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# Formation of intermediate water in the Greenland Sea during the 1990s

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The transformation rates of upper water into intermediate water (500 to 1600 m) of the central Greenland Sea are deduced from annual changes in CFC tracer inventories between 1991 and 2000. Transformation was found to be intermittent in time, mainly taking place in the winters of 1994/1995 and 1999/2000. Formation rates are of the order of 0.2 to 0.9 Sv (1 Sv = $10^6$ m$^3$ s$^{-1}$), equivalent to a 10-year average of up to 0.2 Sv. Associated changes in heat content of the intermediate layer are consistent with a winter-time heat loss of 20 W m$^{-2}$ over 1 month (75 W m$^{-2}$ over 1 week) at the sea surface.

Keywords: Greenland Sea, heat flux, variability, water mass formation.

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## Introduction

The Greenland Sea is a prominent site for water mass transformation. Its wind-driven cyclonic circulation causes a doming of the isopycnals towards the gyre center that promotes convection due to winter-time buoyancy loss. Convection to intermediate depth (of the order of 1500 m) was observed frequently from the late 1980s, whereas deeper convection was never directly observed. The convection to intermediate depth forms Greenland Sea Arctic Intermediate Water (GSAIW) (Swift and Aagaard, 1981; Blindheim, 1990). Here we explore formation rates of GSAIW for the time interval 1991 to 2000 combining hydrographic and transient tracer data along a 75°N section crossing the Greenland Sea gyre.

## Characteristics and formation of GSAIW

The convection process is the first step in the process of ventilating the ocean's interior. The intensity of atmospheric heat loss is the major driver in the process, whereas salt fluxes play a role at least in triggering convection of surface water (Rudels, 1990). Variable surface forcing leads to variable transformation of upper waters in terms of transformed volume and tracer characteristics.

The temporal evolution of temperature and CFC 11 (Figure 1) show a deep penetration of tracers during the winters of 1994/95 and 1999/2000 as a consequence of convection and subsequent transport into the interior. In particular, these convection events changed the CFC inventories substantially (Figure 2).

Formation rates were calculated as the amount of mixed-layer water needed to produce the observed change in CFC inventory. As the ocean does not lose CFCs through its surface (in contrast to for example heat) and atmospheric time histories are quasi-constant over the period considered in this study (Walker *et al.*, 2000), inventories can be assumed either to increase or remain quasi-constant, as upper waters have only weak lateral gradients. Thus, our strategy was to calculate the height of a

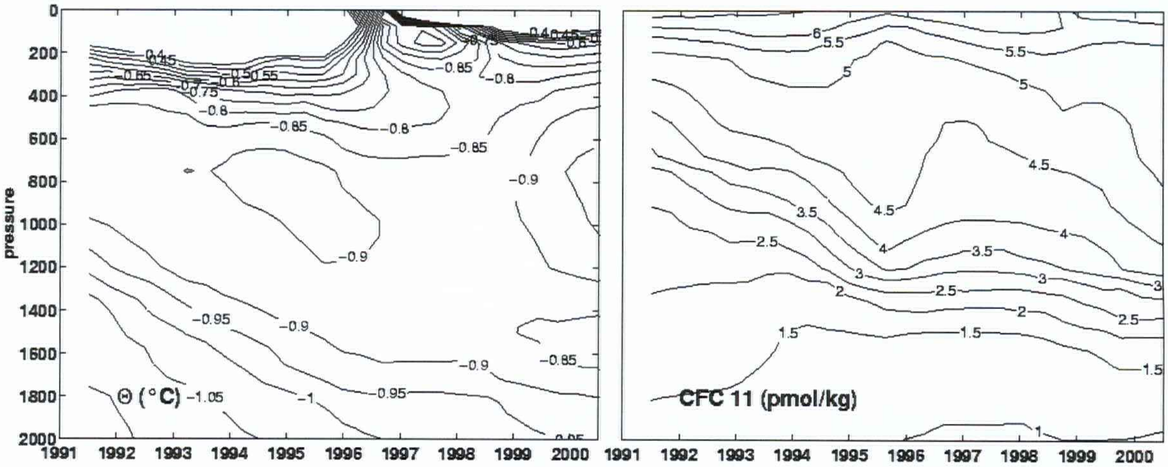

Figure 1. Temporal evolution of potential temperature (°C; left) and CFC 11 (pmol kg$^{-1}$; right) between November 1991 and May 2001. Note the convective events in winter 1994/1995 and 1999/2000 bringing cold water with high CFC 11 signals to intermediate depths. Contours are produced assuming that the tracer signal is imprinted in March of each year of observation.

