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# Deep Water Renewal in the European Polar Seas as derived from a Multi-Tracer Approach



by

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Abstract: A box model for the European Polar Seas has been developed and calibrated with tritium, freon and salinity data. For the production rates we find ca. 0.6 Sv for the Greenland Sea and ca. 1 Sv for the Eurasian Basin. For the exchange rate between the Nansen Basin north of Fram Strait and the Lofoten Basin we find ca. 0.7 Sv for NSDW. Additionally, an exchange between NSDW and GSDW or an internal modification circuit EBDW -> GSDW -> NSDW -> EBDW, accounts for ca. 1.2 Sv. The resulting turnover times caused by deep convective processes are ca. 28 a for the Greenland Sea, ca. 95 a for the Eurasian Basin and ca. 15 a for NSDW due to deep advective fluxes.

## 1 INTRODUCTION

The internal circulation and modification of Deep Waters within the North Polar Seas results in a net production of Deep Water, finally available to the abyssal circulation of the World Ocean at the Greenland - Iceland - Scotland ridges. For the production rates and the inter-basin exchanges box models, tuned with tracer data, present a tool to calculate bulk rates, that otherwise can derived at only with great effort. Therefore we had arranged a suite of conservative and transient tracers to be sampled in the Greenland and Norwegian Seas as well as in the southern tip of the Eurasian Basin. They are evaluated here with an appropriately designed box model. The questions posed are:

- what are the respective production rates for GSDW, NSDW and EBDW ?
- what are the time scales (turnover times) for a complete renewal of the Greenland Sea Deep Water GSDW, Norwegian Sea Deep Water NSDW and the Eurasian Basin Deep Water EBDW within the system ?
- can we deduce from the box model any quantitative statement regarding the internal interaction GSDW <-> EBDW and GSDW <-> NSDW ?

## 2 MODEL CONCEPT

Two different model concepts have been used. In both cases the vertical transports by deep convection are compensated by an equal "upwelling" rate. The main regions for Deep Water renewal are the Greenland Gyre and the Arctic shelves. To check our model results, we also allowed direct renewal of NSDW within the Norwegian Sea. The loss in volume to the upper boxes is balanced by advective transports in the upper box. The upper limit for the lower boxes has been determined by the depth of the deep salinity maximum at ca. 1500 m in the Greenland Sea. Also, below this depth the vertical gradients in water mass properties become very small. The latter argument of low gradient areas is physically comparable to the concept of box models, using "well-mixed" boxes, i.e. units of uniform properties. The GSDW of the deep Greenland Sea Basin box is called GSDW', since the original GSDW is only found in the deep Greenland Sea gyre region.

For the more traditional model (case a) we assume bi-directional exchange at equal rates between the deep Arctic Ocean (EBDW), the deep Greenland Sea (GSDW') and the deep Norwegian Sea (NSDW) (fig. 1a). The exchange of deep waters between the Arctic Ocean and the Greenland Sea has been suggested by recent high quality data (KOLTERMANN, 1985, 1986).

For the second model (case b), a consequence of the deep circulation in the North European Polar Seas has been used, which allows only transport of GSDW to NSDW, but not vice versa. For reasons of mass conservation, EBDW is transported into the Greenland box at the same rate as GSDW leaves the box into the NSDW box. Subsequently NSDW transports into the EBDW box have to be increased (fig. 1b).

The flow of EBDW is modelled following the concept of the deep western boundary current from the Arctic Ocean into the southern Greenland Sea, which provides salt and nutrients to the periphery of the deep basin. Thus the advective salt source of the EBDW and the deep convective negative heat source produce the GSDW'.

