

FORMATION RATES OF LABRADOR SEA WATER INFERED FROM REPEATED SECTIONS

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Since more than three decades oceanic measurements of anthropogenic tracers such as chlorofluorocarbons have served as valuable tools to investigate the spreading and the formation of deep water components in the Atlantic Ocean. The Labrador Sea is of particular interest since it is a place of active winter-time convection and as such the formation region of Labrador Sea Water (LSW). This is the shallowest components contributing to the cold and deep branch of the Meridional Overturning Circulation (MOC). Sedimentary records point to several incidents at various times in the geological past when the MOC had almost ceased [1]. Such shut-downs could be linked to abrupt climate changes. Some climate models predict a declining MOC caused by decreasing LSW formation as a response to global warming [e.g. 2,3]. It is, therefore, highly desirable to monitor changes in the formation rate of dense water produced in the Labrador Sea to understand the link between changes in LSW formation and climate changes.

Observational evidence from the past two decades has shown that the formation history of LSW in the Labrador Sea succumbs to substantial interannual and decadal variability [e.g. 4]. The intensity and extent of the convective process is strongly related to the background density stratification in the water column and to the strength of the atmospheric forcing. Repeated tracer sections on basin-wide scales have yielded valuable information on changes in the LSW formation rate.

Tracers like the chlorofluorocarbon component CFC-12 enter the surface ocean by air-sea gas exchange. The transformation of CFC-12-tagged surface water into deeper water during the convective processes produces a CFC-12 maximum in mid-depths. The more intense the convection, the more chlorofluorocarbons are imported, which in turn results in an increase in the CFC-12 inventory of the respective water mass [5]. Since 1997 the spatial data coverage in the subpolar North Atlantic is sufficient to determine the CFC-12 inventories of LSW on biennial time scales. As an example the CFC-12 inventories for uLSW and dLSW are shown for the year 1997 (Fig. 1). At present, adequate hydrographic and tracer data are available for the years 1997, 1999, 2001, 2003, and 2005. Temporal changes in the CFC-inventories between two years are therefore used to infer LSW formation rates and associated uncertainties following methods described in [4,5,6].

Two types of LSW can be distinguished [7]. Deep Labrador Sea Water (dLSW) is the product of the intense convection happening in the early 1990s, which was associated with mixing depths of more than 2000m. On the other hand, upper Labrador Sea Water (uLSW) is the result of the rather shallow convection observed since 1997 reaching rather moderate depths of 1000-1500m. Both LSW types are defined as density layers with uLSW being limited by the isopycnals $\sigma_\theta = 27.68$ - 27.74 kg/m^3 and dLSW defined to occupy the density

