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The Greenland Sea tracer experiment 1996–2002: Horizontal mixing and transport of Greenland Sea Intermediate Water

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ABSTRACT

In summer 1996, a tracer release experiment using sulphur hexafluoride (SF_6) was launched in the intermediate-depth waters of the central Greenland Sea (GS), to study the mixing and ventilation processes in the region and its role in the northern limb of the Atlantic overturning circulation. Here we describe the hydrographic context of the experiment, the methods adopted and the results from the monitoring of the horizontal tracer spread for the 1996–2002 period documented by ~10 shipboard surveys. The tracer marked "Greenland Sea Arctic Intermediate Water" (GSAIW). This was redistributed in the gyre by variable winter convection penetrating only to mid-depths, reaching at most 1800 m depth during the strongest event observed in 2002.

For the first 18 months, the tracer remained mainly in the Greenland Sea. Vigorous horizontal mixing within the Greenland Sea gyre and a tight circulation of the gyre interacting slowly with the other basins under strong topographic influences were identified. We use the tracer distributions to derive the horizontal shear at the scale of the Greenland Sea gyre, and rates of horizontal mixing at ~10 and ~300 km scales. Mixing rates at small scale are high, several times those observed at comparable depths at lower latitudes. Horizontal stirring at the sub-gyre scale is mediated by numerous and vigorous eddies. Evidence obtained during the tracer release suggests that these play an important role in mixing water masses to form the intermediate waters of the central Greenland Sea.

By year two, the tracer had entered the surrounding current systems at intermediate depths and small concentrations were in proximity to the overflows into the North Atlantic. After 3 years, the tracer had spread over the Nordic Seas basins. Finally by year six, an intensive large survey provided an overall synoptic documentation of the spreading of the tagged GSAIW in the Nordic Seas. A circulation scheme of the tagged water originating from the centre of the GS is deduced from the horizontal spread of the tracer. We present this circulation and evaluate the transport budgets of the tracer between the GS and the surroundings basins. The overall residence time for the tagged GSAIW in the Greenland Sea was about 2.5 years. We infer an export of intermediate water of GSAIW from the GS of 1 to 1.85 Sv (1 Sv = 10^6 m^3 s^{-1}) for the period from September 1998 to June 2002 based on the evolution of the amount of tracer leaving the GS gyre. There is strong exchange between the Greenland Sea and Arctic Ocean via Fram Strait, but the contribution of the Greenland Sea to the Denmark Strait and Iceland Scotland overflows is modest, probably not exceeding 6% during the period under study.

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1. Introduction

The meridional overturning of the oceans (MOC) is an important component of the Earth's climate, being responsible for roughly half of the poleward heat transport demanded of the atmosphere–ocean system (Macdonald and Wunsch, 1996). An important part of the MOC is the thermohaline circulation observed in the North Atlantic and its marginal seas, where warm surface water is cooled by heat loss to the atmosphere, to the point where it can sink by convection. This deep water then spreads world-wide in the deep circulation. Simple models (Stommel, 1961) suggest that the MOC may have multiple stable states, and switching between states has been invoked as a mechanism to explain past rapid climate fluctuations around the Northern North Atlantic during the last 10^5 years (Broecker and Denton, 1989). Furthermore, coupled ocean–atmosphere climate models suggest, to varying degrees, that anthropogenic climate change may cause a slowdown of the Atlantic MOC during the coming century (IPCC, 2001). This adds an important practical motive to our curiosity to understand at a fundamental level the oceanography of the region, and the reasons for past, sometimes rapid and dramatic, climate changes.

Historically, the Greenland Sea (GS) has been recognised as an important location for processes connected to the overturning circulation. It has long been known that Greenland Sea Deep Water (GSDW) can be formed at its center where vertical stratification is weak, by deep convection when the surface water is cooled during late winter (Nansen, 1902, 1906; Helland-Hansen and Nansen, 1909).

In this classical view, the cooled surface water sinks and is replaced by warmer and slightly more saline water from below. The entire water column is progressively mixed with new water from the surface as long as the cooling continues. The water mass sources involved are cold, fresh surface waters and relatively warm saline intermediate waters of Atlantic origin (Carmack and Aagaard, 1973). The amount and density of deep water production by convection each year depends on the severity of the winter cooling.

