The Origin of the North Atlantic Clod Blob Revisited

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THE ORIGIN OF THE NORTH ATLANTIC CLOD BLOB REVISITED

By

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Dedicated to my future self and momentum transfer to the new waves.
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ABSTRACT

The cold blob refers to an observationally unprecedented, gyre-scale, record-breaking cold of mean surface temperature over the subpolar North Atlantic. Its anomalous cold feature goes against the rising trend of global mean surface temperature in the context of a warming climate. Observations show that the Atlantic cold blob emerged in early 2014 and can penetrate deeper into the ocean interior beyond 500m depths. A sudden drop in upper ocean heat content is associated with an accumulative increase in freshwater content. Prior works pointed out that intense surface forcing during two consecutive winters was a primary driver. We hypothesize that surface forcing alone is insufficient for the cold blob to persist. Our analysis shows, for the first time, that variations in the net surface heat fluxes cannot explain the decline in upper ocean heat content during 2014–2017. Therefore, surface forcing fails to explain the origin of the cold blob.

To investigate alternative mechanisms, non-assimilative simulations based on a coupled ocean-ice model (GFDL MOM5/SIS1) with two different atmospheric forcings (MERRA2 and ERA-interim) are employed to examine the transports of mass, heat, and freshwater within the cold blob area. Initial diagnosis verified that both model runs can reproduce the cold blob characteristics at similar magnitudes to Argo observations. Model results show a decreasing trend of heat transport at the southern boundary, implying that reduced poleward ocean heat transport likely accounts for the formation and persistence of the cold blob. This cooling signal from the south is accompanied by a freshening signal. Changes in the residual heat fluxes suggest that reduced warming for the subsurface layer at 100–700 m depths apparently occurred since 2006 before turning into enhanced cooling during late 2013. Variations in the residual freshwater fluxes remain positive for the entire past decade and subsequently result in an accumulative surplus of freshwater content in this area. The model run with incorporated Greenland meltwater estimates sheds light on the relative contribution of meltwater advection. To a great extent, Greenland meltwater can amplify the freshening tendency in the subpolar North Atlantic by approximately up to 200% during the present decade. In the long run, upper ocean cooling and freshening would lead to increased stratification and reduced mixing with deeper waters, therefore enhancing the likelihood that the subsurface cold blob persists.
CHAPTER 1
INTRODUCTION

Interaction between atmosphere–ocean–cryosphere in the Arctic–North Atlantic system plays a key role in regulating the global ocean thermohaline circulation with far-reaching influence on global climate [IPCC, 2013; Lozier, 2012; Lozier et al., 2017]. Changes in Arctic–Subarctic ocean fluxes of mass, heat, liquid freshwater, and ice can subsequently impact thermohaline and convective processes in the northern North Atlantic [Dickson et al., 2007; Dickson et al., 2008; Haine et al., 2015; Yashayaev et al., 2015]. The subpolar North Atlantic (SPNA) is of primary concern regarding a thermohaline catastrophe in terms of heat and freshwater disturbances [Stommel, 1961; Rooth, 1982; Welander, 1982; Bryan, 1986; Stommel, 1993; Whitehead, 2009].

In recent years, considerable attention has been paid to the polar–lower latitude linkage in the northern North Atlantic system [Jung et al., 2015; Böning et al., 2016], including the emergence of an observationally unprecedented cold anomaly—the Atlantic cold blob. The cold blob refers to a gyre-scale, record-breaking cold of mean surface temperature over the SPNA. This observationally unprecedented cold anomaly has persisted all year round in 2015 with potentially up to a 2 °C decline in the annual mean sea surface temperature (SST, Fig. 1.1). Observations from the Argo array show that the cold blob emerged and has persisted over the North Atlantic subpolar gyre since early 2014. Climate scientists have been fascinated by its anomalous cooling against the rising trend of global mean surface temperature in the context of a warming climate (Fig. 1.2). Several studies attempted to explain the underlying mechanisms behind the origin of the cold blob [e.g. Duchez et al., 2016a, 2016b; Yeager et al., 2016; Schmittner et al., 2016; Josey et al., 2018]. However, the cause of this persistent cold anomaly has remained not fully understood.

The cold blob has also been identified as part of a characteristic SST fingerprint of a weakening Atlantic Ocean overturning circulation. This observed fingerprint consists of a cooling in the subpolar gyre region due to reduced heat transport and a warming in the Gulf Stream region due to a northward shift of the Gulf Stream [Caesar et al., 2018; Rahmstorf et al., 2015; Drijfhout et al., 2012]. Given that the North Atlantic subpolar gyre is further freshening through accelerated melting of Greenland ice sheet and Arctic sea ice, it is of considerable concern that the proximity of the persistent cold blob is still poorly known.
Figure 1.1: The cold blob in the subpolar North Atlantic as seen by 2015 annual mean surface temperature anomalies derived from NASA/GISS and Roemmich-Gilson Argo products.

Figure 1.2: Time series of Argo monthly mean SST anomaly over the subpolar North Atlantic (SPNA) (blue line) versus NASA/GISS global mean surface temperature anomaly (red line). SPNA SST experienced a record breaking cold in 2015 against the rising trend of global mean surface temperature.
Variations in SST are basically governed by the heat balance in the ocean mixed layer involving heat exchange through the air-sea interface and subsurface ocean heat transport. There are various explanations across multi-timescale perspectives that describe the variability and trend of SPNA ocean temperatures. This chapter briefly explores related works regarding possible mechanisms (i.e., surface forcing and meltwater advection), and the aspects of the long-term (decadal and interdecadal) and short-term (subannual and interannual) variability in which various independent processes interact.

1.1 Long-term Variability of the Subpolar North Atlantic

The North Atlantic subpolar gyre is known as a key region where the northern limb of the Atlantic Meridional Overturning Circulation (AMOC) drives North Atlantic Deep Water (NADW) formation and ultimately the overturning circulation. The AMOC is a key means by which heat anomalies are sequestered into the ocean interior and modulates the trajectory of climate change.

Thermohaline circulation in the oceans is controlled by freshwater flux and thermal forcing through the air-sea interface. The physical processes involved in these two components of forcings are quite different. The possibility of multiple solutions for thermohaline circulation is initially recognized in the concept of two-box model [Stommel, 1961]. Hitherto, Stommel’s two-box model did not receive much attention until 20 years after its introduction when climate scientists began to seek for possible mechanisms for different climate conditions throughout the geological times. The seminal Stommel’s two-box model was then revised and extended into numerous versions, including the flip-flop oscillator by Welander [1982], the salt regulator theory by Stommel [1993], a three-box model by Rooth [1982] and Bryan [1986], a four-box model by Stone and Krasovskiy [2011], and was later demonstrated and proved in laboratory experiments by Whitehead [2009].

