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An inflated subpolar gyre blows life toward the northeastern Atlantic

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ABSTRACT

Deep convection in the Labrador and Irminger Seas inflates the cold and low-saline subpolar gyre, which is a rich nutrient and zooplankton source for the surrounding warmer waters of subtropical origin. The zooplankton abundances on the south Iceland shelf show characteristic sub-decadal variability, which closely reflect the oceanic abundances of the ecologically most important zooplankton species – *Calanus finmarchicus*. Much higher abundances of this species are observed during years when the winter mixed layer depths (MLD) in the Labrador-Irminger Sea, and over the Reykjanes Ridge are deep. Furthermore, a tight relationship is identified between on-shelf zooplankton abundances and lateral shifts of the biologically productive subarctic front southwest of Iceland. Thus, we suggest that northeastward expansion of the subpolar gyre results in biologically productive periods in the waters southwest of Iceland – both oceanic and on the shelf. In addition to local atmospheric forcing, we find that the MLD and frontal position are also impacted by remote heat losses and convection in the Labrador Sea, through northward advection of unstable mode waters. The sub-decadal oceanic and on-shelf biological production peaks are possibly predictable by half a year (local winter convection to subsequent summer production), and the advective time-lag from the Labrador Sea might induce an even longer predictability horizon (up to 1.5 years).

1. Introduction

The North Atlantic Oscillation (NAO) is typically employed when attempting to associate ecosystem changes to climatic variability in the North Atlantic (Drinkwater et al., 2003; Greene and Pershing, 2000). Since many NAO-ecosystem links broke around the mid-1990s (Drinkwater et al., 2013; Hátún et al., 2007), there is a need to identify other physical metrics in addition to the NAO index. One such metric is the so-called gyre index, reflecting the strength and extent of the North Atlantic subpolar gyre (SPG) (Häkkinen and Rhines, 2004; Hátún et al., 2005). The SPG – a large body of cold and low-saline subarctic water, which circulates counterclockwise (Fig. 1) – declined after the mid-1990s (Häkkinen and Rhines, 2004). This resulted in a sudden warming and salinification in the subpolar North Atlantic due to increased northward intrusion of relatively warm and saline subtropical water from the eastern Atlantic (striped region in Fig. 1) (Bersch et al., 1999; Hátún et al., 2005; Robson et al., 2012). This water mixes with colder and fresher western water masses from the North Atlantic Current (NAC), producing SubPolar Mode Waters (SPMW, checkered region in Fig. 1) (McCartney and Talley, 1982) which flow and spread toward the Barents Sea in the north (Holliday et al., 2008) and the Labrador Sea in the west (McCartney and Talley, 1982). Fundamental ecosystem changes have been observed after this shift (Hátún et al., 2009a), and the gyre index has often been used as a physical metric for these changes (Hátún et al., 2009b; Hovland et al., 2013; Solmundsson et al., 2010). The NAO and the gyre indices co-varied before

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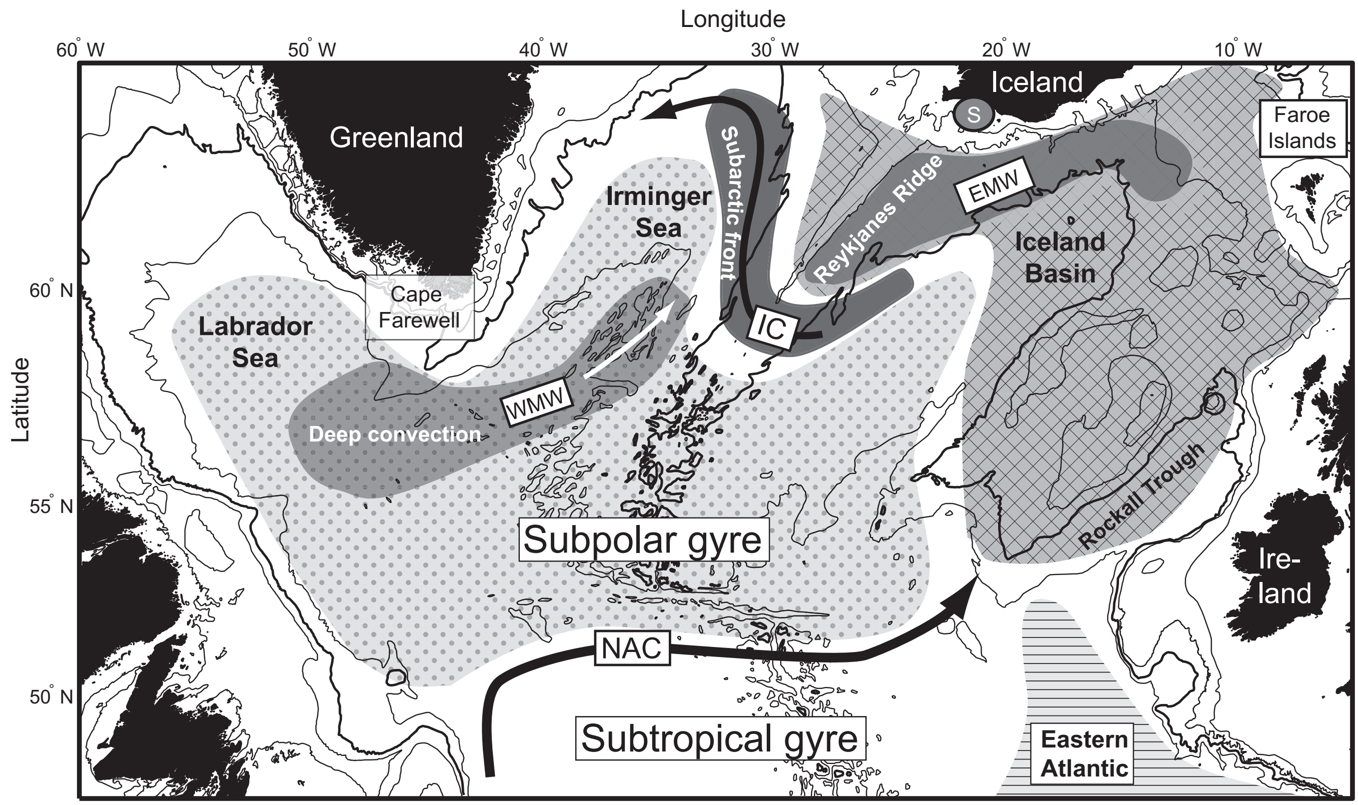

