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The formation rate of North Atlantic Deep Water and Eighteen Degree Water calculated from CFC-11 inventories observed during WOCE

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ABSTRACT

The accumulation of man-made chlorofluorocarbons (CFCs) in subsurface water masses is directly related to their formation rate, and the water mass formation rate can be calculated from its CFC inventory. CFC-11 inventories between 65°N and 10°S in the Atlantic Ocean have been calculated for Eighteen Degree Water (EDW) and the components of North Atlantic Deep Water (NADW) from data collected primarily between 1996 and 1998 as part of the World Ocean Circulation Experiment (WOCE). CFC-11 inventories for individual water masses are 5.4 million moles for EDW, 10.5 million moles for Upper Labrador Sea Water (ULSW) (4.6 million moles south of 42°N), 23.4 million moles for Classical Labrador Sea Water (CLSW), 10.4 million moles for Iceland-Scotland Overflow Water (ISOW), and 8.3 million moles for Denmark Strait Overflow Water (DSOW). The estimated error for these inventories is about ±10%. The sum of the NADW components (ULSW, CLSW, ISOW, DSOW) is 53.2 million moles which is about half of the total CFC-11 inventory, 103.8 million moles, in the North Atlantic Ocean. Maps of water column inventories illustrate the formation mechanisms and spreading pathways within these water masses. The inventories directly reflect the input of newly formed water in the North Atlantic over the time scale of the CFC transient, about 3 decades. The interior regions of the North Atlantic contain most (75–80%) of the CFC-11 inventory in NADW indicating strong recirculation and mixing of newly formed NADW from the DWBC into the interior with a time scale of 2–3 decades. Average water mass formation rates between 1970 and 1997 are: 3.3 Sv for EDW, 3.5 Sv for ULSW (2.0 Sv from the central Labrador Sea and 1.5 Sv from the southern Labrador Sea), 8.2 Sv for CLSW, 5.7 Sv for ISOW, and 2.2 Sv for DSOW. Estimated errors are ±20% for CLSW and ±16% for the other water masses. The total for NADW, which forms the deep limb of the North Atlantic Meridional Overturning Circulation, is 19.6 Sv. An extensive test of the effects of temporal variability on the average formation rate calculated from the CFC inventory indicates that the error

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introduced by the assumption of a constant water mass formation rate is no greater than 15% for CLSW and 10% for the other water masses.

1. Introduction

The formation and spreading of North Atlantic Deep Water (NADW) is a major component of the global thermohaline circulation. NADW contributes approximately 50% of the deep waters formed in the world ocean (Broecker et al., 1998; Orsi et al., 2002), ventilating the North Atlantic and mixing with southern source waters to form the Circumpolar Deep Water that fills the deep Pacific and Indian oceans. Paleoclimate records and numerical models (Manabe and Stouffer, 1988) indicate variability in the rate of NADW formation over glacial/interglacial time scales. Recent work has provided evidence for inter-annual variability in the rates of formation of NADW and its components, Upper Labrador Sea Water (ULSW) (Kieke et al., 2006, 2007), Classical Labrador Sea Water (CLSW) (Dickson et al., 1996), Iceland-Scotland Overflow Water (ISOW) (Hansen et al., 2001), and Denmark Strait Overflow Water (DSOW) (Bacon, 1998). NADW formation and spreading is intimately linked to climate variability.

One of the primary water masses of the thermocline is Subtropical Mode Water. In the North Atlantic, this is also named Eighteen Degree Water (EDW). Its formation is driven by loss of heat from the ocean to the atmosphere in the subtropics and is thus closely linked to climate variability.

Chlorofluorocarbon (CFC) inventories provide an independent method for calculating decadal average rates of water mass formation (Orsi et al., 1999; Smethie and Fine, 2001; Rhein et al., 2002). CFCs are anthropogenic substances that enter the surface ocean through gas exchange with the atmosphere, with well-known atmospheric histories (Cunnold et al., 1997; Walker et al., 2000). While production began in the 1930s, the bulk of CFCs have entered the ocean since 1970. They are transported into the deep ocean through localized processes, which transform surface waters into intermediate and deep water masses. Thus the total amount of CFCs present in a subsurface water mass is directly related to the rate of its conversion from surface or near-surface water. CFCs also provide an analog for the transport of other anthropogenic substances, including CO_2, to the deep ocean.

In this paper we present CFC-derived rates of formation of NADW, its component water masses, and EDW. Most of the data were collected during the North Atlantic phase of the World Ocean Circulation Experiment (WOCE), within 1 year of 1997, by eight different laboratories. An extensive quality control check of the data from these laboratories was carried out and the results of this are presented in the appendix. This work follows that of Smethie and Fine (2001) (hereafter SF2001), with the advantages that the data are more synoptic and have much better spatial resolution in the subpolar region. The data and methods are reviewed in Section 2, the results are presented in Section 3 and discussed in Section 4, and the work is summarized in Section 5.

2. Data and methods

2.1. Data

Cruises used for this study are given in Table 1 and the stations from these cruises that were used are shown in Fig. 1. The CFC-11 data were collected by eight different laboratories and required quality control measures to produce a self-consistent data set. These measures are described in detail in the appendix. Some data outside the 1996–1998 window were used. One North Atlantic cruise completed in 1995, OC269, provided 6 sections across the Deep Western Boundary Current (DWBC) in the subtropics. It was age adjusted to 1997 using factors unique to the ULSW, CLSW, and the underlying mixture of ISOW and DSOW in this region. These factors were determined by comparison with 1997 CFC-11 data from EN311, which reoccupied one of the OC269 stations; and with WOCE lines A20 at 52°W and A22 at 66°W, which were located near or bracketed the other OC269 sections. The adjustments were +37% for ULSW, +22% for CLSW, and +25% for ISOW and DSOW, but have little effect on the total CFC-11 inventories because of the small geographical area. Data from WOCE cruises in the tropical and South Atlantic Ocean collected between 1993 and 1995 were used to provide complete spatial coverage of CFC tagged water masses of North Atlantic origin. However, the CFC inventory in these regions was very small relative to the inventory in the subpolar and subtropical regions and no age adjustment was applied since it would have had little effect on the total CFC inventory for these water masses. One to two percent of the stations had insufficient vertical resolution to accurately calculate the CFC-11 inventory and they were not used.

2.2. Calculation of CFC inventories and map construction

The water column inventory is the amount of CFC per unit area (mol km^{-2}), calculated by vertically integrating a profile of the concentration. We determined the water column inventory for the components of NADW (ULSW, CLSW, ISOW, and DSOW) and EDW. The vertical concentration profile was integrated between the depths of the chosen bounding density surfaces, assuming a linear change in concentration between data points. A separate integration from surface to bottom was also performed to calculate the entire water column inventory.

The water column CFC-11 inventories of the various water masses were objectively mapped (Bretherton et al., 1976) onto a $0.5^\circ \times 0.5^\circ$ grid using a combination of