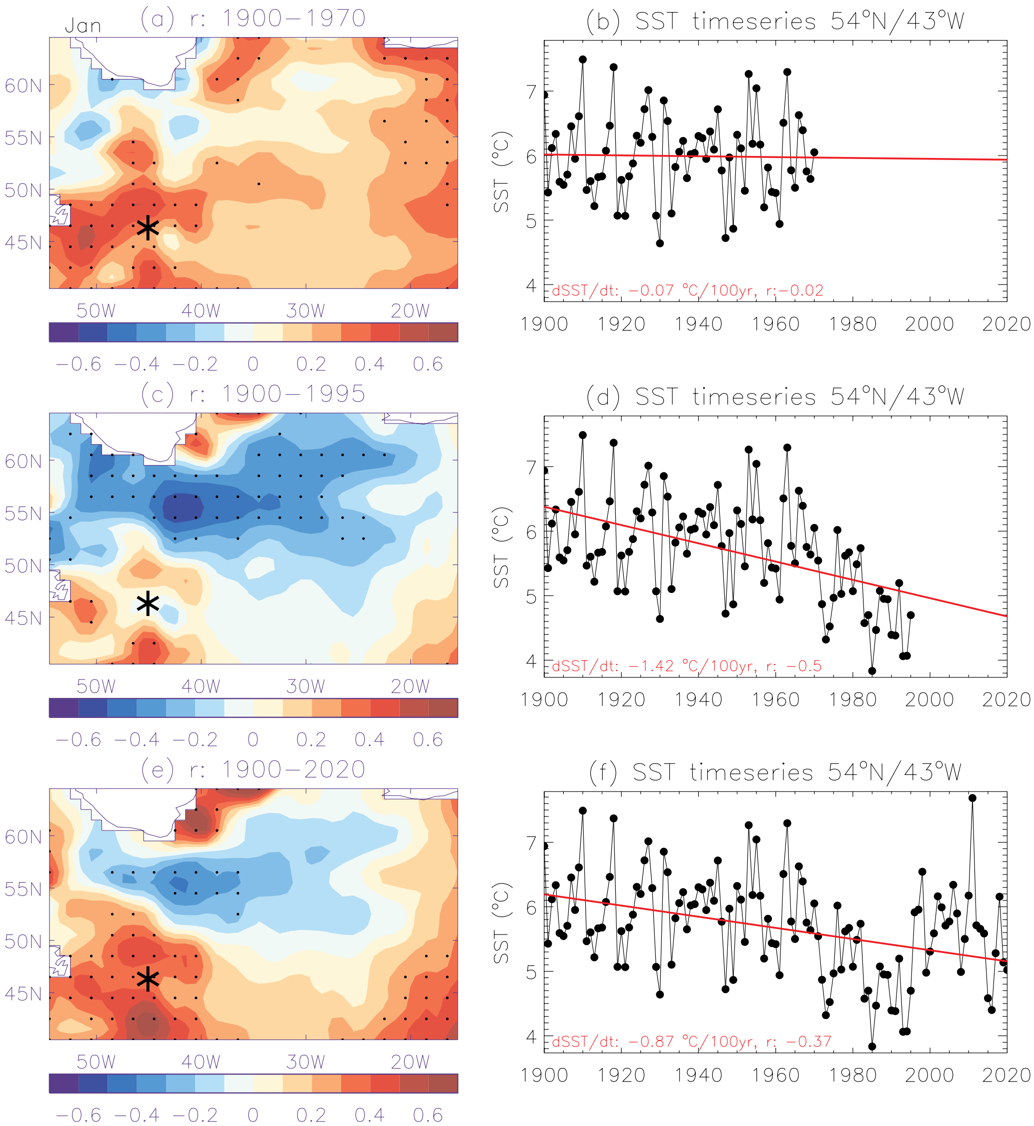

Fig. 2 The Cold Blob derived by linear correlation (*r*) of January grid point HadISST observations with global mean values over the same period for (a) 1900–1970, (c)1900–1995 and (e) 1900–2020. The stippling shows where the linear fit between grid point SST and global mean SST is significant at the 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° to 65°N and 55°–15°W and includes portions of the coastlines of Newfoundland, Greenland and Iceland. An asterisk marks the position of the Flemish Cap in (a,c,e). Figures (b,d,f) show the January time series of HadISST at CB epicentre (54°N 43°W) corresponding to (a,c,e). Gradients of SST trend lines (red) for these three periods are shown as dSST/dt.

Atlantic and East/West Greenland Currents (Allan & Allan, 2024). Although the GSAs and the CB may both be consequences of three freezing periods in the Labrador Sea basin in the late twentieth 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 & Allan, 2024), whereas the CB is most prominent in January–February (Allan & 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 the Flemish Cap (FC in Fig. 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.

b *The Labrador Current(s)*

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 <300 m). The second component derives from the southern Labrador Sea and the Atlantic waters contributing to the West Greenland Current and occupies the deeper (1000–3000 m) slope waters of the western Labrador Sea (Fig. 1). These two components have been respectively labelled as Arctic Labrador Current (LC-AR in Fig. 1) and Atlantic Labrador Current (LC-AT in Fig. 1) by Florindo-López et al. (2020) (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. These two currents coalesce at a point to the west of the Flemish Cap near 50°N 50°W (Fig. 1 and Solodoch et al., 2020) with the combined Labrador Current following the 1000 m isobath along the shelf of the Grand Banks to the TGB (Tail of the Grand Banks) at 43°N 50°W. It is notable that the Labrador Current did not enter the Flemish Pass, the deep channel between the Grand Banks and the Flemish Cap.

c *The North Atlantic Current (NAC)*

The NAC is the major current arising from the bifurcation of the Gulf Stream (GS) near 40°N 46°W (Klein & Siedler, 1989; Krauss et al., 1990) and initially enters the circulation of the Mann Eddy, occupying channels generally >4000 m deep (Rossby, 1996) while skirting the edge of the Flemish Cap, past Northwest Corner (Lazier, 1994) and eventually spreading into well-defined channels taking it across the Mid-Atlantic Ridge (Bower & von Appen, 2008; Stendardo et al., 2020) (Fig. 1). Mertens et al. (2014) have closely analysed the pattern of currents east of the Flemish Cap at 47°N which include the northward-flowing NAC at 43°–41°W and the southward-flowing Newfoundland Basin Recirculation (NBR) current at 39°–37°W. From Fig. 1, it is important to note the prominent role of the Mann Eddy not just in carrying the NAC circulation northwards but in recirculation pathways, particularly the NBR. Also, it appears that at least in 1993–2003, a large part of the initial northward NAC circulation near 45°N passes along the deep channel between the Newfoundland Seamounts (44°N 47°W) and the Grand Banks. This brings the NAC very close to the Labrador Current near 45°N 48°W. Relatively little flow appeared to be from the Mann Eddy near 43°W, east of the Newfoundland seamounts.

d *The significance of the Flemish Cap*

The Flemish Cap is a subsurface island extension of the Canadian continental shelf about 600 km east of Newfoundland (Fig. 1) which rises to within 125 m of the surface at one point. To the east, the Flemish Cap borders on the NAC near 43°W (Colbourne & Foote, 2000; Mertens et al., 2014; Rossby, 1996; Solodoch et al., 2020, Fig. 1) so often there are very considerable differences in temperature and salinity across the Flemish Cap between the cold fresh LC and the warm salty NAC.