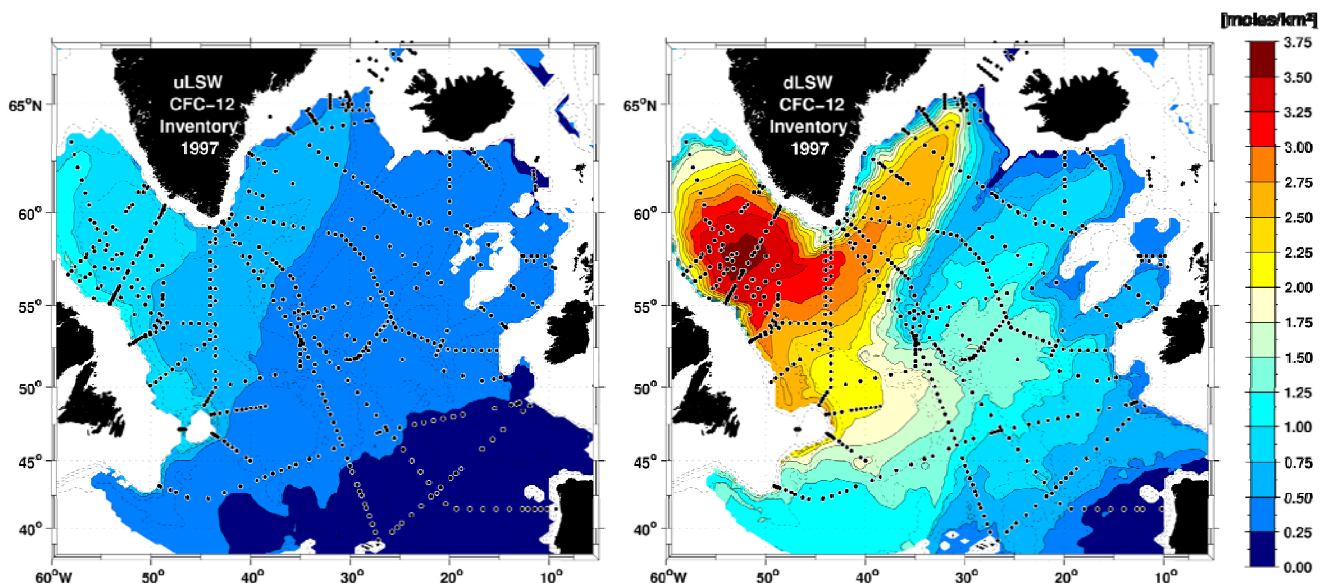


Figure 1: CFC-12 inventories for upper Labrador Sea Water (left) and deep Labrador Sea Water (right) given in moles/km². Dots indicate locations of hydrographic stations where tracer samples have been taken.

range $\sigma_\theta = 27.74\text{-}27.80 \text{ kg/m}^3$ [4,5,6,7]. The difference in the location at depth for each pair of densities defines the layer thickness of each LSW type. Both, CFC-12 concentrations and layer thickness estimates have been spatially extrapolated using a topography-following gridding algorithm. As such, the particular CFC-12 inventory of a water mass is the result of multiplying the area of a grid cell by the gridded average CFC-12 concentration in each water mass at a particular location and by the gridded layer thickness. The respective LSW formation rate is calculated from the difference of two succeeding CFC-12 inventories, divided by the product of density, a degree of tracer saturation assumed for newly formed LSW and an equilibrium CFC-12 concentration. This product is integrated over two years, which is the interval of two successive tracer inventories. Uncertainties in the inventories are estimated using a jackknifing-approach. To do so, a given dataset is subsampled by randomly removing 50% of the available data points. Then, the rms error of all parameters is calculated at all grid points from 100 different subsamples [4,5,6].

In 2005 tracer data coverage outside the Labrador Sea was limited. In the LSW layer high tracer values have been observed to be correlated to low salinities. Therefore, respective correlations were calculated for various regions of the subpolar North Atlantic and for data from various years. This correlation was applied to hydrographic data and thus allowed the reconstruction of CFC-12 estimates in those regions, where tracer data were missing and only hydrographic data were available. A comparison between measured and reconstructed CFC-12 inventories for the years 1997-2003 showed only very small deviations. Therefore, this method allowed providing a reliable estimate for the LSW formation rate in the period 2003-2005, and thus, to further extend the existing time series of LSW formation rate estimates derived from tracer observations.

Presently, the ULSW formation rate time series derived from tracer inventories is still short. But the continued observation of changes in the temporal evolution of LSW formation rates is necessary to reveal future coherency with changes in the MOC. The fact that the atmospheric signal of CFC-12 does not further increase, may hamper in future the detection of an oceanic CFC-12 increase due to water mass formation processes and will lead to greater uncertainties when considering changes in CFC-12 inventories. Atmospheric CFC concentrations peaked during the past decade and have begun to decline slowly. Additionally, dissolved CFC concentrations in upper LSW have almost reached saturation equilibrium with the atmosphere during this period. Therefore, first results from basin-wide measurements of sulphur hexafluoride (SF_6) in the subpolar North Atlantic in 2008 are presented in

conjunction with CFC-12 measurements, and the potential of using the transient signal of SF_6 to estimate LSW formation rates is investigated. This tracer has been increasing almost linearly in the atmosphere for the past several decades. Thus it may have a greater temporal sensitivity to changes in formation rate, making it highly suitable for this task.

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