Our understanding of deep convection has improved substantially in recent decades, enabling a more detailed and process-based description. The convection itself is thought to occur initially in plumes of horizontal scale ~10–100 m. Marshall and Schott (1999), reviewing the deep convection process, describe these as combining to form a "mixed patch" of homogeneous dense water, surrounded by a geostrophically generated rim current. Subsequent to the winter convection, this structure tends to dissipate by the formation of meso-scale eddies generated by baroclinic instabilities in the rim current. In our investigations (Gascard et al., 2002), we have seen little evidence for a link between formation of eddies and the "mixed patch" phase of deep convection in the GS in recent years, but we do see abundant evidence for vigorous eddies that we believe are associated with the deep convection process.

The precise connection of the deep convection sites in the Nordic Seas[2] to the water overflowing into the Northern North Atlantic is not resolved. Clarke et al. (1990) demonstrated that GSDW does not directly overflow into the deep North Atlantic. Instead, the principal overflows, especially through Denmark Strait, are the intermediate waters (that is, they are found at intermediate levels in summer). Intermediate waters of the Nordic Seas (AIW) are generally as dense as the densest water in the North Atlantic and are certainly a substantial contributor to the overflow waters passing across the Greenland–Scotland Ridge. Some AIW is produced during winter, primarily by convection in the Greenland and Iceland Seas. Swift et al. (1980) suggested that intermediate waters from these sources form a major component of water overflowing the Denmark Strait. A strong component of Greenland and Iceland Sea intermediate waters in the Iceland–Scotland overflow is also likely (Mauritzen, 1996).

Recently, Jónsson and Waldimarsson (2004) presented results from year long current measurements and hydrography from the Denmark Strait and, mainly in accordance with Swift et al. (1980) suggest that most of the overflow water could be traced from the sill back into the Iceland Sea north of Iceland. In contrast, Mauritzen (1996) argues that the main source for the Denmark Strait overflow is "Return Atlantic Water" that has flowed north in the Norwegian Sea in the West Spitsbergen Current and recirculated at Fram Strait, returning south as the lower component of the East Greenland Current (EGC) to Denmark Strait, without strong interaction with the Greenland or Iceland Seas. Based on hydrography from the west Icelandic Sea, Buch et al. (1996) suggest that part of the Denmark Strait overflow is Arctic Ocean Deep Water passing the GS as well, without any significant exchange with Greenland Sea water. Rudels et al. (1998) make the case for water of Arctic origin and a stronger exchange with the Greenland Sea. Strass et al. (1993) reported that above the Greenland slope, recirculating Atlantic Water is modified by isopycnal mixing with waters from the central GS.

Age determination from tracers indicates that deep convection in the GS was strong in the 1960s and 1970s (Schlosser et al., 1991). From the mid-1980s onwards, hydrographic surveys found weaker convection with evidence for penetration to 2000 m at maximum. From the mid-1980s, it has become clear that the intensity of convection in the GS and the hydrographic character of its products have been subject to major inter-annual changes and that deep water formation is not a steady-state process. These inter-annual changes have been associated to the impacts of the North Atlantic Oscillation (NAO), the inter-annual shift in atmospheric pressure between the Azorean high and the Icelandic low (Dickson et al., 1996; Furevik, 2001). The recent decrease of deep water production has led to a warming and increasing salinity of the GSDW below 2000 m through increased horizontal exchange with the relatively warm deep waters of the Arctic Ocean and Norwegian Sea (Meincke et al., 1997; Østerhus and Gammelsrod, 1999).

An important question is whether these changes have been, or will be, reflected in the volume or character of the overflowing waters (Hansen et al., 2004). Mauritzen (1996) reported there to be "so far no indications that the flow of any of the dense waters through the Denmark Strait and the Faroe-Shetland Channel is associated with inter-annual variability – all monitoring of the dense overflows indicates transports of O(2–3 Sv) in either place (Hermann, 1967; Ross, 1984; Saunders, 1990; Dickson et al., 1990), even though the reservoirs of the gyres are so small that they would be drained within ~5 years if they were to supply the overflows during a shut-down period". Dickson and Brown (1991) report long-term observations of the Denmark Strait overflow that support this view. Bacon (1998) however, interprets historical hydrographic data to suggest that the Denmark Strait overflow is subject to substantial variation on decadal time scales, and Hansen et al. (2001) have reached a similar conclusion for the Faroe-Shetland overflow, using current meter and hydrographic data.

Several issues therefore need clarification in regard to the production of the North Atlantic Deep Water in the Nordic Seas and specifically the GS: the role of winter convection, diapycnal and isopycnal mixing, the nature of the circulation scheme and how variability observed in the Nordic Seas affects the rates and properties of the waters overflowing into the North Atlantic. This paper describes the commencement and initial results of a sulphur hexa-

[2] Here we use the term 'Nordic Seas' to refer collectively to the Barents Sea, the Norwegian Sea, the Greenland Sea and the Icelandic Sea.