Although the Flemish Cap is normally ice free in winter, pack ice originating in Baffin Bay and the Labrador Sea can extend to the Flemish Cap in February or March during particularly cold years (Colbourne et al., 2016; Colbourne & Foote, 2000; 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 unusual stratification of waters over the Flemish Cap is characteristic of the entire Labrador shelf region: there is a persisting cold (near 0°C) fresh layer 50–100 m below the surface which is prominent in the summer and has been named as the Cold Intermediate Layer or CIL (Colbourne et al., 2016; Colbourne & Foote, 2000; Florindo-López et al., 2020; Petrie et al., 1988; Stein, 2007). The precise reason for the existence of this cold fresh subsurface layer is not well defined.

The findings presented here establish the 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 twentieth century.

2 Data and Methods

Ocean current patterns are derived from the Ocean Surface Current Analysis Real-time (OSCAR) sea surface velocity dataset estimated from sea surface height, surface vector wind and sea surface temperature based on multiple satellites and in situ instruments since 1992 and constrained by a physical fluid dynamics model (Bonjean & Lagerloef, 2002; https://podaac.jpl.nasa.gov/dataset/OSCAR_L4_OC_third-deg_YEARLY). Version 1.4 data at a 1/3 degree latitude and longitude resolution is used over the period 1993–2000 (5-day time resolution). Zonal and meridional currents are averaged and marked as missing if less than 30% of the data is valid, due for example to ice cover. Mean flow current velocity and direction is calculated from the mean zonal and meridional flows and displayed using a logarithmic scale (Fig. 1). A streamline depicting mean surface current of 13 m s^{-1} over the North Atlantic Current region is used to define an approximate climatological mask encompassing the strongest currents in this region while adjacent currents, including for example the Labrador current, are masked out for clarity.

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 for SST 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. 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/

Higher resolution, daily resolved SST was also utilized from the NOAA 1/4° Optimum Interpolation Sea Surface Temperature OISST V2 High Resolution Dataset (https://www.psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html). The Advanced Very High Resolution Radiometer (AVHRR)-only version was used to minimize effects from a changing observing systems, while anomalies are computed relative to a precompiled 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 (2020) Annual Count of Icebergs South of 48 Degrees North, 1900 to Present, Version 1 (Figs. 8a,b). From 1946 to 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 the 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 the Flemish Cap.

In this work, we utilize 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, 2024) (https://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.

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

3 Results

a *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 Figs. 2(a,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 January values of HadSST. We have previously shown that the CB is maximal in winter and is scarcely visible in summer (Allan & 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 the 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 per century, in 1995 when the CB was most intense it was −1.4°C per century and in 2020 it was −0.87°C per 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 (Figs. 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 Fig. 2(f) 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 1970–1995 period to the overall 1900–2020 cooling. Due to 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.

b *Three episodes of cooling at the CB corresponded to three periods of cooling in the SPG and particularly near the Flemish Cap*

To relate the three major cooling periods at CB epicentre to other changes in the N. Atlantic, we investigated the distribution of HadISST SST (Fig. 3a) and OISST SST anomalies (Fig. 3b) in the wider area of the SPNA between Newfoundland and Greenland, adding a 1000-m isobath overlay to identify the positions of the 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 Fig. 1). The path of the NAC is also indicated by an overlay (red) based on Fig. 1 Relative cooling near the Flemish Cap was confirmed from a study of the HadISST SST anomalies and this was particularly evident in 1973 and 1985 when a prominent cold region was seen on or close to the Flemish Cap (Fig. 3a) but 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 and eastwards into the region of the CB around 55°N which was also apparent in 1985 and 1991 but less so in 1973. In contrast, in the warm years (1967, 1978 and 1988) there was no evidence for anomalous cooling at the Flemish Cap, CB epicentre or any other specific site. This evidence gives an initial indication that cold periods at the Flemish Cap could be linked to the cold periods in the SPNA which are visualized as the CB.

These results were confirmed by the OISST anomaly data (Fig. 3b) which offers much higher resolution ($0.25° \times 0.25°$ instead of $1° \times 1°$ for HadISST data) although OISST data only goes back to September 1981. Again, there were strong cold anomalies at the Flemish Cap extending back to the TGB and north of 50°N in the cold years 1985, 1991 and 1994 but not in the warm years 1983, 1988 and 1996. Significantly, the addition of an outline of the path of the NAC copied from Fig. 1 shows that in the cold years surface cooling extended into the NAC, particularly near the western exit from the Mann Eddy at 45°N 48°W and east of the Flemish Cap at 47°N 43°W, see Fig. 1. In contrast, in the warm years the NAC SST showed positive anomalies especially in 1983 where strong positive anomalies occupied much of the NAC path while neutral anomalies covered the Flemish Cap and the Grand Banks.

We compared the time series of HadSST SST anomaly at CB epicentre in February between 1960 and 2020 with the corresponding time series for the Flemish Cap (47°N 45°W) and the southern Labrador Sea (60°N 55°W). Fig. 4(a) shows that there is a good agreement between temperatures at CB epicentre and the 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 the Flemish Cap. Although there is a cool period in the CB trace in 2015–2017 (not shown) it does not correspond with a marked change at the 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 the 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 $3.7° \pm 0.9°C$ (range denotes standard deviation). Correlation between temperatures at the Flemish Cap and CB epicentre from 1964 to 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 the Flemish Cap after 1990 compared with temperatures in the Labrador Sea and at the CB. Such a systemic warming at the Flemish Cap in the early 1990s can explain why cooling near the Flemish Cap in the 1990s was less evident than in 1985 and 1973 (Fig. 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 the Flemish Cap.

There were three main troughs in the SST time series for the southern Labrador Sea (Fig. 4a) but these were in 1972, 1983–1984 and 1993, leading the minima at the 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 1960–1990 which shows that the maximum correlation between the Flemish Cap and Labrador Sea time series is reached when the Flemish Cap data is shifted backwards by a year (Fig. 4b). On the other hand, there is no significant lag between the Flemish Cap time series and that for CB epicentre. These results suggest that it takes about a year for surface water (and ice) in the Labrador Sea to reach the Flemish Cap but that there is a relatively rapid equilibration of surface water SST between the Flemish Cap and CB epicentre. It should be noted that the 1991–1994 episode of cooling in the CB is made up of two separate periods centred on 1991 and 1993–1994 and this is true also for the 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 (Fig. 4a).

The high correlation between surface temperatures at the Flemish Cap and those at the CB (Fig. 4), the apparent cold surface water connection between these two locations which are about 800 km apart (Figs. 3a,b) and the evidence for the movement of cold anomalies at the Flemish Cap into the NAC path (Fig. 3b) suggests the possibility that cold anomalies at the Flemish Cap might be carried to the CB via the NAC whose path via Northwest Corner comes close to the CB epicentre at 54°N 43°W.(Fig. 1 and Mertens et al. 2014).