All three deep water masses show slightly but distinctly differing Θ/S-properties. Adding the available tracer data for tritium $^3H$, freon F-11 and helium $\delta^3He$, the hydrographic and transient tracer data provide a unique parameter space. The relevance of the tracers for the individual water masses is summarized below in TAB.(1), (high "++", medium "+" and low "-" levels):

| TAB.(1) | tracer content GSDW | EBDW | NSDW |
|---|---|---|---|
| tritium | + | - | - |
| F-11 | + | - | - |
| $\delta^3He$ | + | + | - |
| salinity | - | ++ | + |
| temperature | - | ++ | + |

We calibrated the models with a simultaneous fit to tracer and hydrographic data. A fit to tritium, freon and salinity proved to be the most consistent set. For helium and potential temperature additional sources and sinks cannot be excluded.

For potential temperature and salinity we used data from recent investigations in the European Polar Seas including the cruises "Knorr" TTO, 1981, "Hudson" 82-001, 1982, "Meteor" 61, 1982, "Polarstern" MIZEX and ARCHY in 1984. Tritium data were available from measurements of the Inst. f. Umweltphysik, University of Heidelberg ("Meteor" 42, 1976, "Meteor" 52, 1979, "Meteor" 61, 1982, "Polarstern" MIZEX and ARCHY, 1984) and of the Tritium Laboratory at the University of Miami (GEOSECS,1972 - OSTLUND et al., 1974; "Knorr" TTO, 1981 - OSTLUND, 1983). From the "Meteor" 52, 1979,"Meteor" 61, 1982, "Polarstern" MIZEX and ARCHY, 1984 cruises $\delta^3$He data were also used. For F-11 the average values for the deep Greenland and Norwegian Seas published by BULLISTER a. WEISS (1983) have been used. Measurements in Fram Strait indicate, that the F-11 concentration in EBDW parallels that of NSDW (BULLISTER, 1984; SMETHIE et al., 1986). We assumed an average value of 0.28 pmol/kg for EBDW in August 1984 based on the values reported by SMETHIE et al. (1986).

The hydrographic parameters for the deep boxes have been depth- and volume-averaged, the tritium and $\delta^3$He data were used as depth-weighted averages. The tracer concentrations for the upper boxes have been prescribed. We used the well-known tritium input function given by DREISSIGACKER a. ROETHER (1978), adjusted to the surface values of the Norwegian and the Greenland Seas. For F-11 and He we assumed solubility equilibrium at the sea surface, following for F-11 BULLISTER (1984) and THIELE (1985), for He BENSON a. KRAUSE (1980). Details of the models and their calibration are given by HEINZE (1986). In addition, the input functions for the surface had to be defined differently from the known literature. Since the surface Atlantic waters are in constant contact with the atmosphere only in the open Norwegian Sea, the traditional input functions have been used for the respective upper box. In the Arctic Ocean and the Greenland Sea, the Atlantic water is subducted to intermediate depths. It is covered by ice and a layer of polar surface water in the Arctic Ocean throughout the year. In the Greenland Sea the Atlantic is recirculated at intermediate depths. For both basins the contact with the atmosphere has ceased, and the input function from the surface Atlantic Water is carried along. To account for this effect, the input function for the Atlantic Water has been time-delayed for the Arctic Ocean and the Greenland Sea box following SCHLOSSER (1985). Proportional to the tritium decay, the accumulation of $^3$He has been accounted for. The tritium source on the Arctic shelves from freshwater input has been modelled after OSTLUND (1982).

By using simple budget equations, the distribution of the transient tracers tritium, freon F-11 and He as the $^3$He anomaly $\delta^3$He as well as potential temperature and salinity have been modelled. The tracer concentrations are varying in time, $\Theta$ and S have been assumed to be stationary.

The model was fitted to the data by varying the free parameters. As free parameters we used transports and production rates, the time-delay for the intermediate layers of the Arctic Ocean and Greenland Sea and the percentage rate of surface water to intermediate waters in the upper layers of the Greenland Sea. As fitting procedure we used a reduced chi-square test according to QUAY et al. (1983). Errors have been estimated in varying each free parameter, leaving the other parameters at the value needed for the best fit until the chi-square test indicated an unacceptable result ( $\chi^2_\nu > 1$).

