Progress in Oceanography 78 (2008) 1–11

Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

Transports of Nordic Seas water masses and excess SF_6 through Fram Strait to the Arctic Ocean

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ARTICLE INFO

Article history:
Received 21 July 2005
Accepted 26 June 2007
Available online 1 May 2008

Keywords:
Water masses
AIW
Transient tracers
SF_6
Geostrophy
LADCP
North Atlantic
Arctic Ocean
Nordic Seas
Fram Strait

ABSTRACT

To determine the exchanges between the Nordic Seas and the Arctic Ocean through Fram Strait is one of the most important aspects, and one of the major challenges, in describing the circulation in the Arctic Mediterranean Sea. Especially the northward transport of Arctic Intermediate Water (AIW) from the Nordic Seas into the Arctic Ocean is little known. In the two-ship study of the circulation in the Nordic Seas, Arctic Ocean – 2002, the Swedish icebreaker Oden operated in the ice-covered areas in and north of Fram Strait and in the western margins of Greenland and Iceland seas, while RV Knorr of Woods Hole worked in the ice free part of the Nordic Seas. Here two hydrographic sections obtained by Oden, augmented by tracer and velocity measurements with Lowered Acoustic Doppler Current Profiler (LADCP), are examined. The first section, reaching from the Svalbard shelf across the Yermak Plateau, covers the region north of Svalbard where inflow to the Arctic Ocean takes place. The second, western, section spans the outflow area extending from west of the Yermak Plateau onto the Greenland shelf. Geostrophic and LADCP derived velocities are both used to estimate the exchanges of water masses between the Nordic Seas and the Arctic Ocean. The geostrophic computations indicate a total flow of 3.6 Sv entering the Arctic on the eastern section. The southward flow on the western section is found to be 5.1 Sv. The total inflow to the Arctic Ocean obtained using the LADCP derived velocities is much larger, 13.6 Sv, and the southward transport on the western section is 13.7 Sv, equal to the northward transport north of Svalbard. Sulphur hexafluoride (SF_6) originating from a tracer release experiment in the Greenland Sea in 1996 has become a marker for the circulation of AIW. From the geostrophic velocities we obtain 0.5 Sv and from the LADCP derived velocities 2.8 Sv of AIW flowing into the Arctic. The annual transport of SF_6 into the Arctic Ocean derived from geostrophy is 5 kg/year, which is of the same magnitude as the observed total annual transport into the North Atlantic, while the LADCP measurements (19 kg/year) imply that it is substantially larger. Little SF_6 was found on the western section, confirming the dominance of the Arctic Ocean water masses and indicating that the major recirculation in Fram Strait takes place farther to the south.

1. Introduction

The transports of volume, heat and salt between the Nordic Seas, comprising the Greenland, Iceland and Norwegian seas, and the Arctic Ocean are part of the global thermohaline circulation and influence the climate of the Arctic. The intermediate waters leaving the Arctic Ocean directly contribute to the overflow and to the global thermohaline circulation (Mauritzen, 1996a,b; Rudels et al., 1999; Anderson et al., 1999). Oceanic sensible heat advected into the Arctic Ocean contributes to the heat balance of the Arctic and may affect the formation rate of sea ice (Martinson and Steele, 2001). The export of sea ice and low salinity surface water could weaken the convection and deep-water formation and thus the production of overflow water in the Nordic Seas (e.g. Stigebrandt, 1985).

The main exchanges occur through Fram Strait, the only deep passage between the Arctic Ocean and the rest of the world oceans (Fig. 1). More than 90% of the sea ice and half of the liquid freshwater export from the Arctic Ocean take place through Fram Strait, the remainder passing through the Canadian Arctic Archipelago

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0079-6611/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pocean.2007.06.004