This possibility was investigated further by examining the relationship of cold anomalies at the Flemish Cap to those at the CB and the NAC using the Hovmoeller plots shown

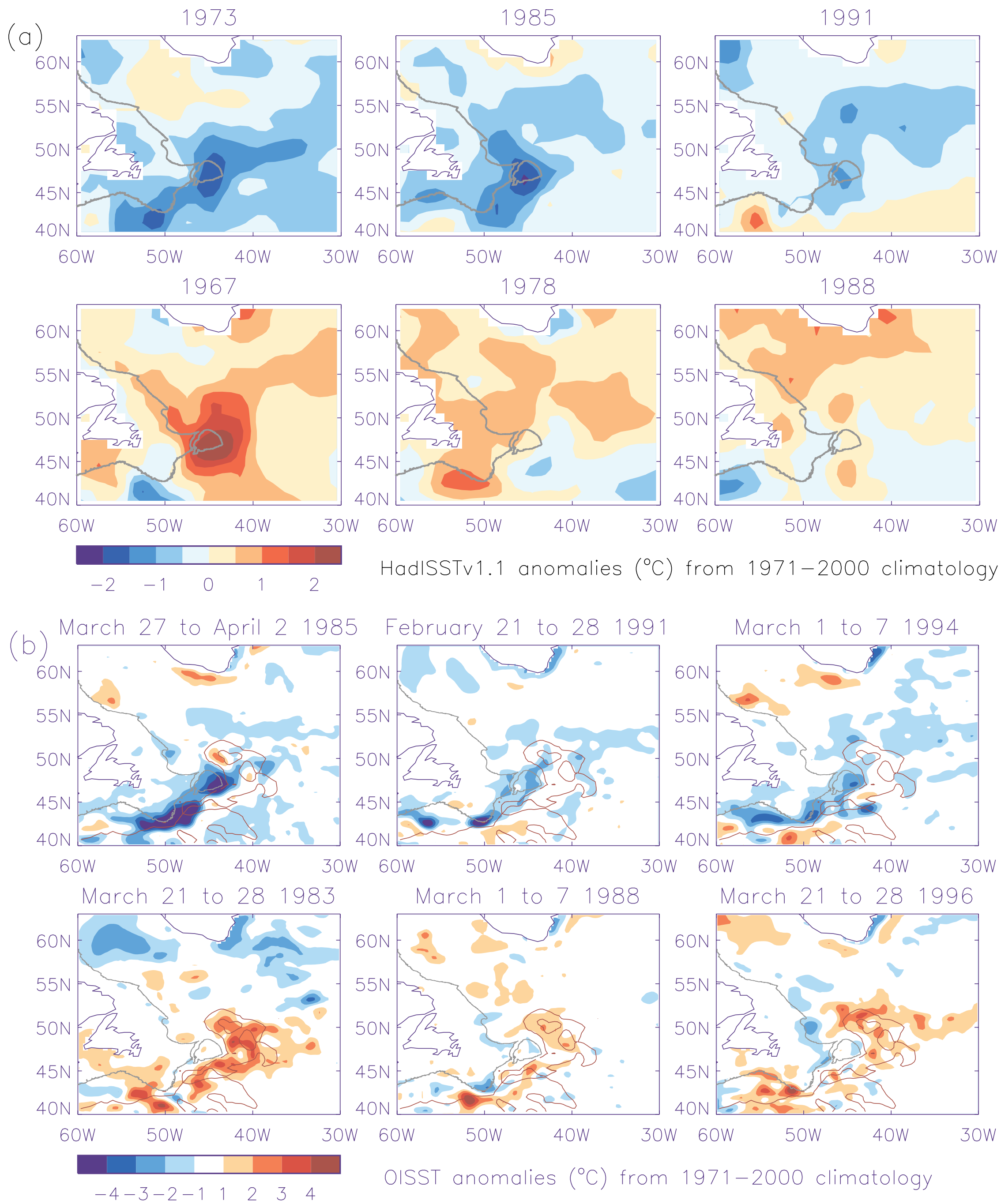

Fig. 3 Latitude–longitude plots of (a) HadISST SST anomaly for January–March mean in 1973, 1985 and 1991 (cold years at Flemish Cap) and 1967, 1978 and 1988 (warm years at Flemish Cap). (b) OISST SST anomalies in selected weeks of the cold years 1985, 1991 and 1994 and the warm years 1983, 1988 and 1996. The gray line overlay is the 1000 m isobath which marks the positions of Flemish Cap (centred on 47°N 45°W) and the Tail of the Grand Banks (43° N 50°W). The outline of the path of the NAC (red, based on Fig. 1) is added to Fig. 3(b).

in Fig. 5(a) (time vs latitude at 47°N) and Fig. 5(b) (time vs longitude at 44°W). Fig. 5(a) covers longitudes between the Newfoundland coast and the path of the NAC east of the Flemish Cap and demonstrates well-defined cold periods in the spring of the years around 1985 and 1990–1994 centred on 44°W but extending as far as 42°W, well within the path of the NAC (Fig. 1). The subsidiary cool region near 47°W seems likely to correspond to the Labrador Current (Fig. 1). It is apparent that between 1982 and 1986, the cold anomalies were generally much larger over the Flemish Cap than over the Labrador Current. The warm anomalies east of the Flemish Cap (43°W–40°W) most likely correspond to the surface component of the NAC (Mertens et al., 2014).

Fig. 5(b) covers latitudes between the south of the Flemish Cap and the coast of Greenland at 44°W and shows that in addition to the strong cold signals in the spring of years in

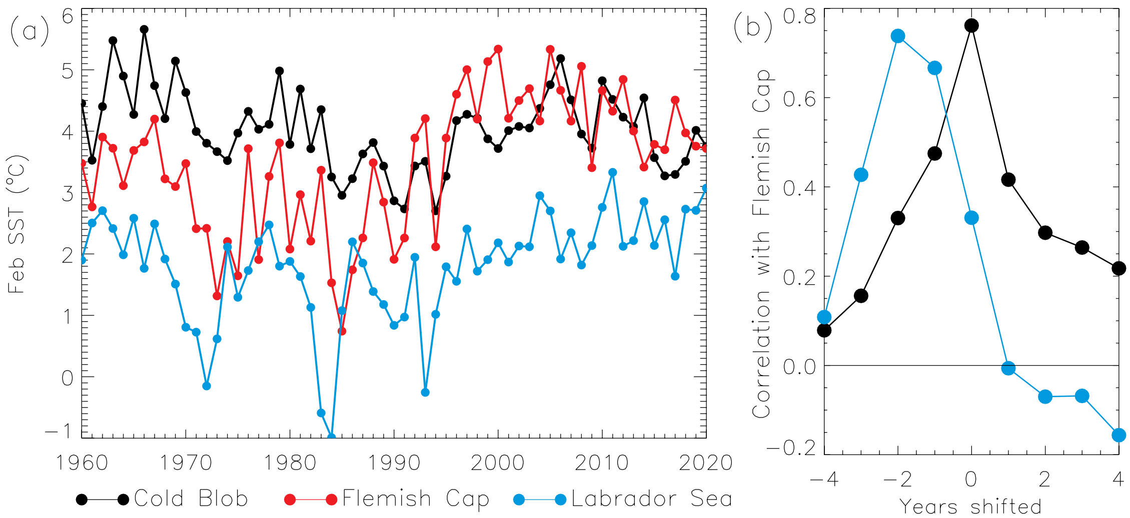

Fig. 4 (a) HadISST SST time series for February from 1960 to 2010 comparing Flemish Cap (47°N 45°W) with CB epicentre (54°N 43°W) and the southern Labrador Sea (60°N 55°W). (b) Variation in the correlation between the HadISST time series (1960–1990) for Flemish Cap and those for the Labrador Sea and CB epicentre when the latter two time series are shifted forwards or backwards in time relative to Flemish Cap.