## 3 RESULTS

In fig.(2) the input functions for the best fit of the model (case b) are shown. The respective model curves for the deep boxes are given in fig.(3). The results are summarized in TAB.(2) and fig.(4).

For the best fit the models gave the following results:

- For the production rate of the Greenland Sea Deep Water GSDW we find 0.55 - 0.59 Sv ($10^6$ km /s), for the EBDW 0.90 - 1.01 Sv. The turnover times based on deep vertical convection are 27 - 29 a for the GSDW and 88 - 99 a for EBDW.
- There is no vertical convection in the Norwegian Sea from the surface.
- The exchange rate between NSDW and EBDW amounts to 0.72 - 0.74 Sv. Model (b) shows an increased transport from NSDW to EBDW of 1.93 Sv. The Greenland Sea supplies 1.15 - 1.19 Sv of GSDW' to the Norwegian Sea. The overall turnover time for NSDW caused by advective fluxes amounts to 15 - 16 a. NSDW is a mixture of ca. 60 % GSDW' and 40 % EBDW.
- The traditional model (a) requires 1.15 Sv NSDW for the Greenland Sea Box, which then leads to no transport of EBDW from the Arctic Ocean to the Greenland Sea. Case (b), which has no transport of NSDW to GSDW', requires 1.19 Sv of EBDW for the Greenland Sea. This agrees with the present interpretation of recent data from the ICES Deep Water Project. This does not change the gross inflow- and outflow rates.
- The mean Θ/S boundary values of the source water masses from the model are -1.8 °C to -1.5 °C and 34.84 to 34.88 for GSDW and -0.8 °C to -0.6 °C and 34.94 to 34.97 for EBDW.
- The percentage of surface water contributing to GSDW amounts to 52 - 56 %.
- The input functions for the intermediate waters had to be delayed for ca. 6 a for both the GSDW and the EBDW.

TAB.(2) Box model results. (values in brackets = errors estimated from the reduced chi-square test)

| | case (a)<br>GSDW <-> NSDW | | case (b)<br>EBDW -> GSDW -><br>-> NSDW -> EBDW | |
|---|---|---|---|---|
| **production rates (Sv):** | | | | |
| GSDW | 0,59 | (0,37 - 0,74) | 0,55 | (0,38 - 0,68) |
| NSDW | 0 | ( 0 - 0,12) | 0 | ( 0 - 0,13) |
| EBDW | 1,01 | (0,18 - 1,79) | 0,90 | (0,15 - 1,62) |
| **exchange rates (Sv):** | | | | |
| GSDW' -> NSDW | 1,15 | (0,58 - 2,15) | 1,19 | (0,64 - 2,33) |
| GSDW' <- NSDW | 1,15 | (0,58 - 2,15) | 0 | |
| EBDW -> GSDW' | 0 | ( 0 - 1,92) | 1,19 | (0,64 - 2,33) |
| EBDW <- GSDW' | 0 | ( 0 - 1,92) | 0 | |
| EBDW <-> NSDW | 0,72 | (0,12 - 1,77) | 0,74 | ( 0 - 1,94) |
| **turnover times (a):** | | | | |
| GSDW' (convection) | 27 | | 29 | |
| EBDW (convection) | 88 | | 99 | |
| NSDW (advection from GSDW') | 25 | | 25 | |
| NSDW (advection from EBDW) | 41 | | 39 | |
| NSDW (advection, total) | 16 | | 15 | |
| **percentage of surface and intermediate waters for GSDW (%):** | | | | |
| surface w. | 52 | (26 - 77) | 56 | (24 - 87) |
| intermediate w. | 48 | (23 - 74) | 44 | (13 - 76) |
| **time-delay for the input functions of the intermediate waters (a):** | | | | |
| for GSDW | 7,1 | (1,1 - 15,5) | 5,6 | ( 0 - 16,9) |
| for EBDW | 6,3 | ( 0 - 20,3) | 6,5 | ( 0 - 20,6) |
| **average Θ/S boundary values:** | | | | |
| for GSDW Θ | -1.5 | | -1.8 | |
| S | 34.88 | | 34.84 | |
| for EBDW Θ | -0.8 | | -0.6 | |
| S | 34.94 | | 34.97 | |