Several studies suggested that fluctuations in the AMOC have been linked to low-frequency variability of SPNA SSTs [e.g. Lozier, 2012; Buckley and Marshall, 2016]. On intra-annual timescales, variability in AMOC is large and primarily reflects the response to local wind forcing; meridional coherence of anomalies is limited to that of the wind field. On interannual to decadal timescales, AMOC changes are primarily geostrophic and related to buoyancy anomalies on the western boundary of the ocean basin.
Variability of the SPNA SST anomaly and its association with changes in the AMOC have been documented [e.g. Buckley et al., 2012; Buckley et al., 2014]. The so-called Atlantic warming hole located at the central SPNA is directly related to the AMOC strength on multidecadal to centennial timescales [Drijfhout et al., 2012; Menary and Wood, 2017]. A recent unprecedented weakening stage of the AMOC seems to be predominantly influenced by human-induced climate change as an external forcing [Rahmstorf et al., 2015]. This implies that the observed SPNA cooling trend is plausibly initiated by an anthropogenic reduction in the AMOC strength and poleward heat transport. Alternatively, the recent AMOC slowdown is believed to be part of decadal variability [Jackson et al., 2016] and the SPNA cooling is linked to record low densities in the deep Labrador Sea where a long-term freshening also plays a role [Robson et al., 2016].

The cold blob is primarily thought to be an abrupt cooling of the North Atlantic subpolar gyre. This rapid cooling appears to be consistent with a collapse of the local deep-ocean convection based on a model ensemble study under the fifth Coupled Model Intercomparison Project (CMIP5) framework [Sgubin et al., 2017]. Still, whether the cold blob is part of decadal variability remains unclear due to varying representation of the subpolar gyre stratification in climate model simulations.

**1.2 Short-term Variability of the Subpolar North Atlantic**

The North Atlantic Oscillation (NAO) is known as the first mode of atmospheric variability, with the largest variability in the cold season. It predominantly forces North Atlantic SSTs at seasonal to interannual time scales. The NAO generates SST anomalies mainly by surface air-sea turbulent heat exchanges and upper ocean mixed layer changes. A positive NAO is followed by negative SST anomalies in the SPNA and off the eastern coast of North Africa, as well as positive SST anomalies in the western subtropical gyre. This pattern is generally referred to as the SST tripole [Hurrell et al., 2003] with an opposite phase for a negative NAO.

Numerous studies have established a link between decadal SPNA SST variability and ocean thermohaline circulation changes driven by cumulative winter NAO buoyancy forcing [McCarthy et al., 2015; Delworth et al., 2016]. Positive winter NAO anomalies are associated with anomalous turbulent heat loss from the SPNA upper ocean and anomalous Ekman transports that tend to cool the SPNA, and negative anomalies are associated with anomalies of the opposite sign [Deser et al., 2010].
Yeager et al. [2016] proposed that the North Atlantic cold blob was a result of consecutive responses to intrinsic NAO variability regulating at distinct timescales. First, a slow response associated with the cumulative effect of the frequent weak and negative winter NAO conditions in the post 1995 decades (winters between 1996 and 2013) results in persistent ocean-driven reduction of SPNA upper ocean heat content and, at last, the recent AMOC spindown [Yeager et al., 2015]. Second, a fast response associated with the recent strong and positive winter NAO conditions in recent years (winters of 2014 and 2015) gives rise to atmospheric extraction of heat and perturbation of surface ocean currents (Ekman transport). Meanwhile, the intrinsic variability of NAO forcing likely contributed to prominently enhanced cooling rates in the SPNA through anomalous air-sea heat flux and Ekman effects.

The NAO not only modulates short-term climate variability, but also excites some consequences in long-term climate variability. Climate models showed that observed multidecadal NAO variations can induce multidecadal AMOC variations and subsequently result in extended poleward ocean heat transport from the North Atlantic to the Arctic [Delworth et al., 2016]. These findings suggest that transport through both the western and southern boundaries are of interest.

### 1.3 Surface Forcing

An initial investigation of the unprecedented North Atlantic cold blob pointed out that intense surface forcing during two consecutive winters 2013/14 and 2014/15 was a primary driver, causing extreme heat loss that primarily induced the cold blob to form [Duchez et al., 2016a; Duchez et al., 2016b]. Similarly, the cold blob feature is consistent with a re-emerged cold subsurface anomaly that was driven by extreme surface heat loss in winter 2013/14 [Grist et al., 2016] and in the subsequent winter 2014/15 further extreme heat loss was observed but displaced northwards from that seen in winter 2013/14. The 2014/15 heat loss is associated with a prolonged positive state of the NAO, which is characterized by stronger westerly winds resulting from an intensification of the meridional surface pressure gradient. Consequently, the SPNA experienced severe heat loss to the atmosphere. Specifically, low SST in the subpolar gyre was explained through variability in surface cooling, not by reduced heat advection [de Jong and de Steur, 2016]. This finding will be re-examined in chapter 3.
1.4 Meltwater Advection

Alternatively, temperature advection and freshwater fluxes could influence the cold blob and might have different timing than the surface forcing. Freshwater fluxes from the melting of Greenland Ice Sheet (GIS) is evidently increasing [Bamber et al., 2012; Box and Colgan, 2013; Haine et al., 2015; Yang et al., 2016] and may be impacting the ocean’s thermohaline and convective processes in the North Atlantic. GIS is considered to be the reservoir that stores the largest amount of freshwater in the northern high latitudes. The Beaufort Gyre in the Arctic Ocean also shows a growing freshwater content [Proshutinsky et al., 2015]. Freshwater accumulation is among priority concerns regarding the role and consequences of changing freshwater fluxes within the Arctic–North Atlantic system. The driving mechanism for freshwater accumulation in the North Atlantic subpolar gyre also remains unclear since the geostrophic field is divergent in a cyclonic gyre.

Prior work showed that freshwater from western and eastern GIS has markedly different fates on a decadal timescale [Gillard et al., 2016]. GIS freshwater entering the interior of the Labrador Sea originates mainly from east Greenland, whereas freshwater from west Greenland predominantly accumulates in Baffin Bay before exported southward along the Labrador Shelf. Furthermore, a new estimate of the recent freshwater flux from Greenland using updated GRACE satellite data suggested that recent freshening in the vicinity of Greenland is likely reducing the formation of dense Labrador Sea Water (LSW) and potentially weakening the AMOC strength [Yang et al., 2016].

Buckley and Marshall [2015] suggested that the gyre circulation is responsible for transporting freshwater into the North Atlantic basin to satisfy the freshwater budget, while the overturning circulation transports freshwater out of the basin. Hence, the AMOC is potentially unstable because a reduction in its strength is expected to decrease the salinity of the North Atlantic and potentially further decrease NADW formation. However, such arguments assume that the gyre circulation does not adjust to changes in the AMOC, an assumption that is questionable given that the mean gyre circulation currently transports freshwater into the Atlantic Basin, compensating for the freshwater export by the atmosphere and the AMOC.
1.5 Detailed Research Questions

The origin of the persistence of the cold blob is still not fully understood. Our hypothesis is that the wintertime surface air-sea heat fluxes alone cannot have maintained the cold anomaly all year round over 2014–2016. We speculate that the freshwater fluxes from the ongoing melting of Arctic sea ice and Greenland ice sheet can be a key mechanism responsible for the persistent cold blob to form. This research aims to investigate the relative contribution of freshwater content in the origin and development of the cold blob and to illustrate the possible pathways of freshwater. One of the reasons that prior work has focused on surface fluxes rather than advection is that the geostrophic field is divergent in a cyclonic gyre, preventing any advection into the region.