the mid-1980s and early 1990s corresponding to the latitude of the Flemish Cap (47°N) it also shows a cold signal centred on 52°–56°N corresponding to the cool regions shown in Figs. 2–4(a) which would contribute to the CB. There is an apparent lateral correspondence between the cooling periods at the 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 the Flemish Cap and the CB (see also Fig. 4a). The distance between the Flemish Cap and the CB via Northwest Corner is about 900 km and the mean current velocity in the NAC is about 0.3 m s^{-1} (Fig. 1) so the transit time would be about a month so it would be difficult to see a significant time difference between the Flemish Cap and the CB in Fig. 5(b).

Fig. 5(c) compares bathymetry with OISST anomaly along a line at 47°W from 50°W to 40°W passing through the centre of the Flemish Cap. It illustrates the position of Flemish Pass (near 47°W), the plateau of the Flemish Cap (46°–44°W) and the steep slope between 44°W and 43°W descending to 4.5 km at 41°W. We compared the OISST SST anomaly data for 1983 and 1985 (respectively warm and cold years at the Flemish Cap) along this section to determine if cold anomalies moving east from the Flemish Cap could reach as far as the NAC. In May 1985, the greatest surface negative anomaly (−5.5°C) was observed at 43°W 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°W on the edge of the Flemish Cap plateau.

In contrast, in 1983 when there were marked positive anomalies in the NAC region (Fig. 4a) there was little evidence for cold anomalies at the Flemish Cap (45°W). In 1983 and other years (1980, 1988 Fig. 4a), when there was no cold anomaly at the Flemish Cap, there was still a small cold anomaly in the slope region (44°–43°W) (Fig. 4d) so that even in warmer years the slope waters were relatively cold. Thus waters from the 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 (Fig. 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 the Flemish Cap and the NAC.

c *The three major cold periods at the Flemish Cap and the CB are each associated with expansion of sea ice eastwards as far as the Flemish Cap.*

The results illustrated in Figs. 3–5 extend previous findings of a relationship between cold periods in the Labrador Sea and low temperatures in the SPNA (Deser & 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 (Allan & Allan, 2024). In each case, in subsequent years (1973–1974, 1984–1985, 1994) this anomalous Labrador Sea ice greatly diminished and was presumed to be carried south together with meltwater by the LC-Atlantic Current initially (Fig. 1).

Fig. 6(a) shows marked expansions of sea ice cover (SIC) and SIC anomaly in the Labrador Sea basin in 1972, 1983 and 1993 but as this ice disappeared in the Labrador Sea in the following year, there was increased ice near Newfoundland which extended as far as the Flemish Cap in 1973–1974, 1985 and 1993–1994, the coldest periods at the Flemish Cap (Figs. 3 and 4). 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 Fig. 1).

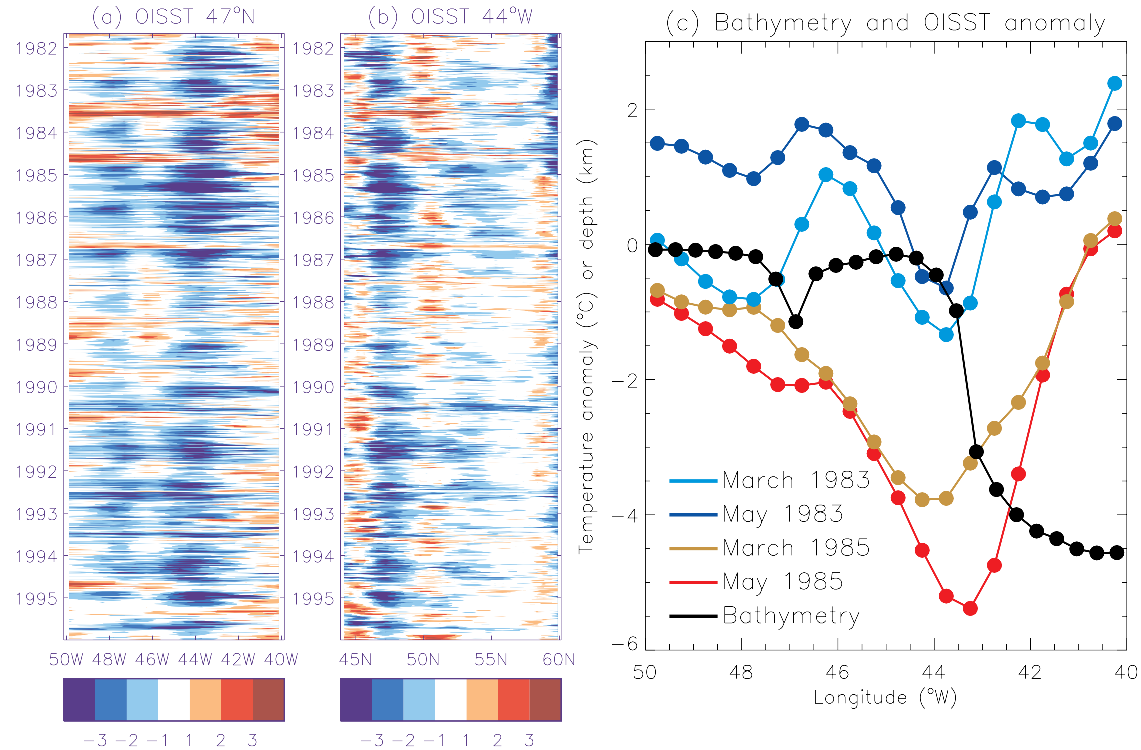

Fig. 5 OISST anomalies associated with Flemish Cap and the CB between 1982–1996: (a) time-longitude plot of OISST anomalies at 47°N between 50°W and 40°W; (b) time-latitude plot of OISST anomalies at 44°W between 45°N and 60°N. (c) Comparison of OISST anomalies with bathymetry in March and May 1983 and 1985 on a transect line at 47°N between 50°W and 40°W. Depth is shown in kilometres (black dots).