## 4 CONCLUSIONS

The resulting turnover times for the Greenland - Norwegian Seas and the exchange rates agree well with the results of SMETHIE et al. (1986). The production rate of GSDW according to our model is slightly lower considering the upper limit of 1500 m for the deep boxes instead of 1700 m. In our model the salt balance has explicitly been carried out. The modelled Θ/S-values for the Deep Waters and for the respective source water masses support our results.

Model runs showed discrepancies for potential temperature and $\delta^3He$ from the data. The temperatures were slightly too low for the Norwegian Sea. For the Arctic Ocean and the Greenland Sea the deviation was less. For $\delta^3He$ the results were ca. 1-2 % too low in all three deep boxes. These differences have to be explained, at present, with sources and sinks we have not formulated in the model. For $^3He$ one cannot exclude that primordial sources are present in the area, which is dominated by mid-ocean ridges. One possible heat source might be the geothermal heat flux (LANGSETH and VON HERZEN, 1968).

The low tritium value in the Greenland Sea for 1982 (fig. 3a) indicates the lack of deep convective events during winter 1981/82. This is in agreement with hydrographic data showing rather low salinities in the upper layers during that period (CLARKE, 1986; CLARKE et al., 1986).

Our calculations do not significantly modify the existing estimates for the turnover times und exchange rates. They show, however, that it is possible to fit the data with a second, probably more realistic circulation scheme.

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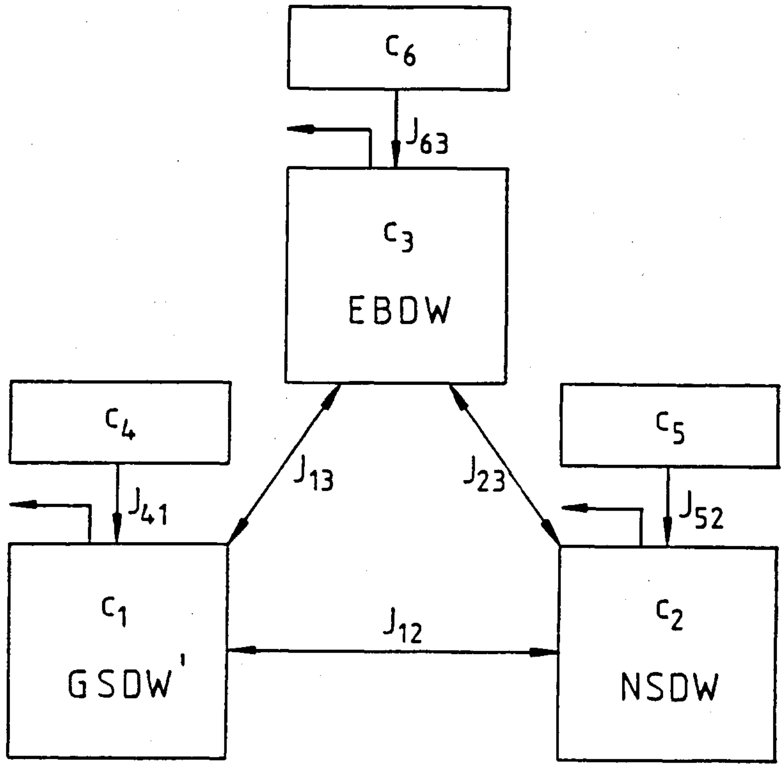


Fig.(1a) Box model concept "case a".
Exchange between NSDW ans GSDW′ at equal rates.