Specific questions are (1) What mechanisms are responsible for surface cooling? (2) Is the subsurface ocean important to the heat budget for the cold blob? (3) How does the subsurface ocean contribute to the cold blob? and (4) How does the meltwater advection contribute to the cold blob? The first two questions will be addressed by examining the energy budget for the cold blob region. This approach will demonstrate the relative importance of surface heat fluxes and ocean heat advection and will address the behavior and timescale of their contributions. The latter two questions focus on temperature and salinity advection, providing some insights into the nature of the energy and freshwater budgets.
CHAPTER 2

OBSERVATIONS AND CHARACTERISTICS OF THE COLD BLOB

2.1 Introduction

Since the cold blob was recognized largely based on its 2015 record breaking cold of annual mean surface temperature, there has been no consensus regarding its exact definition and specific location. We define our study area and methodology for characterizing the cold blob in section 2.2 and describe the data sets in section 2.3. Oceanographic features of the cold blob are discussed in sections 2.4 and 2.5.

2.2 Methodology for Characterizing the Cold Blob

The cold blob predominantly covers most parts of subpolar gyre in the North Atlantic. In this study, the cold blob area is primarily defined by its 2014–2016 mean SST anomaly map (Fig. 2.1). The anomalies are relative to the 2004–2015 mean SST. We specify a grid box that highlights the area with relatively high magnitude cold anomalies. It is located around the central part of the subpolar gyre between 45–60°N and 20–40°W. All statistical calculations will be based on this specified grid box in order to avoid some highly chaotic features from the Gulf Stream near Newfoundland.

To determine the anomalies of geophysical variables along the surface and ocean column, data are statistically standardized by removing the seasonal cycle determined from the monthly mean climatology for the period of 2004–2015. This means the term ‘anomalies’ of all oceanographic and meteorological parameters in this study is statistically relative to 2004–2015 climatology. This 12-year period climatology is chosen because of changes in the reliability of the ocean observing system, which are mentioned and elaborated on in the next section. Additionally, this climatology can better represent and capture the recent climate variability and trend during the past decade.
Figure 2.1: 2014–2016 mean sea surface temperature anomaly (SST) in the subpolar North Atlantic. The dashed grid box highlights the location of the cold blob where the record breaking cold anomaly exists. This area is located around the central subpolar gyre between 45–60°N and 20–40°W.

Some calculations related to thermodynamic conversion of oceanic variables are processed using TEOS-10 GSW toolbox version 3.05 [IOC et al., 2010; McDougall and Barker, 2011]. Specifically, ocean heat content and freshwater content are calculated based on the following formulas:

\[
OHC = C_p \rho_o \int_{-h}^{0} (T - T_{ref}) \, dz \\
FWC = -\frac{1}{S_{ref}} \int_{-h}^{0} (S - S_{ref}) \, dz
\]

respectively, where \(OHC\) is ocean heat content in J m\(^{-1}\), \(FWC\) is freshwater content in m of water, \(C_p\) is the specific heat capacity of seawater, \(\rho_o\) is the seawater density at sea level pressure, \(h\) is water depth, \(T_{ref}\) is a reference temperature and \(S_{ref}\) is a reference salinity. In this study, averaged 12-year period of 2004–2015 is used as a baseline for the reference temperature and 35 psu is chosen as the reference salinity for the North Atlantic.
2.3 Data Sets

The Atlantic cold blob has been seen from several global surface temperature products. Both in situ and satellite observations can detect the existence of the persistent cold blob at a comparable magnitude (not shown here). The data sets mainly used in this section are based on Argo and quality controlled subsurface ocean temperature and salinity analyses (EN4) products. The first data set is known as the Roemmich-Gilson Argo Climatology, which is grounded from optimal interpolation described in Roemmich and Gilson [2009]. It is an Argo-only product obtained from Scripps Institution of Oceanography (http://sio-argo.ucsd.edu/). We also check the sampling density and show that the number of monthly Argo profiles is sufficient year round in this region (Fig. 2.2).

The second data set is a compilation of a variety of ocean profiling instruments since early 20th century by UK Met Office Hadley Centre (https://www.metoffice.gov.uk/hadobs/en4/). It is quality controlled using objective analyses with uncertainty estimates described in Good et al. [2013] together with a new correction scheme based on Gouretski and Reseghetti [2010]. Data coverage includes Argo, World Ocean Database (WOD), and all other available observational systems across the global oceans (e.g. the Beaufort Gyre Experiment).

![Figure 2.2: The sampling density of Argo monthly profiles in the central subpolar North Atlantic.](image)
2.4 Characteristics of the Cold Blob

The magnitude of the cold blob’s monthly mean SST anomalies can be as large as approximately -2°C, as seen in 2015 (Fig. 2.3). This extreme goes beyond regional variations during the past decade. However, its accompanying mean sea surface salinity anomalies were not revealed when the cold blob was initially documented. The change in sea surface salinity lagged the change in SST.

In addition to its surface characteristics, observations show that the oceanic cold blob emerged and has persisted over the central subpolar North Atlantic since early 2014 (Fig. 2.4). Hovmoller plots based on Argo data display the evolution of ocean temperature and salinity anomalies of the cold blob from the surface through mid-depths. The cold anomaly can penetrate deeper into the ocean interior beyond 500 m depth. For the first time, we show that the cooling and freshening tendencies in the upper ocean are apparently associated with the warmer and saltier layers at mid-depths below (1000-2000 m). Hence, it appears likely that surface freshening leads to surface cooling through increased stratification. This surface freshening likely originates in early 2010 as a result of 2009 summer melt season. Therefore, there might be some relationship between cooling and freshening signals in this region.

![Figure 2.3: Time series of standardized anomalies of monthly mean sea surface salinity (SSS, blue) and sea surface temperature (SST, orange) within the cold blob area (45–60°N, 20–40°W) from the Argo gridded product.](image-url)
We then look closer at the upper 500 m ocean profiles of key thermodynamic parameters, i.e. absolute salinity, potential temperature, potential density, and spiciness. (Figs. 2.5 and 2.6). A Hovmoller plot of absolute salinity demonstrates, for the first time, strong pulses of freshwater in the central subpolar gyre since 2010. This fresher-than-usual surface water penetrates down to deeper depths and modulates the subsurface salinity content in later years. In addition to surface freshening, a Hovmoller plot of potential temperature also shows that wintertime surface cooling appears to be more pronounced during the 2013/14 and 2015/16 winters. Accordingly, the combined surface cooling and freshening generate a chimney of well-mixed convecting column as seen by strong layer outcropping and thickened surface isopycnal layers (pycnostads) during 2014–2016. Although there is some density compensation between cooling and freshening signals, a Hovmoller plot of spiciness confirms the same depth profile patterns.