From Fig. 6(a), it appears that although the ice in the Labrador Basin started off in the LC-Atlantic (east of the 1000 m isobath) in 1972, 1983–1984 and 1993, the ice anomaly was subsequently largely transferred to the LC-Arctic (west of the 1000 m isobath) at a point around 55°N 54°W, far away from the point where the two currents combined (about 50°N 50°W, see Introduction). Possibly in the cold years there was a physical transfer of ice from the Labrador Sea basin (LC-Atlantic) to the LC-Arctic near 55°N 54°W but the mechanism of such a transfer is obscure. An alternative possibility is that much of the ice east of the 1000 m 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 the Flemish Cap and more icebergs survived to reach the Flemish Cap.

In Fig. 6(a), we illustrate the position (broken circle) of the Labrador Sea region of deep convection ~~region~~ (RDC) 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 RDC defined by Marshall (1998) for 1997 and Yashaeyev and Loder (2016, 2017) for 2002–2016 which had the highest thickness of Labrador Sea Water 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 RDC but still left it mostly as open water which would have allowed deep convection to occur in response to rapid intense surface cooling. The proximity of labile ice would have lowered the surface temperature in the RDC to near zero and contributed cold, low salinity meltwater which may have undergone deep convection in response to periods of strong ocean cooling in winter (Visbeck et al., 1995).

Fig. 6(b) compares the time series of mean March SIC in the Labrador Sea basin (box 1 in Fig. 6a) with that near the Flemish Cap (box 2) and shows that there is a 1–2 year lag between major peaks of SIC in the Labrador Sea (1972, 1983–1984, 1990–1991, 1993) and the Flemish Cap (1993–1994, 1985, 1993, 1994), similar to the lag for temperature shown in Fig. 4(a). The low temperature periods at the Flemish Cap and the CB (Fig. 4a) were therefore related to the progress of sea ice eastwards across the Flemish Cap although the maximum extent reached only as far as 45°W, far short of the NAC at 43°W. There were subsidiary Labrador Sea SIC peaks in 2009–2012 and thereafter but there was little evidence for corresponding peaks in ice near the Flemish Cap, consistent with the small changes in SST at the Flemish Cap over this period (Fig. 4a).

d *Drainage of anomalous Labrador Sea ice meltwater into the SPG follows the LC-Atlantic path*

Although it appears from Fig. 5 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

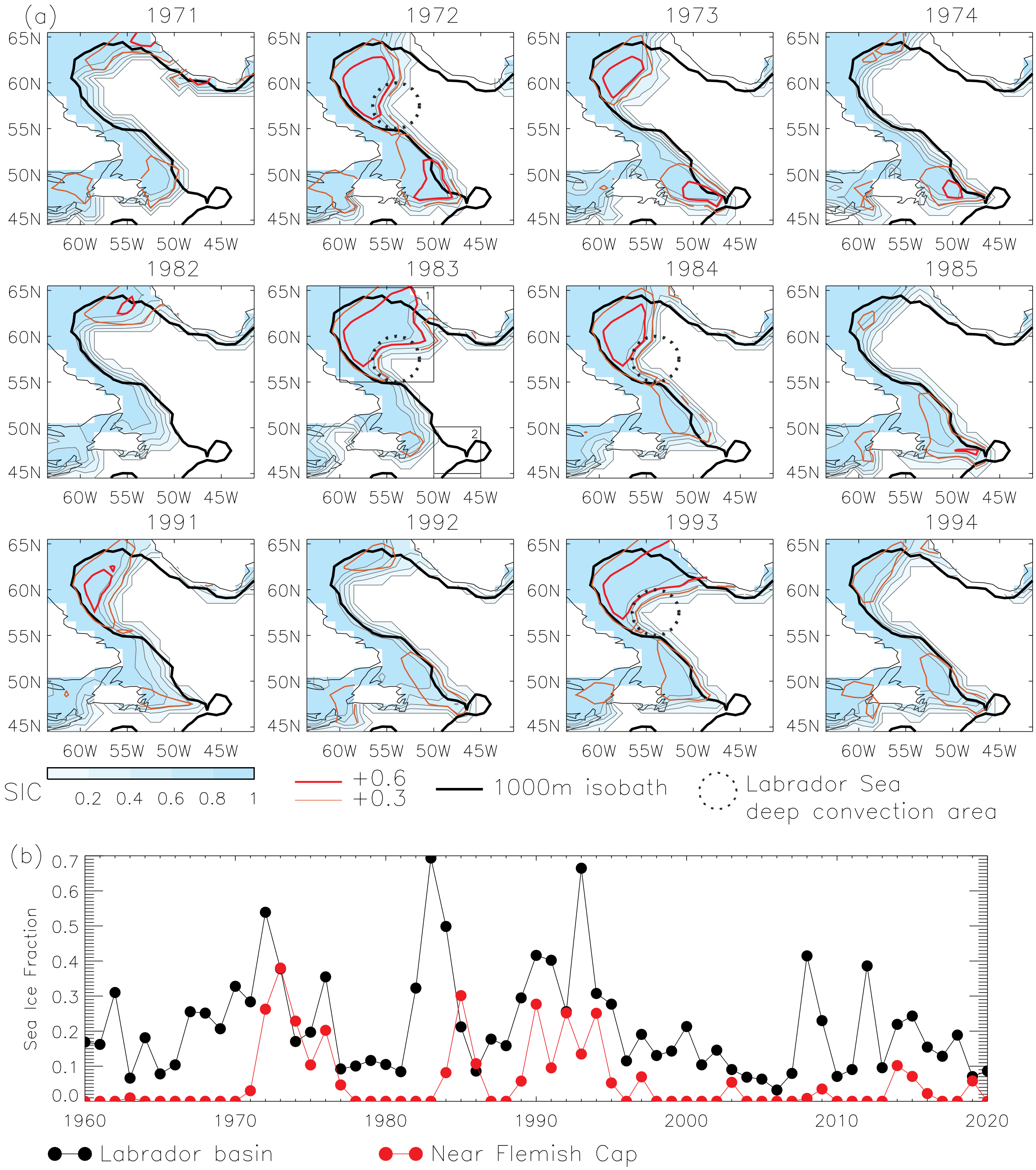

Fig. 6 (a) Sea ice fractional cover (SIC, HadISST2 dataset) in March of 1971–1974, 1982–1985 and 1991–1994 in the area between 45°–65°N and 65°–40°W. SIC is represented by blue shades and gray contours while SIC anomalies are represented by red (0.6) and brown (0.3) contours. The position of the 1000 m isobath is shown in black and defines the Labrador Sea basin and the position of Flemish Cap (elliptical region at 45°W). The position of the Labrador Sea deep convection region is shown as a dashed circle centred on 57°N 54°W. Boxes 1 and 2 shown for 1983 define respectively the areas corresponding to the Labrador Sea basin (55°–65°N 60°–50°W) and the area close to Flemish Cap (45°–50°N 50°–45°W). (b) Mean SIC time series from 1960 to 2020 comparing boxes 1, 2 in (a).

might be drained because this could possibly contribute to cooling of the SPNA and contribute to the CB. Allan and 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 (Belkin et al., 1998). 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 Fig. 6. On 8 September 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 the 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 1000 m isobath. This suggested that the initial drainage of the Labrador Sea meltwater was through the LC-Atlantic (slope) current (Fig. 1) and not the LC-Arctic (shelf) current which carries ice (Fig. 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 (Allan & Allan, 2024; Belkin et al., 1998). 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 SPNA before dispersing to the southeast and west by November 15.