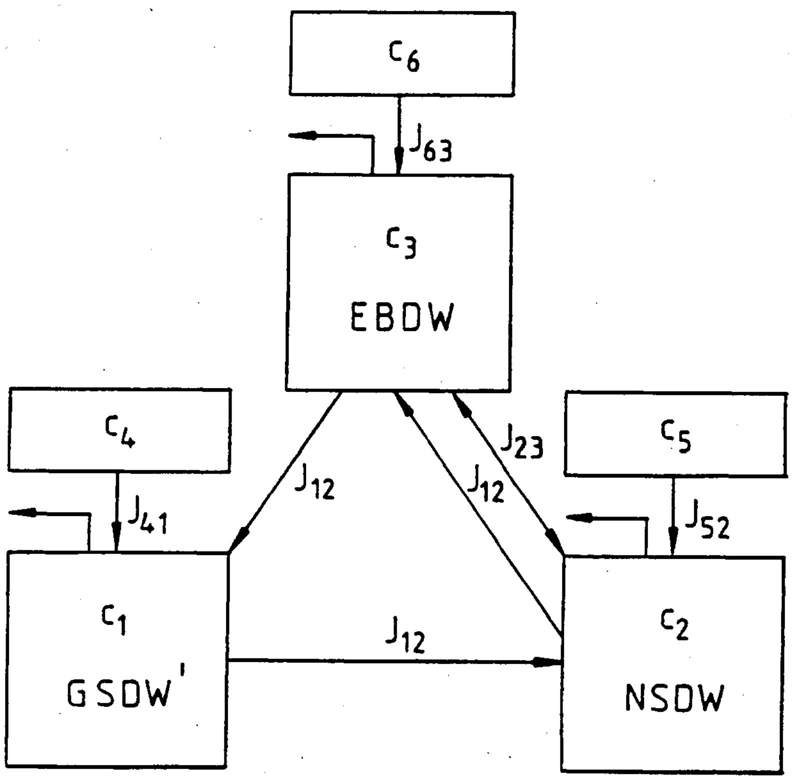


Fig.(1b) Box model concept "case b".
Internal circuit EBDW->GSDW′->NSDW->EBDW.

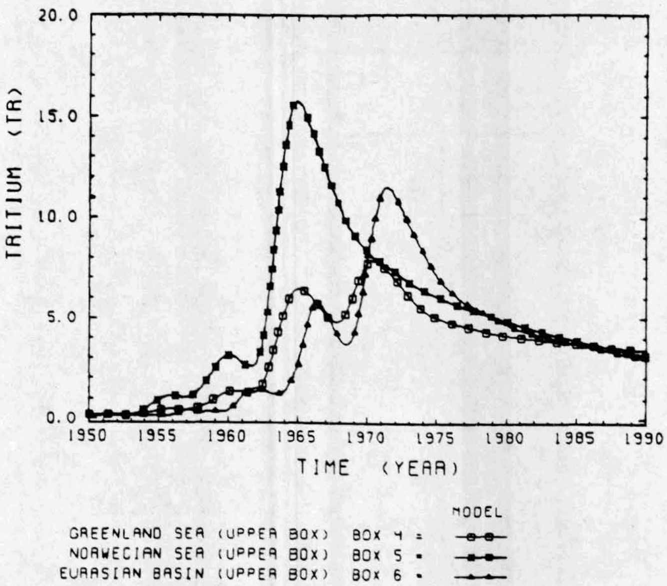


Fig.(2a)
Input functions
for tritium.

