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Thermohaline forcing and interannual variability of northwestern inflows into the northern North Sea

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ABSTRACT

A long-established, 127 km-long hydrographic section in the northern North Sea at 59.28°N that runs from the eastern coast of Orkney (2.23°W) to the central North Sea (0°) crosses the path of the main inflows of Atlantic water. Data from 122 occupations between 1989 and 2015 are examined to determine the annual cycle and long-term trends of temperature, salinity and depth-varying geostrophic flow across the section. In an average year, the geostrophic flow referenced to the seafloor is at its narrowest (40 km) in winter, during which time it is driven by the strong horizontal salinity gradient; the horizontal temperature gradient is very weak. Velocity exceeds 4 cm s^{-1}, but transport is at a minimum (0.11 Sv). In the deeper water in the east of the section, thermal stratification develops throughout summer and persists until October, whereas the west is tidally mixed all year. The bottom temperature gradient becomes the primary driver of the geostrophic flow, which is fastest (9 cm s^{-1}) in September and broadest (100 km) in October. Maximum transport (0.36 Sv) occurs in October. Throughout the summer, the horizontal salinity gradient weakens, as does its contribution to the flow. However, it nevertheless acts to broaden the flow west of the location of the strongest horizontal temperature gradient. Section-mean de-seasoned temperature is found to be positively correlated to the Atlantic Multidecadal Oscillation and negatively correlated to the North Atlantic Oscillation. These results refine our understanding of the thermohaline forcing of Atlantic inflow into the northern North Sea, particularly in relation to the salinity distribution. Understanding the variability of this inflow is important for understanding the dynamics of the North Sea ecosystem.

1. Introduction

The North Sea is a shallow shelf sea on the northwestern European continental shelf that lies between the United Kingdom and continental Europe (Fig. 1). Inflow to the North Sea from the North Atlantic occurs through the English Channel (English Channel Inflow), between the Orkney and Shetland Islands (Fair Isle Current, FIC), along the eastern coast of the Shetland Islands (East Shetland Atlantic Inflow, ESAI), and along the western slope of the Norwegian Trench (Norwegian Trench Inflow) (Otto et al., 1990; Svendsen et al., 1991; Turrell et al., 1996). Outflow occurs primarily in the Norwegian Coastal Current (NCC) (Damm et al., 1994). The approximate locations of these flows are illustrated in Fig. 1. These currents are, in turn, largely fed by the Shelf-Edge Current, which flows northwards along the European continental margin (Turrell et al., 1996; Marsh et al., 2017). Input to the FIC also occurs from the Scottish Coastal Current, a northward flow along the western coast of Scotland. The Channel Inflow is weak compared with the northern inflows (Otto et al., 1990; Winther and Johannessen, 2006). The Norwegian Trench Inflow is the largest by volume transport (Otto et al., 1990; Winther and Johannessen, 2006) but it retroflects within the Norwegian Trench and flows out with the NCC. Consequently, it is the FIC and ESAI, the northwestern inflows, that have the greatest effect on conditions in the northern North Sea. The waters of the northwestern inflows approximately follow the 100 m isobath southwards down the eastern coast of Scotland before turning eastwards between 57.5 and 58°N and flowing towards Norway. Within the North Sea, the circulation is broadly cyclonic (Otto et al., 1990; Hill et al., 2008).

The rate of oceanic inflow strongly influences the region's ecosystem (Lindley et al., 1990; Holliday and Reid, 2001; Edwards et al., 2002; Beaugrand, 2004), and the FIC and ESAI provide pathways for perturbations of oceanic origin to propagate into the North Sea

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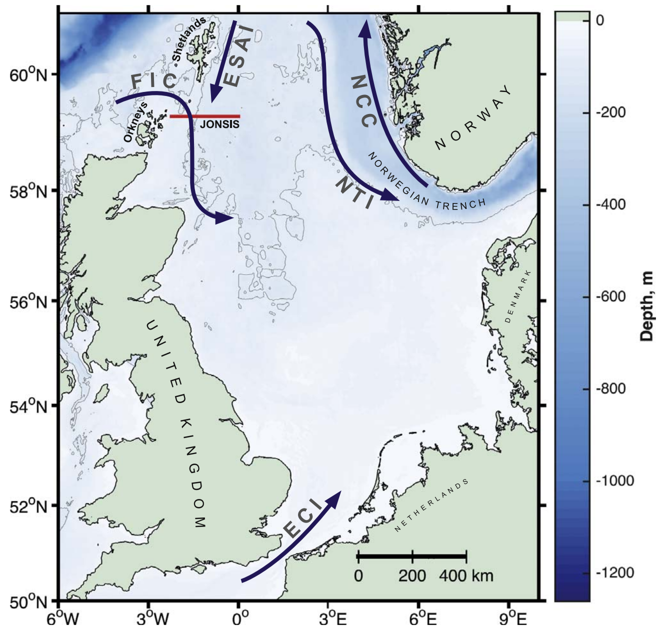

Fig. 1. Bathymetric map of the North Sea. The location of the JONSIS line and the approximate paths of the Fair Isle Current (FIC), East Shetland Atlantic Inflow (ESAI), Norwegian Trench Inflow (NTI), Norwegian Coastal Current (NCC) and English Channel Inflow (ECI) are shown (Otto et al., 1990; Turrell, 1992). Shading indicates depth from 0 to 1250 m; the 100 m isobath is marked in grey. Bathymetric data are from the GEBCO_08 grid, version 20100927 (www.gebco.net).