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 (Fig. 5). There is a possibility that the meltwater corresponding to the Great Salinity Anomalies contributed to the CB but the timing of the meltwater efflux (October–November) does not fit the timing of the CB which was aligned to spring in years when sea ice (Fig. 6) and icebergs (Fig. 8) reached the Flemish Cap.

e *Did icebergs reach the Flemish Cap and did they enter the NAC?*

Although sea ice reached the Flemish Cap in certain years between 1970 and 1995, there is no evidence from Fig. 5 that ice reached as far as the NAC whose path runs west of the Newfoundland seamounts at 44°N and east of the Flemish Cap (Fig. 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 the Flemish Cap before melting. Recent modelling data suggests that only the very largest (>4×10^8 tonnes) icebergs calved in West Greenland could reach the 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 Fig. 8(a). 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 these observations relates only to 1965–1980. Further south, most icebergs were observed over the Flemish Cap and as far as the path of the NAC (Fig. 1) which was largely bounded by the 4000 m isobath, consistent with the work of Mertens et al. (2014) and Solodoch et al. (2020). The data in Fig. 8(b) shows that in the colder years 1972, 1985 and 1994 (Figs. 2a and 5a), iceberg numbers were high and many not only reached the 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 the Flemish Cap (Fig. 7b).

In the coldest years, icebergs also reached the area where the 4000 m isobath and the NAC come closest to the Flemish Cap (Fig. 8b). Indeed, the largest cold anomalies appear to be south of the Flemish Cap (Fig. 3) 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 the Flemish Cap (1972–1974, 1983–1985 and 1990–1994, Fig. 5b). 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'.

The Grand Banks appears to exclude most icebergs probably because it is relatively shallow (<100 m) and any relatively small icebergs which reached the Grand Banks would soon melt. Much of the Flemish Cap is deeper than 250 m and can accommodate larger icebergs. Exclusion of icebergs from the Grand Banks implies that most icebergs reaching 50°N have a draft larger than 100 m and thus exceed about 4×10^6 tonnes according to the classification of Parayil et al. (2022). Icebergs would only be excluded from the Flemish Cap if they had drafts larger than about 200 m (4×10^7 tonnes). From a modelling study of trajectories of icebergs calved from Jakobshaven (Illulissat) in West Greenland, Parayil et al. (2022) showed that only the very largest icebergs (initial mass >4×10^8 tonnes and calving draft >230 m) would survive as far as 47°N 43°W (east of the Flemish Cap and within the NAC region).

From the moorings data of Mertens et al. (2014) east of the Flemish Cap, the fast (20–30 cm s^{-1}) northward current characteristic of the NAC at the surface extends westwards as far as 43°W so icebergs which reached 43°W could be

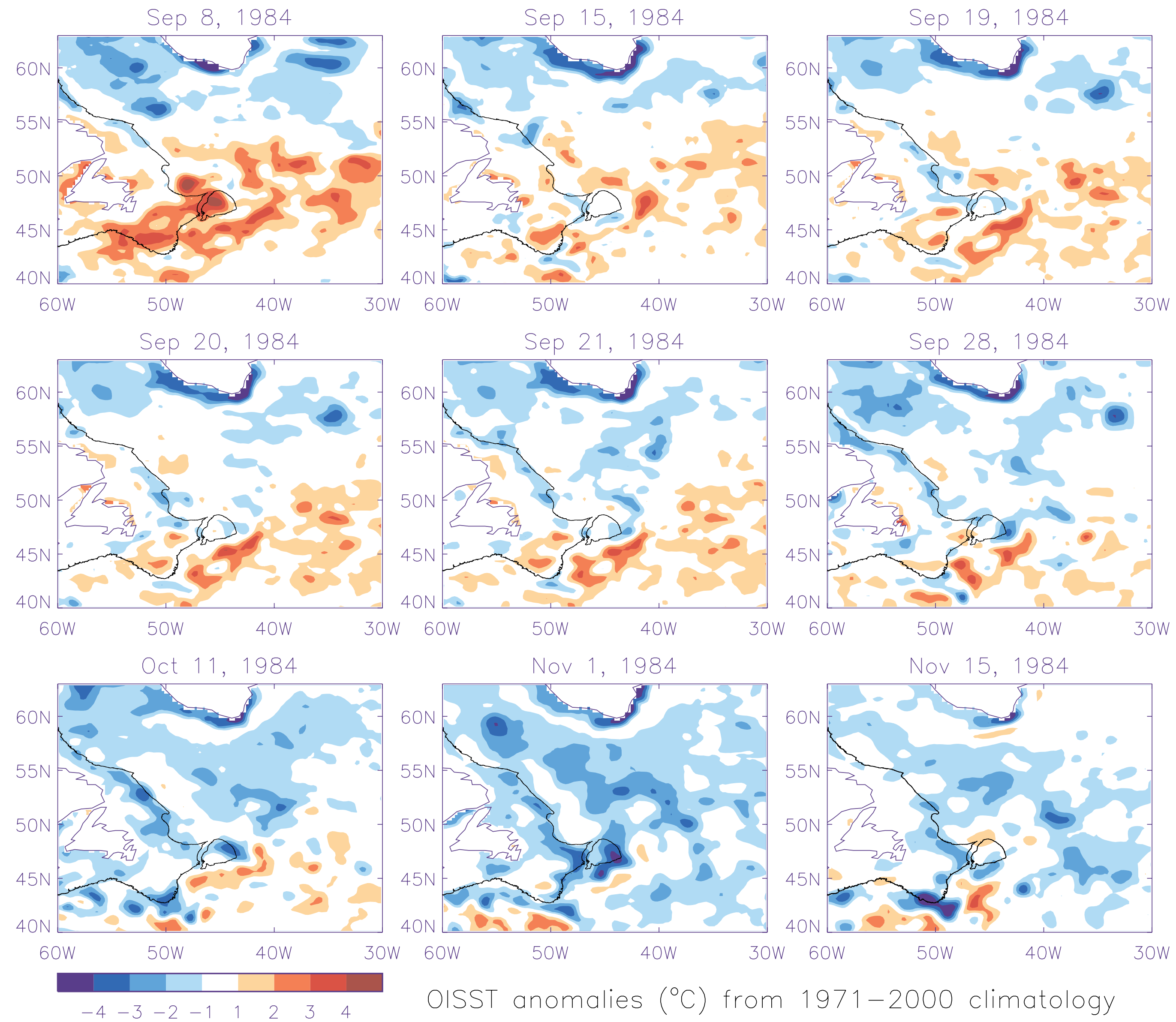

Fig. 7 Drainage of cold water from the southern Labrador Sea into the SPG in the fall of 1984. Changes in OISST SST anomaly are shown from 8 September 8 to 15 November 1984 during the final efflux of cold water from the southern Labrador Sea after melting of the ice accumulated in the 1983–1984 winter. The black line is the 1000 m isobath which represents part of the steep slope down to deep water (>3000 m) and is distinct from the Labrador shelf region (generally <400 m deep in this region).

drawn into the NAC. This is further evidence that in some years, introduction of icebergs and cold meltwater from the 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, Fig. 1) (Lazier, 1994; Rossby, 1996) passes near 53°N 45° W, not far from CB epicentre at 54°N 43°W (Fig. 1) so it is possible that delivery of cold water to the SPNA from the 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.