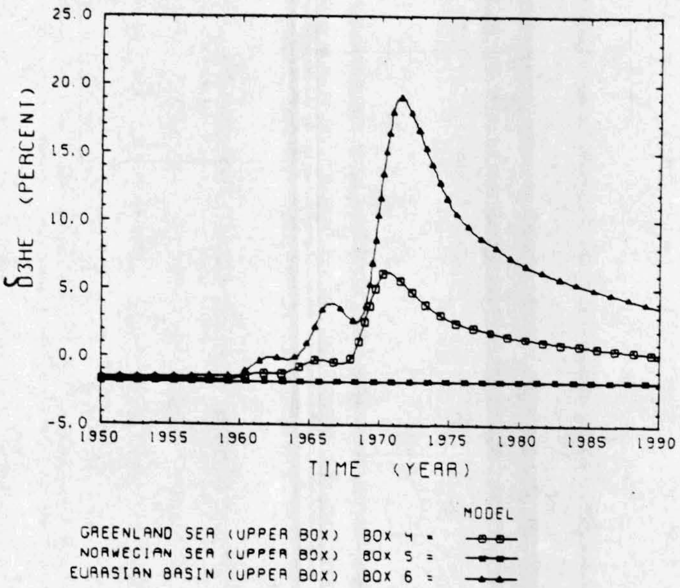


Fig.(2b)
Input functions
for $\delta^3He$.

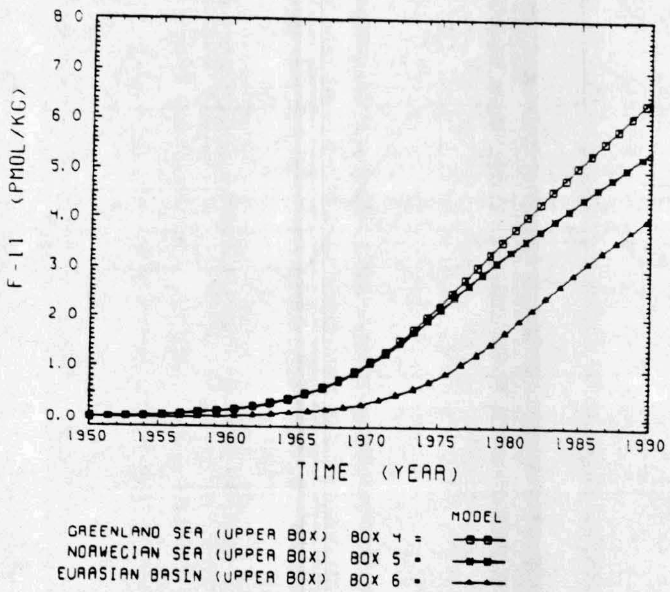


Fig.(2c)
Input functions
for F-11.

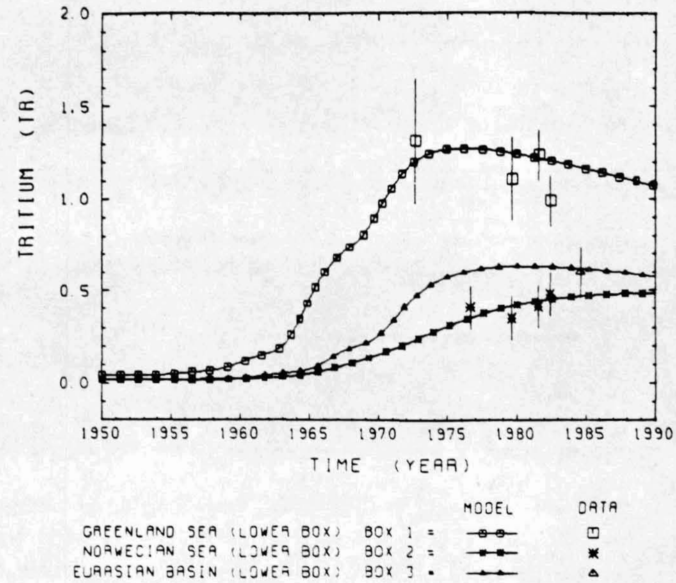


Fig.(3a)
Model functions for deep waters, tritium.