(Dickson et al., 1988; Holliday and Reid, 2001; Edwards et al., 2002). Reliable models of contaminant pathways and of water quality depend on accurate knowledge of these inflows (Taylor, 1987; Turrell and Henderson, 1990); reliable models of phytoplankton and nutrient distributions depend on proper physical modelling (Skogen and Moll, 2005). In the last decade, the EU's Marine Strategy Framework Directive has placed on EU member states the responsibility of ensuring "good environmental status" (EU, 2008) for their territorial waters, so providing a regional regulatory driver to efforts to improve our understanding of the physical and ecological dynamics of the North Sea.

The FIC has been described in broad terms as a southward-flowing current, approximately 30 nautical miles (56 km) wide (Svendsen et al., 1991), that flows through the Fair Isle Gap between the Orkney and Shetland islands (Dooley, 1974). In the North Sea, it is found close to the eastern coast of the Orkneys (Svendsen et al., 1991) in the approximate region of the 100 m isobath (Dooley, 1974; Winther and Johannessen, 2006). The ESAI is a more recent discovery than the FIC. In his review of the circulation of the northern North Sea, Dooley (1974) did not find evidence of a persistent inflow to the east of the Shetlands, but studies since then have found evidence of such a flow (Turrell, 1992; Turrell et al., 1996). Winther and Johannessen (2006) note that the ESAI is a more diffuse flow than the FIC, but that average transports in the two currents are similar. Between 57.5 and 58°N, the combined inflow turns east and flows towards the Norwegian coast in what has become known as the Dooley Current (Dooley, 1974; Otto et al., 1990; Winther and Johannessen, 2006). Little water from northwestern inflows reaches the southern North Sea (Pohlmann and Puls, 1994).

Previous studies in the region (e.g. Turrell, 1992) have separated the Atlantic inflow into wind-driven and non-wind-driven components, and have assumed that the wind-driven component represents the depth-constant flow that remains once the bottom-referenced geostrophic shear has been removed from the velocity profile. Subsequent references to wind- and non-wind-driven flow follow this convention.

The Atlantic inflow exhibits seasonal variations (Dooley, 1983; Turrell, 1992). It is thought to be primarily non-wind-driven in summer and primarily wind-driven in winter (Dooley, 1983; Otto et al., 1990; Svendsen et al., 1991; Turrell, 1992; Pohlmann and Puls, 1994; Winther and Johannessen, 2006). During the spring, stratification develops offshore of both the Orkney and Shetland archipelagoes as atmospheric heating warms the surface, isolating cool, dense waters left over from the previous winter beneath the thermocline (Svendsen et al., 1991; Turrell, 1992; Turrell et al., 1996; Hill et al., 2008). Closer to the shore, tidal currents are sufficiently strong that the water column remains fully mixed even when deeper, offshore waters are stratified (Svendsen et al., 1991). The density front that emerges between these two regions drives an along-front jet between the dense bottom water in the offshore, stratified region and the lighter water in the coastal mixed region (Svendsen et al., 1991; Turrell, 1992; Hill et al., 2008). This density pattern is common on the northwestern European shelf and makes the FIC and ESAI part of the thermohaline circulation that is a common feature on the northwestern European continental shelf in summer (Brown et al., 1999; Hill et al., 2008). The zonal salinity distribution reinforces this density pattern. The waters of the FIC originate along the western coast of Scotland where, prior to entering the North Sea, they are mixed with fresh water of terrestrial origin (Turrell et al., 1990; Turrell, 1992). The salinity gradient between water that exhibits this fresh water influence and more saline water found offshore may be traced around the northern coast of Scotland (Dooley, 1974). The lack of major river systems on, and the relatively small landmass of, the Orkney and Shetland Islands, means that further appreciable addition of fresh water to the FIC and ESAI from terrestrial sources does not occur in the vicinity of these archipelagoes.

The switch to a wind-driven regime occurs because wind forcing is stronger in winter (Coelingh et al., 1996; Siegismund and Schrum, 2001). Winds from the west and north tend to force an anti-clockwise circulation around the northern North Sea, a pattern that promotes inflow of water from the northwest (Furnes, 1980). The correlation between volume transport in the inflows and the North Atlantic Oscillation (NAO; Hurrell et al., 2003), an index which characterises the meridional pressure difference across the North Atlantic and the strength of westerly winds in the region, is higher at this time of year than it is in summer (Winther and Johannessen, 2006; Hjøllo et al., 2009). The breakdown of thermal stratification is also important (Turrell et al., 1990): the disappearance of the thermocline enhances Ekman transport throughout the water column (Winther and Johannessen, 2006) and reduces the density difference between near- and offshore regions, lessening the influence of the horizontal density gradient on the circulation (Turrell, 1992). A horizontal salinity gradient persists between the low-salinity coastal water and the high-salinity water of Atlantic origin towards the centre of the North Sea (Turrell, 1992), but Prandle (1984) estimates that it drives a flow an order of magnitude less than that driven by the wind.

Our understanding of the annual cycle of non-wind-driven flow in the Atlantic inflow has, to date, been based on observations from limited periods of time. Previous studies have relied on current meter records from a few months and on hydrographic observations from single cruises (e.g. Furnes, 1980; Turrell et al., 1990; Brown et al., 1999). Descriptions of the hydrography and flow in the region based on long-term observations are lacking in the literature. Volume fluxes are known to be limited by narrow sampling windows when estimated from observations (Hjøllo et al., 2009), and the role of non-wind-driven forcing in winter is not well understood (Dooley, 1983). Furthermore, the effect of horizontal temperature and salinity gradients on the non-wind-driven flow is yet to be considered separately. That stratification and horizontal temperature gradients influence the current has been understood for some time (Backhaus and Maier-Reimer, 1983; Turrell, 1992), as has the role of thermohaline circulation in the shelf seas more generally (Hill et al., 2008). The influence of horizontal salinity gradients on the Atlantic inflow has received less attention, and no attempt has been made to describe and quantify the separate influence of temperature and salinity gradients.