If icebergs can reach the Flemish Cap and enter the NAC, then equally, icebergs reaching the TGB are likely to enter the Gulf Stream/NAC a short distance east of the TGB and contribute to the cooling of the NAC which is subsequently transferred to the CB. There were cold anomalies near the TGB in years where there were strong cold anomalies near the Flemish Cap (Fig. 3). 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 the Flemish Cap

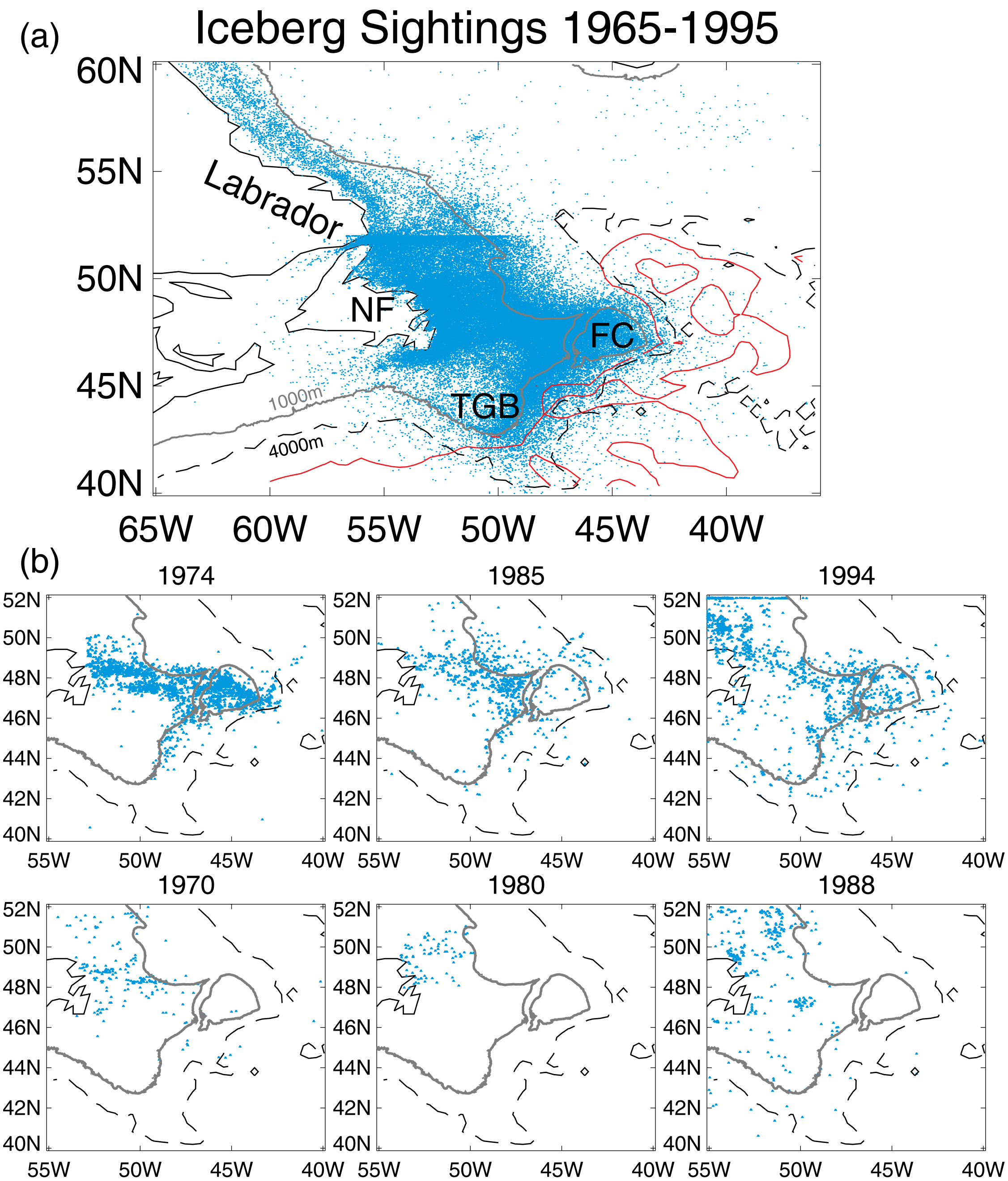

Fig. 8 (a) New icebergs plotted at their first sighting latitude and longitude between 1965 and 1995. Also included are the 1000 m isobath (gray line) to show the positions of the TGB (43°N 50°W) and the Flemish Cap (FC) (see Fig. 1), the 4000 m isobath (dashed line) and the outline of the path of the NAC (from Fig. 1). The discontinuity near 52°N is believed to be an observational artefact because 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. (b) Observed icebergs in |May 1972, 1985 and 1991 when temperatures at the Flemish Cap were unusually low and in 1970, 1980 and 1988 when temperatures were relatively high (see Fig. 4a).

as well as icebergs whereas no sea ice appears to get further south than 46°N (Fig. 6a). This would mean that icebergs transferred via the Flemish Cap to the NAC are more likely to survive than those entering via the Labrador Current along the shelf of the Grand Banks. However, the main conclusion to be derived from Fig. 8 is that in the particularly cold periods, some initially very large icebergs reached as far as the NAC east of the Flemish Cap whereas in warmer years, not only were there many fewer icebergs in total but none reached the Flemish Cap or the NAC.

4 Discussion

It was noted 30 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 et al., 2002; Deser & Blackmon, 1993). Consistent with this evidence, we show here that the three major periods of Labrador Sea ice expansion in the late twentieth century (Fig. 5) 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 (Fig. 4a), the epicentre of a region of long-term cooling we call the North Atlantic Cold Blob (CB; Fig. 2, see Introduction). Without these three cold periods between 1970 and 1995, there would have been no significant CB (Fig. 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 twentieth century cold periods in the data. Thus the 'century-long' cooling trend is really a trend that existed between 1970 and 1995, but not before or after. The long-term CB does include the 2014–2016 cold period, but this is a relatively small contributor to the overall negative gradient (Fig. 2f) and probably represents a different cooling mechanism occupying a different location as noted in the Introduction.

We observed also that temperatures at CB epicentre were well correlated with three similar but colder periods at the Flemish Cap (Figs. 1,3,4a), which occupy 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 (Fig. 1). It is initially surprising that there should be such a close link between temperature at the Flemish Cap and CB epicentre which are separated by 800 km of ocean, but there is evidence for a physical connection between cool surface water at the Flemish Cap and the CB in the three cold periods in the 1970s, 1980s and 1990s (Fig. 3). We propose that the link between the cold anomalies at the Flemish Cap and the CB is provided in part by the normal northward pathway of the NAC east of the Flemish Cap, via the gyre known as Northwest Corner (Figs. 1,3).