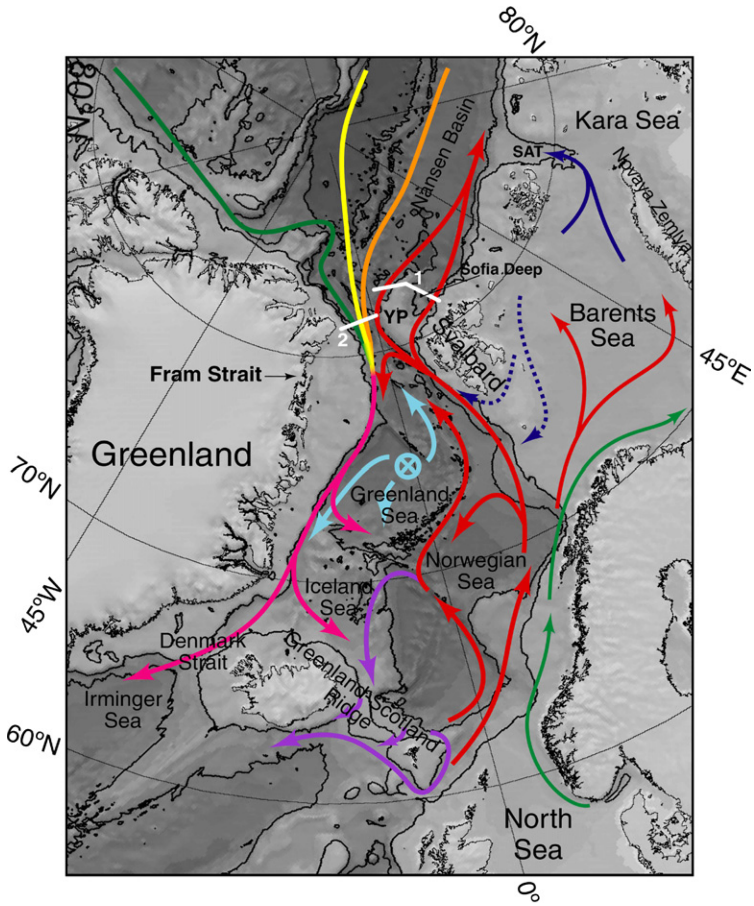

Fig. 1. The circulation of Atlantic and intermediate waters in Fram Strait and in the Nordic Seas and the locations of Oden sections 1 and 2. SAT = St. Anna Trough, YP = Yermak Plateau.

(Aagaard and Carmack, 1989; Dickson et al., 2007). The Atlantic water in the West Spitsbergen Current carries the bulk of the oceanic sensible heat into the Arctic Ocean, even if the inflow of Atlantic water over the Barents Sea is of comparable magnitude (Rudels, 1987; Blindheim, 1989). In addition to Atlantic water, the West Spitsbergen Current also transports Arctic Intermediate Water (AIW) and Nordic Seas deep waters into the Arctic Ocean. The East Greenland Current (EGC) carries Arctic Atlantic, intermediate and deep waters as well as cold, low salinity surface water out of the Arctic Ocean (Rudels, 1987).

Considerable uncertainty still exists about the transports through Fram Strait, in spite of several years of moored current measurements and ice transport observations at the sill at 79°N within the EU VEINS (Variability of Exchanges In the Northern Seas) and ASOF-N (Arctic and Subarctic Ocean Fluxes) programmes. This is largely due to the strong recirculation occurring in the strait and to the presence of both baroclinic and barotropic eddies, which increase the gross northward and southward flows across the section but, perhaps, contribute less to the exchanges of different water masses between the Nordic Seas and the Arctic Ocean. The northward and southward transports estimated from the current measurements are large, above 10 Sv, with a net southward transport of 1–2 Sv (1 Sv = 10^6 m^3 s^{-1}). However, large seasonal as well as annual variabilities are found (e.g. Fahrbach et al., 2001; Schauer et al., 2004).

The water masses of the Arctic Ocean and the Nordic Seas are distinct and different. The Polar Surface Water (PSW) and the Arctic Atlantic Water (AAW) of the Arctic Ocean are colder and less saline than the Warm Surface Water (WSW) and the Atlantic Water (AW) from the Nordic Seas. The Arctic Ocean deep waters, the Canadian Basin Deep Water (CBDW) and Eurasian Basin Deep Water (EBDW) on the other hand are warmer and more saline than the corresponding Nordic Seas Deep Waters (NDW). Here a simplified version of the water mass classification suggested by Rudels et al. (2005) is used (see Table 1).

In the intermediate density range the Θ–S curves of the water columns from the two areas cross and a separation becomes more difficult (Fig. 2). In the upper Polar Deep Water (uPDW) of the Arctic Ocean the temperature decreases and the salinity increases with depth and the uPDW is stably stratified in both temperature and salinity. The AIW created in the Nordic Seas forms a salinity minimum, and close to its origin in the Greenland Sea also a temperature minimum, leading to an unstable stratification in salinity above and an unstable stratification in temperature below the minima. The salinity minimum can be identified in and north of Fram Strait and serves as a marker for the AIW (Fig. 2 and Table 1). However, such subtle differences are difficult to take into account when transports are computed and when the water masses are separated and identified solely by isopycnals.

The identification of the AIW is presently possible, due to the tracer release experiment initialized in August 1996 within the ESOP-2 programme (European Subpolar Ocean Programme) (Watson et al., 1999) when 320 kg of sulphur hexafluoride (SF_6) was injected into the Greenland Sea Gyre at the density surface $\sigma_\theta = 28.0492$ ($\sigma_{0.5} = 30.4268$), approximately within the layer of the AIW presently being ventilated. The SF_6 now serves as a marker for the AIW (see Olsson et al., 2005a,b; Tanhua et al., 2005a; Messias et al., 2008). SF_6 observations during the Arctic Ocean – 2002