The analysis of subsurface ocean temperature and salinity profiles shows some relationship between ocean heat content and freshwater content in the North Atlantic subpolar gyre (Fig. 2.7). The anomalies of depth-integrated ocean heat content and freshwater content between upper 700 m and 2000 m depths are relatively not different, suggesting that the cooling and freshening disturbances are primarily constraint in the upper 700 m depth. We demonstrate, for the first time, that a sudden drop in the upper ocean heat content is associated with an accumulative increase in the freshwater content. Contrary to the past decade, there is evidence of increased freshwater content accumulating in the central subpolar gyre in recent years (Fig. 2.8).

This finding illustrates that freshwater export from higher latitudes can influence the heat and salt budgets in the upper ocean mixed layer where the persistent cold blob emerged. Meanwhile, this freshened upper ocean lens might somehow reduce the vertical ocean heat transfer from beneath the thermocline depth, leading to positive climate feedback mechanisms of reduced warming and enhanced cooling over the region.

Sea surface height anomaly can be used as a measure of the subpolar gyre strength [Hakkinen and Rhines, 2004]. We also explore the relationship between sea surface height and ocean heat content anomalies, and show that both anomalies are well correlated but the relationship becomes relatively weaker when the cold blob emerged since early 2014 (Fig. 2.9). It implies that the cooling and freshening signals can apparently interfere some dynamic and thermodynamic processes behind the subpolar gyre mechanisms.
Figure 2.4: Hovmoller plots of standardized anomalies of monthly mean temperature (upper) and salinity (lower) within the cold blob area (45–60°N, 20–40°W) from the Argo gridded product. The Y-axis is the water column from the surface to 2000 m depth.
Figure 2.5: Hovmoller plots of monthly mean salinity (upper) and potential temperature (lower), within the cold blob area (45–60°N, 20–40°W) from the Argo gridded product. The Y-axis is the water column from the surface to 500 m depth.
Figure 2.6: Hovmoller plots of monthly mean potential density (upper) and spiciness (lower) within the cold blob area (45–60°N, 20–40°W) from the Argo gridded product. The Y-axis is the water column from the surface to 500 m depth.
Figure 2.7: Time series of standardized monthly mean anomalies of ocean heat content (upper) and freshwater content (lower) within the cold blob area (45–60°N, 20–40°W) from Argo gridded product. Different colored lines indicate different reference depths to which the anomalies are calculated and integrated from the ocean surface.
Figure 2.8: Freshwater content relative to 35% isohalines in the subpolar North Atlantic during the period 2004–2006 compared to the period 2014–2016. An increase in freshwater content in the central gyre has been noticed in recent years.

Figure 2.9: Time series of standardized monthly mean of AVISO sea surface height anomaly and Argo ocean heat content anomaly. The relationship becomes relatively weaker since the cold blob emerged in early 2014.
2.5 Chapter Summary

Observations show that the Atlantic cold blob emerged and has persisted over the central subpolar North Atlantic since early 2014. The cold anomaly can penetrate deeper into the ocean interior beyond 500m depth. The cooling and freshening tendencies in the upper ocean are apparently associated with the warmer and saltier layers at mid depths below (1000–2000 m). A sudden drop in upper ocean heat content is associated with an accumulative increase in freshwater content. There is an evidence of increased freshwater content accumulating in the central subpolar gyre in recent years. However, the sources of freshwater export from higher latitudes still remain unknown.
CHAPTER 3
SURFACE FORCING

3.1 Introduction

Previous works pointed out wintertime surface cooling as a primary driver of the cold blob [Duchez et al., 2016a, 2016b; de Jong and de Steur, 2016; Grist et al., 2015; Josey et al., 2018]. However, our hypothesis is that surface forcing alone is insufficient for the cold blob to persist year round during 2014–2017. This chapter will revisit the potential of surface forcing as the origin of the persistent cold blob by reinvestigating the surface air-sea fluxes of heat and freshwater over the subpolar North Atlantic. We detail our methodology in section 3.2 and describe the data sets in section 3.3. The roles of surface thermal forcing and atmospheric freshwater input are discussed in section 3.4.

3.2 Methodology for Examining the Surface Forcing

The cold anomalies are apparently associated with the freshening signals over the region (recall Fig. 2.4). We look at the surface forcing to examine whether the anomalous features of the cold blob can be explained by surface air-sea exchange. In this context, changes in upper ocean heat content must be explained by the variation of net surface air-sea heat fluxes, and changes in upper ocean freshwater content must be explained by the variation of net atmospheric freshwater fluxes. Our analysis is based on the year 2004 forward in corresponding to oceanographic data in previous chapter.

We compare the area integration terms of net surface heat fluxes versus upper ocean heat content as follows:

\[ \iint OHC \, dA \propto \iint Q_{\text{net}} \, dA \, dt \]

and net atmospheric freshwater fluxes versus upper ocean freshwater content as follows:

\[ \iint FW C \, dA \propto \iint (P - E) \, dA \, dt \]
where $OHC$ is the upper ocean heat content integrated to a reference depth. $Q_{\text{net}}$ is the net surface heat fluxes, $P - E$ is net atmospheric freshwater flux, $FWC$ is the upper ocean freshwater content at a reference depth, and $A$ is a domain study area as described in previous chapter.

### 3.3 Data Sets

The net surface air-sea heat fluxes ($Q_{\text{net}}$) is the sum of net shortwave radiation ($nSW$), net longwave radiation ($nLW$), sensible heat flux ($SHF$), and latent heat flux ($LHF$) as follows:

$$Q_{\text{net}} = nSW + nLW + SHF + LHF$$

where all heat fluxes have the convention of being positive downward into the ocean. In this study, we combine two data sets from two different reliable sources. The first two terms are surface radiative heat fluxes obtained from the National Aeronautics and Space Administration (NASA) Clouds and the Earth’s Radiant Energy System (CERES) version 4.0 [Kato et al., 2013]. The latter two terms are surface turbulent heat fluxes obtained from Woods Hole Oceanographic Institute (WHOI) Objectively Analyzed air-sea Fluxes for the Global Oceans (OAFlux) version 3 [Yu and Weller, 2007]. These two products were gridded at $1^\circ \times 1^\circ$.

The net atmospheric freshwater fluxes are referred to as precipitation minus evaporation (P–E). In this study, we use total precipitation and evaporation synoptic monthly means from European Reanalysis (ERA) interim product [Dee et al., 2011] from the European Centre for Medium-Range Weather Forecasts (ECMWF).