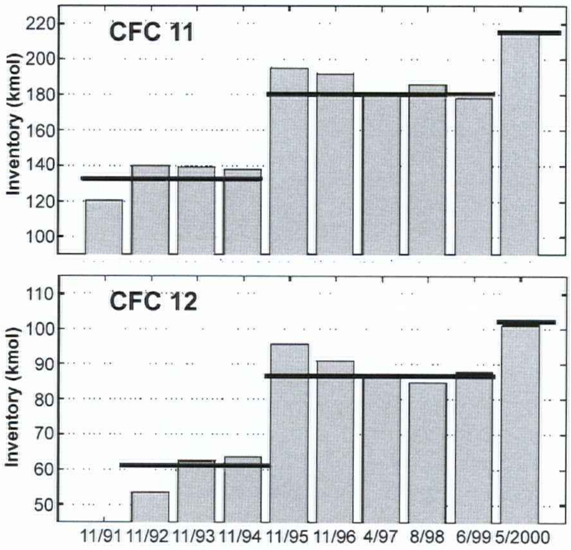

Figure 2. Change in CFC 11 and CFC 12 inventories ($1 \times 10^3$ mol) considering an area of $4.5 \times 10^{10}$ m$^2$ and a depth range from 500 to 1600 m. Note the inventory change between 1994/95 and 1999/2000.

column of upper waters required to yield the observed increases in the CFC inventory over time. We assumed that the Atlantic Water layer plays a role in the convection process and analyzed the changes in inventories in the water column that reaches from below the core of this layer (500 m depth) to a depth of 1600 m, where no increase in CFC was observed during the 1991 to 2000 time interval (Figure 1).

For CFC 11 we found an increase in the inventory of about 30 to 40 kmol in both winters with corresponding values for CFC 12 between 20 and 30 kmol (Figure 2). This translates into replacement of a water layer of 100 to 200 m depth, corresponding to volumes between 4.5 and $9 \times 10^{12}$ m$^3$, respectively (radius of gyre $1.2 \times 10^5$ m). These numbers assume that the CFCs are completely confined in the gyre after convection and only "older waters" are removed from the gyre by the addition of recently ventilated, high CFC waters. However, considering a 50% entrainment of "older water" with a pre-convective CFC inventory, water equivalent to a column of about 300 m thickness has to be exchanged to yield the observed increase in CFC inventories.

## Export of newly formed water

The related export of water from the convective site (subduction) is most likely caused by isopycnal eddy transfer, as shown by Khatiwala and Visbeck (2000) for the Labrador Sea. They found a relaxation time of the density field in the order of 7 months. Using this value we obtain a transport between 0.3 and 0.6 Sv for both winters, which increases to 0.9 Sv using a 50% entrainment. The annual average transport is in the order of 0.1 to 0.2 Sv, because only two major convection events occurred during the 10 years for which data were analyzed. The average numbers compare well with the findings of Rhein (1996) averaging over the 1980s and early 1990s.

Although a salinification of the intermediate layer is observed over the 10 years, interannual salinity changes do not appear to be significant. In contrast, temperature is affected in a sense that the convection interrupts the general warming trend in the layer (0.02 K yr$^{-1}$) by holding the average temperature at a constant level between successive winters. Surface heat fluxes calculated from this value yield reasonable values of about 20 W m$^{-2}$ if averaged over 1 month or 75 W m$^{-2}$ if averaged over 1 week.

## Conclusions

The transformation of surface water into intermediate water in the Greenland Sea during the 1990s was found to be intermittent in time (two main events) and associated with an average transport of about 0.2 Sv. Frequently, the North Atlantic Oscillation (NAO) index is used as indicator for the atmospheric forcing and thus convection activity. A positive (negative) index is related to weak (strong) convection activity in the Greenland Sea. Since the mid-1970s, a generally positive NAO index (with a few exceptions) prevailed and the highest values were observed in the 1990s. Thus, if this correlation holds, low GSAIW formation rates are not surprising. As the GSAIW spreads into the Nordic Seas, lower formation rates may have consequences for the ventilation of the deeper waters in this region. However, the present data set is not sufficiently dense to provide hard evidence for such a conclusion.

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