Fig. 1. Map of the subpolar North Atlantic Ocean. The subpolar gyre and the eastern source water area are shown with the dotted and striped regions, respectively, and the SPMW mixing region is illustrated with the checkered region. The core WMW (Western Mode Water) and EMW (Eastern Mode Water) regions, and the subarctic frontal zone, are shown with deeper gray shades. The currents - NAC (North Atlantic Current), IC (Irminger Current) – are outlined with the arrows. The 200 m, 1000 m, 2000 m (thick line) and 3000 m isobaths are shown, and the location of the on-shelf zooplankton measurement site is shown with the gray oval, marked with an 'S'.

1995, but while the NAO index switched to average values after a sudden dip during winter 1995–1996, the gyre index continued to decline (Häkkinen and Rhines, 2004; Hátún et al., 2005).

Strong surface heat losses over subpolar waters during the winter, represented by a high NAO index, cause deep convection and the production of homogenous mode waters of varying density classes (Brambilla and Talley, 2008a). Two main density classes of mode water meet at the Reykjanes Ridge. First, the isopycnals of the denser mode water (potential densities, σ_θ, around 27.55) have their winter surface outcrop in the southern Irminger Sea and Labrador Seas, and the characteristic of this water mass is therefore modified by air-sea interaction over these regions. This water type is hereafter termed Western Mode Water (WMW, Fig. 1). Second, the long-term trend of the lighter mode water ($\sim 27.45\sigma_\theta$, here termed Eastern Mode Water, EMW, Fig. 1) core properties is determined by the relative contribution of water from the subtropical gyre and the SPG, respectively (Hátún et al., 2005; Thierry et al., 2008) as well as by air-sea interactions along the eastern flank of the Reykjanes Ridge, and around the northern periphery of the Iceland Basin (Brambilla et al., 2008b; Thierry et al., 2008). The subarctic front marks the boundary between WMW and EMW in the Irminger Sea, and between EMW and more stratified waters in the central Iceland Basin - Labrador Sea Water (LSW) at depth and a lighter water type above (Fig. 1). The subpolar front determines the position of the Irminger Current and the main flow in the Iceland Basin. The transit time of WMW and the even denser LSW, from the Labrador Sea into and north through the Irminger Sea is about a year, which gives some prediction potential to this system (Deshayes et al., 2007; Sy et al., 1997; Yashayaev et al., 2007).

The convective western part of the SPG is a large nutrient reservoir and a center of abundance for *Calanus finmarchicus* (Heath et al., 2008) (Fig. 2). The mixing of WMW into the EMW, along the subarctic front in the northeastern Irminger Sea (Despres et al., 2011), will enrich the warmer and more saline EMW with nutrients and thus fuel primary production (Sanders et al., 2005). *C. finmarchicus* diapause at depth during winter, and high abundances are observed near the interface between EMW and the WMW/LSW the frontal zone of the NE Irminger Sea, and near the boundary between EMW and both LSW and the Iceland-Scotland Overflow Waters (ISOW) in the Iceland Basin (Gislason and Astthorsson, 2000; Heath et al., 2008). These animals start mating during their ascent toward the surface waters in March–April (Gislason et al., 2000). Eggs and larvae are produced in the surface layers and are an important food item for larger zooplankton (e.g. euphausiids, Silva et al., 2014) and fish larvae (e.g. cod and redfish larvae, Bainbridge and McKay, 1968).

On the shelf, *C. finmarchicus* provide likewise an efficient trophic pathway from primary producers to higher trophic levels (Gislason et al., 2000). The south Iceland shelf is devoid of *C. finmarchicus* during winter, and must therefore be repopulated during spring from the overwintering populations (Gislason and Astthorsson, 2000). The NW Iceland Basin has been suggested as the principal oceanic source, because the influx of oceanic water is likely to be most direct there (Valdimarsson and Malmberg, 1999), but advection of animals from the Irminger Sea is also possible (Gislason and Astthorsson, 2000).

The general biological production, ranging from *C. finmarchicus*, through euphausiids and fish is much higher in the NE Irminger Sea, compared to the NW Iceland Basin (Gudfinnsson et al., 2014). For example, the main redfish (*Sebastes mentella*) spawning grounds are closely aligned with the frontal zone along the western side of the Reykjanes Ridge (dark gray in Figs. 1 and 4) (Pedchenko, 2005) and hooded seals (*Cystophora cristata*), likely praying on