In addition, ocean vector winds are obtained from Cross-Calibrated Multi-Platform Ocean Surface Wind Vector Analyses (CCMP) version 2 [Atlas et al., 2011]. The CCMP v2 processing combines intercalibrated radiometer wind speeds, QuikSCAT and ASCAT scatterometer wind vectors, moored buoy wind data, and ERA-Interim model wind fields, and applies a Variational Analysis Method to produce $0.25^\circ$ gridded vector winds. This data set is obtained from Remote Sensing Systems (http://www.remss.com/).
3.4 Surface Forcing Analysis

Our analysis of surface air-sea heat fluxes shows extreme heat loss during two consecutive winters, 2013/14 and 2014/15 (Fig. 3.1). This was mainly due to surface turbulent heat fluxes caused by relatively greater storminess (Fig. 3.2). Wintertime extreme heat loss over this region is primarily storm-induced. The area of strong heat loss in winter 2013/14 covered the whole part of subpolar gyre where the cold blob emerged, while that in winter 2014/15 the area covered only the northern part of the gyre (i.e., the Irminger and Labrador Seas) with accompanying strong heat gain over the large area below. There could be some compensation between heat loss and heat gain over this region during winter 2014/15, subsequently resulting in the claim that extreme heat loss is a primary driver of the persistent cold blob is invalid.

We then analyze if there is a relationship between surface thermal forcing and ocean heat storage over this region. Fig. 3.3 shows a comparison between area-integrated net surface heat fluxes versus area-integrated upper ocean heat content. In general, the variations in area-integrated net surface heat fluxes are much smaller than the variations in area-integrated ocean heat content. It apparently suggests that there was a relationship breakdown since 2014, if it ever existed. Meanwhile, variations in net surface heat fluxes cannot explain a sudden drop in upper ocean heat content over this region in recent years. We confirm this finding by replacing the net surface heat fluxes to different data sets, e.g. NCAR/NCEP (Fig. 3.4) and ECMWF/ERA-interim (Fig. 3.5). Our argument is still valid.

Similar to surface thermal forcing, we also investigate the atmospheric freshwater fluxes. Fig. 3.6 shows a comparison between area-integrated net atmospheric freshwater fluxes versus area-integrated upper ocean freshwater content. Noted that the variations in area-integrated upper ocean freshwater content are by two orders of magnitude greater than the variations in area-integrated atmospheric freshwater input (evaporation minus precipitation). Like surface thermal forcing, the same argument holds true. Variations in atmospheric freshwater fluxes cannot explain the continuing rise of upper ocean freshwater content over this region in recent years. An accumulative increase in upper ocean freshwater content can be noticed since 2010. Therefore, surface forcing does not explain the origin of the cold blob.
Figure 3.1: Dec-Jan-Feb means of net surface, turbulent and radiative heat fluxes in 4 consecutive winters during 2013–2016 over the subpolar North Atlantic from NASA/CERES and WHOI/OAFlux products. The right column is net radiative heat fluxes that are relatively small. Extreme heat loss (blue shaded contour) during winters 2013/14 and 2014/15 was identified as a primary driver of the cold blob.
Figure 3.2: Probability density functions (PDFs) of CCMP monthly mean wind speeds over the subpolar North Atlantic in recent years (colored solid line) compared to 2000–2017 mean (black line). Dec-Jan-Feb 2014 and 2015 PDFs show relatively higher storminess over this region.
Figure 3.3: Time series of area-integrated net surface heat fluxes versus upper ocean heat content based upon 100 m (upper) and 700 m (lower) reference depths. Both parameters are converted into Joule for comparison. Dotted lines display 12-month running means. Net surface heat fluxes are from combined WHOI/OAFlux and NASA/CERES products. It clearly suggests that variations in surface thermal forcing cannot explain the decline in ocean heat content during 2014–2016 as previously documented.
Figure 3.4: As in Fig. 3.3 but the net surface heat fluxes are from NCAR/NCEP product.
Figure 3.5: As in Fig. 3.3 but the net surface heat fluxes are from ERA-interim product.
Figure 3.6: Time series of area-integrated net atmospheric freshwater fluxes versus upper ocean freshwater content based upon 100 m (upper) and 700 m (lower) reference depths. Both parameters are converted into km$^3$ for comparison. Data sets are from ERA-interim product. It clearly suggests that variations in net atmospheric freshwater fluxes cannot explain the accumulative increase in upper ocean freshwater content over the subpolar gyre region.
3.5 Chapter Summary

Strong surface cooling in two consecutive winters, 2013/14 and 2014/15, was suggested in prior work as a primary driver of the cold blob. We revisited the potential of surface forcing to justify whether the cold blob was initiated by surface air-sea exchange. Our analysis shows that variations in surface thermal forcing alone cannot explain the decline in upper ocean heat content during 2014–2016. Likewise, variations in atmospheric freshwater fluxes cannot explain the accumulative increase in upper ocean freshwater content. Therefore, the origin of the persistent cold blob is not fully understood. Alternative mechanisms must be within the subsurface ocean transports.
CHAPTER 4
HEAT AND FRESHWATER BUDGETS

4.1 Introduction

Since air-sea surface fluxes do not explain the origin of the North Atlantic cold blob, alternative mechanisms must be within the subsurface ocean. Prior work shows that melting of the Greenland Ice Sheet has only a relatively small impact on SST over the North Atlantic, therefore surface meltwater fluxes are unlikely to have influenced the cold blob [Schmittner et al., 2016]. Our hypothesis is that upper ocean cooling and freshening signals seen in the cold blob are due to subsurface ocean transports from higher latitudes, regardless of their origins whether it is Greenland ice sheet, Arctic sea ice, or river discharges. We speculate that upper ocean cooling and freshening may lead to increased stratification and reduced mixing with deeper waters, therefore enhancing the likelihood that subsurface cold blob persists. Occasional wind-induced mixing could expose these cold waters.

This chapter will determine the heat and salt budgets in the surface mixed layer of the ocean within the cold blob area. We expect to identify the source and pathways of colder and less salty than-usual waters that could potentially be the origin of the cold blob. We explain our methodology in section 4.2 and describe the data sets in section 4.3. Results in the materials covered in this chapter are most of the work remaining to complete. We estimate the timeline of our study in section 4.4.

4.2 Methodology for Examining the Heat and Freshwater Budgets

The transfer of mass, momentum, and energy across the surface ocean mixed layer where turbulent mixing processes are energetic provides the source of almost all oceanic motions in the upper ocean. The thickness of the mixed layer determines the mechanical inertia of the layer that directly interacts with the atmosphere. The depth of the surface ocean mixed layer can vary in both space and time.

We determine the ocean transports of heat and salt in the ocean’s mixed layer with the aim of tracking changes in energy and freshwater fluxes coming in and going out the cold blob area.
Ocean heat and freshwater transports are calculated based on Bacon and Fofonoff [1996] and Bacon et al. [2015] as follows:

\[ Q = \int \int \rho C_p \theta v \, dA = \int \int \frac{C_p \theta v}{g} \, dx dp \]

\[ F = \int \int \rho \left(1 - \frac{S}{S_{ref}}\right) v \, dA \]

respectively, where \( Q \) is ocean heat transport in \( J \, s^{-1} \), \( F \) is freshwater transport in \( kg \, s^{-1} \), \( C_p \) is the specific heat capacity of water, \( \rho \) is the seawater density, \( \theta \) is the potential temperature, \( v \) is the meridional or zonal velocity of ocean currents, \( S_{ref} \) is a reference salinity and \( A \) is a cross section area. Different procedures in calculating the mixed layer depths based on temperature and salinity criterions for heat and salt budget analysis are applied separately based on the fact that temperature and salinity profiles in the ocean mixed layer have different characteristic thicknesses.