The important role of the 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 twentieth century. It was only in the coldest years at the Flemish Cap and the CB that unusually cold water (Fig. 3), sea ice (Fig. 6) and icebergs (Fig. 8) reached the Flemish Cap and icebergs were observed east of the Flemish Cap in the path of the NAC close to 43°W (Fig. 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 the 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 the Flemish Cap and the CB (Fig. 4) and for indications of continuity between cold regions near the Flemish Cap and those in the CB region (Fig. 3). There is a possibility that eddy transport and recirculation (Fratantoni & McCartney, 2010) from an unusually cold Labrador Current near the TGB cooled the NAC in 1970–1995 and there is evidence for enhanced cooling near the TGB extending into the NAC (Fig. 3b) in the colder years. It would be unsurprising if increased ice and icebergs in the LC-Arctic caused a cooling of the Labrador Current as far south as the TGB and this could contribute to cooling of the NAC even though ice and icebergs were less evident at the TGB than across the Flemish Cap. Thus we are open to the possibility that it was not just the Flemish Cap which contributed to the cooling of the NAC in 1970–1995 but also the normal sites of interaction between the Labrador Current and Gulf Stream/NAC near the TGB.

Each of the three main cold periods near the Flemish Cap (Fig. 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 (Fig. 6). It is a normal annual event for sea ice from Baffin Bay, Hudson Bay and the northern Labrador Sea to be carried in the LC-Arctic towards Newfoundland but in the 1970s, 1980s and 1990s, there were periods of high SIC anomaly over the Labrador Sea basin which is not usually ice-covered (Fig. 6). 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, 1983–1984 and 1993) with the highest SIC in the Labrador Sea basin (Fig. 6). Most icebergs in this region appear to have come from Baffin Bay or West Greenland, carried in the LC-Arctic (Wilton et al., 2015; Fig. 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 the Flemish Cap (Fig. 6). Based on the changes in SIC anomalies (Fig. 6), it appears that south of 55°N, little ice remained east of the 1000 m isobath (i.e. in the LC-Atlantic) but there were increases in sea ice in the LC-Arctic west of the 1000 m isobath and this extra ice would make it more likely that icebergs in the LC-Arctic would survive as far as the 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 the 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 the results shown in Fig. 6. 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 1000 m isobath (i.e. LC-Atlantic) south of 55°N (Fig. 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 the 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 the Flemish Cap, consistent with observations of large numbers of icebergs between 1960 and 1998 reaching further east than the Flemish Cap (Fig. 8a) while sea ice reached no further than the centre of the Flemish Cap (Fig. 6). The critical role of the 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 the 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 the 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 (Fig. 5) but some icebergs did reach the path of the NAC between the TGB and the Flemish Cap (Fig. 8a,b). However, in the cold years 1974, 1985 and 1994 (Fig. 8b) most of the icebergs appeared to be routed over and around the Flemish Cap so that the most important influences cooling and freshening the NAC would have been sea ice reaching the Flemish Cap and icebergs passing east of the Flemish Cap into the NAC. Icebergs reaching so far east would have been of the largest size with a calving draft approaching 250 m (Parayil et al., 2022) so would have been more likely to become grounded at some points on their journey south. This would slow their progress and could help to explain why there was a year's delay between temperature changes in the Labrador Sea and those at the Flemish Cap (Fig. 4a).

The connections between SST anomalies at the CB and sea ice and icebergs reaching the 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 Fig. 2a) so the negative anomalies registered were considerably less those we have measured at the Flemish Cap and the CB epicentre.

The three episodes of sea ice expansion in the Labrador Sea basin which contributed to 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 & 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 the 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 twentieth 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 the Flemish Cap (Fig. 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 the Flemish Cap and as far as the NAC could their cold influence be seen to be transferred to the CB via the NAC. We emphasize, however, that sea ice reaching the 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 melting in transit than the few percent which are visible near the Flemish Cap.

The Flemish Cap cold periods are more intense than those at the CB (Fig. 4a) so it might be anticipated that there would be a CB centred on the Flemish Cap. The reason for the absence of such a feature is that warmer periods at the Flemish Cap dominate the long-term trend there and render it positive (Fig. 2). This is consistent with the increasingly positive trends in this region after 1995 (Figs. 3b and 4b, c) and may be associated with the reduction in sea ice and icebergs reaching the Flemish Cap after 1995 (Figs. 5,7). A more fundamental reason for the cessation of the cold periods at the Flemish Cap and the CB is that the anomalous periods of ice expansion in the Labrador Sea no longer occurred (Fig. 6) because the precursor Odden ice ceased to form, probably associated with reductions in Arctic ice expansion after 1990 (Allan & Allan, 2024).

We note also that the mysterious Cold Intermediate Layer (CIL; see Introduction) 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 the CIL represents spring and summer iceberg meltwater, particularly because Moon et al. (2018) showed that iceberg meltwater tends to gather not at the surface but in a layer about 50–150 m below the surface which may be sustained into the fall. This behaviour is typical of the CIL which is a cold fresh layer 50–100 m below the surface often remaining through the summer. In contrast, melting sea ice would be expected to leave meltwater on the surface and not 100 m down. The existence of the CIL over the Flemish Cap is consistent with our demonstration here that icebergs reach the 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 the Flemish Cap and the NAC is the major factor. It seems unlikely that a primary cooling of the SPNA due to atmospheric influences could on three separate occasions in the late twentieth century transmit cold water to an even colder and more restricted area at the Flemish Cap (Figs. 3–5). We note that even recent proponents of the idea that atmospheric cooling is primary only ascribe 62% or 50% to this source (He et al., 2022; Li et al., 2022).

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 & Allan, 2024) 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 the 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 & 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 (He et al., 2022; Li 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 & 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 (Fig. 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 & Allan, 2019) when it is defined by cold water, ice and icebergs reaching the 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 preceding fall when there is no sea ice or icebergs (Fig. 7). Thus the CB and 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 & 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 the 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 (Fig. 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 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 (Marshall et al., The Lab Sea Group, 1998). There is previous evidence that variable sea ice over deep water can precondition the onset of deep convection over the Nordbukta in the Greenland Sea, one of the few other sites of deep convection in the Northern Hemisphere (Visbeck et al., 1995).

Strong deep convection in the Labrador Sea in the winter of 1972 occurred suddenly after a long period of shallow convection over the preceding decade (Lazier, 1980) and coincided with a marked increase in SIC close to the RDC (Fig. 6). A very large deep convection event (>2000 m) 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 the Flemish Cap although not on the scale of the 1990s event (Fig. 6).

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 (see Introduction). Our demonstration here of the connection between the CB and accumulation of ice and icebergs at the Flemish Cap raises the possibility that the CB has its origin in ice and iceberg meltwater carried to the SPNA via the NAC. However, this mechanism appears to be largely confined to the last decades of the twentieth century which does not support current attempts to link long-term cooling of the North Atlantic with twenty-first century reductions in AMOC and changes in N. Atlantic climate.

Disclosure statement

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