Recall that surface forcing fails to explain the origin of the cold blob. We expect that changes in mixed layer ocean heat budget must be explained by ocean heat transports and changes in the mixed layer salt budget must be explained by freshwater transports. In addition to tracking freshwater fluxes in the Arctic-North Atlantic system, we also calculate freshwater exports through the Davis and Denmark Straits in order to identify the possible pathways of the ocean anomalies. We also consider the ocean transports from lower latitudes to examine if there is any signal from the Gulf Stream system. It is possible that a large spatial scale atmospheric forcing influences transport from higher latitudes simultaneous with modification of transport from lower latitudes, and that a mixing of two different water masses is needed to explain the cold blob.

### 4.3 Data Sets

Model simulations are employed to obtain ocean vector currents, temperature, salinity, and surface air-sea heat fluxes. We choose model simulations from Simple Ocean Data Assimilation (SODA) reanalysis products [Carton and Giese, 2008; Carton et al., 2018a; Carton et al., 2018b]. Although earlier versions of SODA were initiated as ocean reanalysis products by implementing
a data assimilation scheme, new generations of SODA also deliver non-assimilative simulation under the Ocean Model Intercomparison Project (OMIP) framework.

SODA version 3 uses the coupled Modular Ocean Model (MOM) version 5 and Sea Ice Simulator (SIS) version 1 with eddy permitting resolution (1/4° x 1/4° x 50 vertical levels). This horizontal resolution is approximately equivalent to 28km at the equator down to less than 10km at polar latitudes. Both MOM and SIS were developed at the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory (NOAA/GFDL). This has been a major upgrade from earlier versions that were based on Parallel Ocean Program (POP).

Two sets of model simulations with different forcing and bulk formula are chosen in this study (Table 4.1). These sets of simulations were run using the same reanalysis system and initial conditions, but with forcing provided by different atmospheric reanalyses. SODA3.3.0 and SODA3.4.0 are OMIP simulations beginning with the same initial conditions and subject to the same forcing as SODA3.3.1 and SODA3.4.1, respectively. The only difference is that there is no data assimilation. Furthermore, SODA3.4 simulations were run with incorporating Greenland discharge estimates based on Bamber et al. [2012]. This could possibly simulate more realistic freshwater fluxes within the Arctic-North Atlantic system. Each set of simulations contains monthly ocean state variables and surface air-sea fluxes mapped onto the regular Mercator horizontal grid at 50 vertical levels spanning the period 1980–2015.

<table>
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<tr>
<th>Simulation</th>
<th>Data Assimilation</th>
<th>Forcing</th>
<th>Bulk Formula</th>
<th>Years</th>
</tr>
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<td>MERRA2</td>
<td>Large-Yeager</td>
<td>1980–2015</td>
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<tr>
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<td>MERRA2</td>
<td>COARE4</td>
<td>1980–2015</td>
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<tr>
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<td>ERA-Interim</td>
<td>Large-Yeager</td>
<td>1980–2015</td>
</tr>
<tr>
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<td>yes</td>
<td>ERA-Interim</td>
<td>Large-Yeager</td>
<td>1980–2015</td>
</tr>
<tr>
<td>SODA 3.4.2</td>
<td>yes</td>
<td>ERA-Interim</td>
<td>COARE4</td>
<td>1980–2015</td>
</tr>
</tbody>
</table>

Table 4.1: Model simulations with their forcing and bulk formula

ERA-Interim: European Reanalysis Interim by the European Centre for Medium-Range Weather Forecasts (ECMWF)
MERRA2: Modern-Era Retrospective analysis for Research and Applications version 2
COARE4: Coupled Ocean–Atmosphere Response Experiment (COARE) bulk algorithm 4
Our initial diagnosis shows that SODA3.3 and SODA3.4 series can reproduce the cold blob in terms of ocean anomalies of temperature (Figs. 4.1 and 4.2) and salinity (Figs. 4.3 and 4.4) at similar magnitudes to the Argo observations. Moreover, we also validate the skills of two different non-assimilative model simulations (SODA3.3.0 and SODA3.4.0) in reproducing the ocean heat and freshwater content anomalies found in the Argo product (Fig. 4.5). Both model runs give fairly good agreement with observation regarding area averaged changes in heat and freshwater storage. Additionally, the modeled net surface heat fluxes are verified with CERES/OAFlux and NCAR/NCEP (Fig. 4.6). Noted that two simulations were run using different atmospheric forcings. SODA3.3.0 ran with Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA2), whereas SODA3.4.0 used European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis Interim (ERA-Interim).

At this point, we have ensured that both assimilative and non-assimilative simulations are appropriate for further analysis in ocean mixed layer heat and salt budgets. We expect to be able to identify the surfaces through which heat and salinity modify the cold blob. This would set the stage for future work to trace those backwards in time to indicate a possible source of the water contributing to the cold blob. We also examined different criteria in specifying the upper ocean mixed layer depths and its spatio-temporal changes using temperature, salinity, and density points of view. Nevertheless, since the cold blob involves with prominent cooling and freshening aspects, we decided to stick with a density criterion. In this study, the mixed layer criterion is defined as the depth at which potential density gradient relative to the one at a near-surface reference depth is greater or equals to 0.03 kg m\(^{-3}\).

With respect to budget analysis, we first calculate the ocean transports of mass, heat and freshwater coming into the cold blob from the two different non-assimilative model simulations. The cold blob area and boundaries are defined consistently with observations in Section 2.2 (recall Fig. 2.1). Signs are flipped at the northern and eastern boundaries in such a way that the incoming fluxes into the cold blob area become positive. The SI units are then converted into Sverdrup (Sv). Noted that 1 Sverdrup equals to \(10^9\) kg s\(^{-1}\) or \(10^6\) m\(^3\) s\(^{-1}\). Then, we perform a budget analysis of heat and freshwater in the upper ocean, and look for a possible explanation regarding the cooling and freshening signals involving with the origin and time evolution of the persistent cold blob.
Figure 4.1: Hovmoller plots of standardized anomalies of monthly mean ocean temperature within the cold blob area (45–60°N, 0–20°W) from non-assimilative SODA3.3.0 (upper), assimilative SODA3.3.1 (middle) and Argo gridded product (lower). The Y-axis is the ocean column from the surface down to 2000 m depth.
Figure 4.2: Hovmoller plots of standardized anomalies of monthly mean ocean temperature within the cold blob area (45°–60°N, 0°–20°W) from non-assimilative SODA3.4.0 (upper), assimilative SODA3.4.1 (middle) and Argo gridded product (lower). The Y-axis is the ocean column from the surface down to 2000 m depth.
Figure 4.3: Hovmoller plots of standardized anomalies of monthly mean ocean salinity within the cold blob area (45–60°N, 0–20°W) from non-assimilative SODA3.3.0 (upper), assimilative SODA3.3.1 (middle) and Argo gridded product (lower). The Y-axis is the ocean column from the surface down to 2000 m depth.
Figure 4.4: Hovmoller plots of standardized anomalies of monthly mean ocean salinity within the cold blob area (45–60°N, 0–20°W) from non-assimilative SODA3.4.0 (upper), assimilative SODA3.4.1 (middle) and Argo gridded product (lower). The Y-axis is the ocean column from the surface down to 2000 m depth.
Figure 4.5: Comparison of the upper 700 m ocean heat (upper) and freshwater (lower) content anomalies within the cold blob area between Argo product (black solid line) and two different non-assimilative model simulations (colored solid lines).
4.4 Analysis of Heat and Freshwater Budgets

Transports of mass, heat, and freshwater within the cold blob area are examined using non-assimilative model simulations (SODA3.3.0 and SODA3.4.0). We illustrate the time series of mass versus heat transports (Figs. 4.7 – 4.10) and then mass versus freshwater transports (Figs. 4.11 – 4.14). Initially, we calculated the upper ocean mixed layer depth based on density criterion. In the subpolar gyre, the mixed layer depths vary greatly and range between roughly 50 m and 150 m (recall Fig. 2.6). However, the cold blob can penetrate deeper beyond the local mixed layer depths and is apparently constrained in the upper 700m (recall Fig. 2.7). We then decided to perform the budget analysis using certain reference depths rather than mixed layer depths, to better account for the vertical extent of the cold blob.

First, we examine the heat budget in the upper 700m ocean mixed layer of the cold blob. At the western boundary (Fig. 4.7), both simulations show that the mass transport slightly increases while changes in the heat transport remain unnoticeable. It apparently suggests that more mass transports at this location come with a fraction of meltwaters and its colder than usual properties. At the eastern and northern boundaries (Figs. 4.8 and 4.9), variations in the mass and heat transports remain roughly constant. At the southern boundary (Fig. 4.10), both simulations show
a decreasing trend of mass and heat transports. Accordingly, the cooling signal can be inferred from the reduced poleward ocean heat transport which likely accounts for the formation and persistence of the cold blob.

Second, we investigate the freshwater budget in the analogous framework with the heat budget. At the western boundary (Fig. 4.11), model results demonstrate that the freshwater transports, unlike the heat transport, go along with the mass transports. Both mass and freshwater transports clearly display an increasing trend. At the eastern boundary (Fig. 4.12), variations in the mass transports remain unnoticeable whereas reduced freshwater imports are obviously seen. At the northern boundary (Fig. 4.13), there are no long-term variations in both mass and freshwater fluxes. At the southern boundary (Fig. 4.14), the mass transports illustrate a declining trend, while the freshwater transports show a long term rising trend. Consequently, model simulations suggest that freshening signals come from the west and the south.

Next, we include the net surface fluxes in a budget analysis of heat and freshwater in the upper 700m depths. The residual heat fluxes based on different reference depths are calculated (Fig. 4.15). This term is referred to a combination of the vertical heat fluxes from larger scale motions, convective mixing and entrainment. Apparently, there is a decreasing trend of the residual heat fluxes, indicating stronger downward transport of heat. We subsequently subtract \( Q_{\text{res,100m}} \) from \( Q_{\text{res,700m}} \) to eliminate the seasonal wind induced turbulent mixing in the upper 100m depths (Fig. 4.16). The long term declining trend in the residual heat fluxes suggests that reduced warming for the 100 m to 700 m layers occurred since 2006 and turned into enhanced cooling with a sudden drop during late 2013 and early 2014.

For freshwater budget, the residual freshwater fluxes are calculated (Fig. 4.17). Note that the net atmospheric freshwater input, known as evaporation minus precipitation (E–P), is comparatively small and negligible. The residual freshwater fluxes remain positive for the entire period, resulting in an accumulative surplus of freshwater content in this area (Fig. 4.18). Furthermore, we compare the freshwater storage in the cold blob area between two simulations (Fig. 4.19). Both simulations show that increased freshwater storage over the subpolar gyre grows up substantially during the present decade and continues rising. As SODA3.4.0 run incorporated Greenland meltwater estimates based on Bamber et al. [2012], approximate 200% difference in FW storage in the current decade could imply the relative contribution of Greenland meltwater.
Figure 4.7: Mass versus heat transports in the upper 700 m ocean depths along the western boundary of the cold blob area from SODA3.3.0 (upper) and SODA3.4.0 (lower) simulations. Noted that 1 Sverdrup (Sv) equals to $10^9$ kg s$^{-1}$ or $10^6$ m$^3$ s$^{-1}$. 
Figure 4.8: As in Fig. 4.7 but for the eastern boundary of the cold blob area.
Figure 4.9: As in Fig. 4.7 but for the northern boundary of the cold blob area.
Figure 4.10: As in Fig. 4.7 but for the southern boundary of the cold blob area.
Figure 4.11: Mass versus freshwater transports in the upper 700 m ocean depths along the western boundary of the cold blob area from SODA3.3.0 (upper) and SODA3.4.0 (lower) simulations. Noted that 1 Sverdrup (Sv) equals to $10^9$ kg s$^{-1}$ or $10^6$ m$^3$ s$^{-1}$.
Figure 4.12: As in Fig. 4.11 but for the eastern boundary of the cold blob area.
Figure 4.13: As in Fig. 4.11 but for the northern boundary of the cold blob area.
Figure 4.14: As in Fig. 4.11 but for the southern boundary of the cold blob area.
Figure 4.15: Residual heat fluxes in the upper ocean of the cold blob area calculated with different reference depths from SODA3.3.0 (upper) and SODA3.4.0 (lower) simulations.
Figure 4.16: Residual heat fluxes between 100–700 m subsurface layers of the cold blob area from SODA3.3.0 (upper) and SODA3.4.0 (lower) simulations.
Figure 4.17: Residual freshwater fluxes in the upper 700 m ocean depths of the cold blob area calculated from SODA3.3.0 (upper) and SODA3.4.0 (lower) simulations.
Figure 4.18: Comparison between the net ocean transport, net atmospheric input and freshwater storage in the upper 700 m ocean depths of the cold blob area from SODA3.3.0 (upper) and SODA3.4.0 (lower) simulations. All terms are converted into cubic meter for comparison. The net atmospheric input is comparatively small and negligible.
4.5 Chapter Summary

Surface forcing fails to explain the origin of the cold blob. We hypothesize that upper ocean cooling and freshening signals seen in the cold blob are mainly due to subsurface ocean transports. Two different non-assimilative model simulations are employed to investigate the transports of mass, heat, and freshwater within the cold blob area. Initial diagnosis verified that both model runs can reproduce the cold blob characteristics at comparable magnitudes with Argo observation.

Analysis of heat and freshwater budgets is carried out with the aims of identifying the possible sources and pathways of the water contributing to the cold blob. Model results show a decreasing trend of mass and heat transports at the southern boundary, implying that reduced poleward ocean heat transport likely accounts for the formation and persistence of the cold blob. Furthermore, increased freshwater fluxes are found at the western and southern boundaries.

Heat budget analysis reveals a change in the residual heat fluxes and suggests that reduced warming occurred since 2006 and turned into enhanced cooling with a sudden drop during late 2013 and early 2014. For freshwater budget, the residual freshwater fluxes remain positive for the entire past decade and subsequently results in an accumulative surplus of freshwater content in
this area. Increased freshwater storage over the North Atlantic subpolar gyre grows up substantially during the present decade and continues rising. The simulation with incorporating Greenland meltwater estimates based on Bamber et al. [2012] reveals that approximate 200% amplification in freshwater storage in the present decade could imply the relative contribution of Greenland meltwater. Accordingly, upper ocean cooling and freshening would lead to increased stratification and reduced mixing with deeper waters, therefore enhancing the likelihood that subsurface cold blob persists.
CHAPTER 5
DISCUSSION AND CONCLUSIONS

The cold blob refers to an observationally unprecedented, gyre-scale, record-breaking cold of mean surface temperature over the subpolar North Atlantic. Its persistent cold anomaly has drawn attention against the rising trend of global mean surface temperature under the context of a warming climate. Several studies attempted to explain the underlying mechanisms behind the origin and evolution of the cold blob [e.g. Duchez et al., 2016a; Duchez et al., 2016b; Yeager et al., 2016; Schmittner et al., 2016; Josey et al., 2018]. However, the origin of the persistent cold blob is not fully understood.

Observations show that the Atlantic cold blob emerged and has persisted over the central subpolar North Atlantic since early 2014. The cold anomaly can penetrate deeper into the ocean interior beyond 500 m depths. The cooling and freshening tendencies in the upper ocean are apparently associated with the warmer and saltier layers at mid depths below (1000–2000 m). A sudden drop in upper ocean heat content is associated with an accumulative increase in freshwater content. There is an evidence of increased freshwater content accumulating in the central subpolar gyre in recent years.

Intense surface cooling in two consecutive winters 2013/14 and 2014/15 was suggested in prior works as a primary driver of the cold blob [Duchez et al., 2016a; Duchez et al., 2016b; Grist et al., 2016; de Jong and de Steur, 2016]. We revisited the potential of surface forcing to justify whether the cold blob was initiated by surface air-sea exchange. Our analysis shows, for the first time, that variations in surface thermal forcing alone cannot explain the decline in upper ocean heat content during 2014–2016. Likewise, variations in atmospheric freshwater fluxes cannot explain the accumulative increase in upper ocean freshwater content. Therefore, surface forcing fails to explain the origin of the cold blob.

To investigate alternative mechanisms, we hypothesize that upper ocean cooling and freshening signals seen in the cold blob are mainly due to subsurface ocean transports. Two different non-assimilative model simulations are employed to investigate the transports of mass, heat, and freshwater within the cold blob area. Initial diagnosis verified that both model runs can reproduce the cold blob characteristics at similar magnitudes to Argo observations.
Analysis of ocean transports of heat and freshwater in the upper 700 m depths from two different model simulations provides some insights regarding the possible sources and pathways of the water contributing to the cold blob. Model results show a decreasing trend of heat transports at the southern boundary, implying that reduced poleward ocean heat transport likely accounts for the formation and persistence of the cold blob. Furthermore, increased freshwater fluxes are found at the western and southern boundaries, suggesting that freshwater likely comes from higher latitudes through the Labrador Sea and enters the subpolar gyre loop before accumulating in the region.

Heat budget analysis reveals a change in the residual heat fluxes and suggests that reduced warming for the 100–700 m layers occurred since 2006 and turned into enhanced cooling with a sudden drop during late 2013 and early 2014. For freshwater budget analysis, the residual freshwater fluxes remain positive for the entire past decade and subsequently results in an accumulative surplus of freshwater content in this area. Increased freshwater storage over the North Atlantic subpolar gyre grows up substantially during the present decade and tends to continue rising. The excess freshwater could be from 3 main sources: Arctic sea ice loss, Greenland ice sheet melting, and increased river runoff. The model simulation with incorporating Greenland meltwater estimates based on Bamber et al. [2012] reveals that approximate 200% amplification in freshwater storage in this region during the present decade could imply the relative contribution of Greenland meltwater. Accordingly, upper ocean cooling and freshening would lead to increased stratification and reduced mixing with deeper waters, therefore enhancing the likelihood that subsurface cold blob persists.
REFERENCES


BIOGRAPHICAL SKETCH

Tachanat Bhatrasataponkul grew up in Thailand and always enjoys various aspects of life. His fascination with the ocean stems from his childhood spent reading Japanese comic books and Greek Mythology. He received his bachelor’s and a master’s degrees in marine science from Chulalongkorn University where he was hooked on oceanography with an initial intention to escape the lecture rooms and involve being outdoors. It was too late when he later realized that physics behind the ocean motions is not easy at all. He dived deeper into the various subjects of geophysical fluid dynamics and became passionate about high latitude oceanography. He then got selected as a finalist for the Royal Thai Government Scholarship to pursue a higher degree aboard.

Upon completion of his Ph.D. in Physical Oceanography at the Florida State University, he will resume his position as a faculty at the School of Marine Technology, Burapha University where he taught basic oceanography and meteorology classes before coming to the United States.

Throughout his academic endeavor, he always sought for a reasonable excuse to learn new things at different parts of the world. He got selected to many competitive summer schools, e.g. NASA/JPL Summer School (Pasadena, CA), DAMTP/FDSE Summer School (Paris, France), Alpine Summer School (Valsavarenche, Italy), Ocean Salinity Workshop (Hamburg, Germany), MOMSEI Summer School (Qingdao, China), IOC/IOGOOS Workshop (Perth, Australia), FAMOS Workshop (Woods Hole, MA), GRC Ocean Mixing Workshop (Andover, NH) and Graduate Climate Conference (Pack Forest, WA).

Struggles and setbacks in graduate school made him become a fitness enthusiast with deep curiosity in exercise, nutrition, and biohacking secrets. He earned many professional credentials from several top-notch fitness industries, e.g. National Academy of Sports Medicine (NASM), National Strength and Conditioning Association (NSCA), American Council of Exercise (ACE), International Sports Sciences Association (ISSA), and Precision Nutrition (PN).

During his teenage years, he participated in numerous extracurricular activities at both national and international levels until he was awarded the 2004 Thailand National Outstanding Youth Award. He is truly a world wanderer having been to more than one third of the world across 5 continents in his early 30s. He shared his success journey as a chapter in the pocketbook entitled "Beyond What If" which has become an Amazon international bestseller.