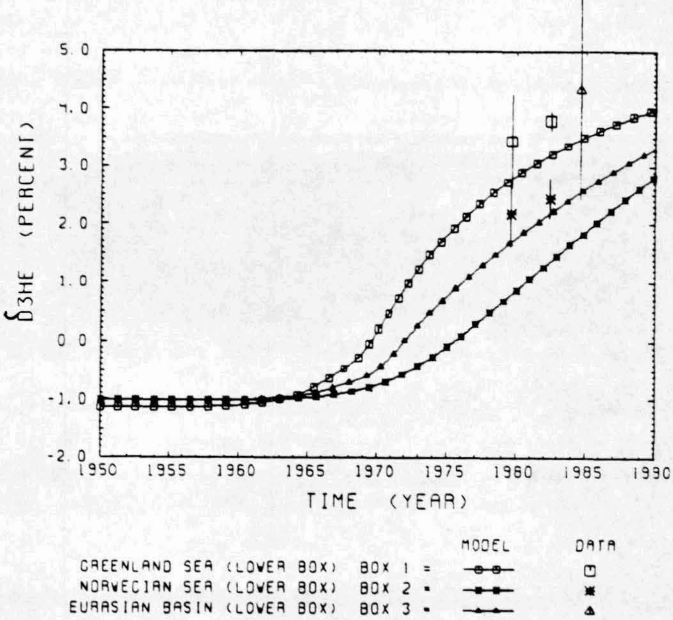


Fig.(3b)
Model functions for deep waters, $\delta^3He$.

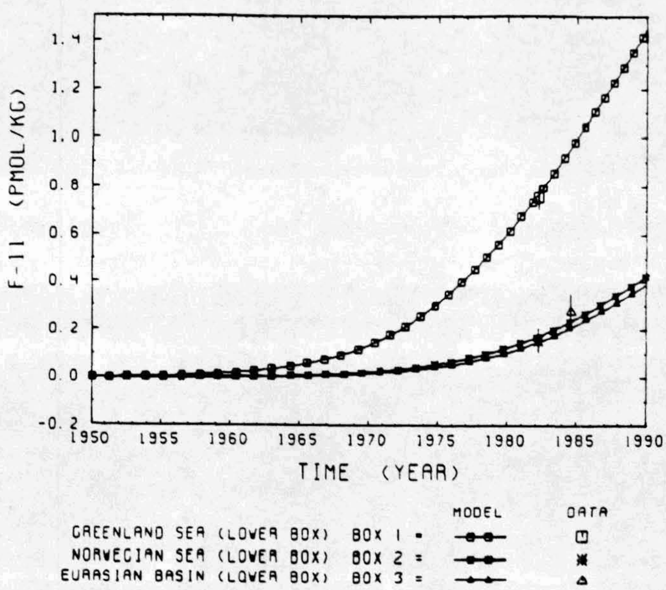


Fig.(3c)
Model functions for deep waters, F-11.

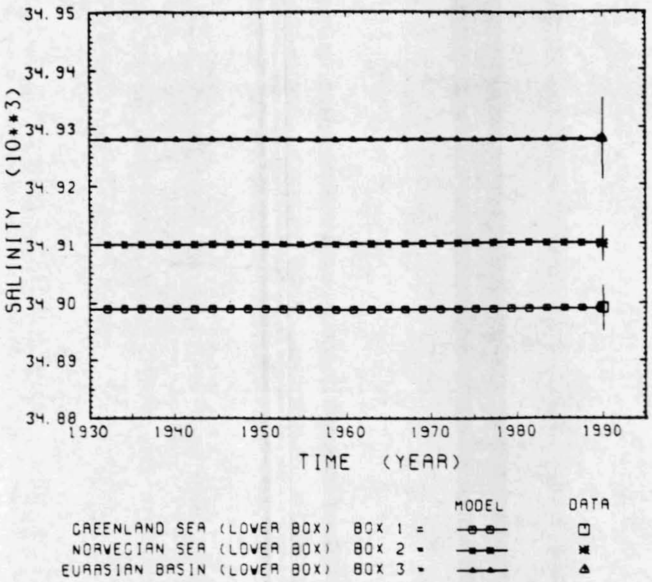


Fig.(3d)
Model functions
for deep waters,
salinity.

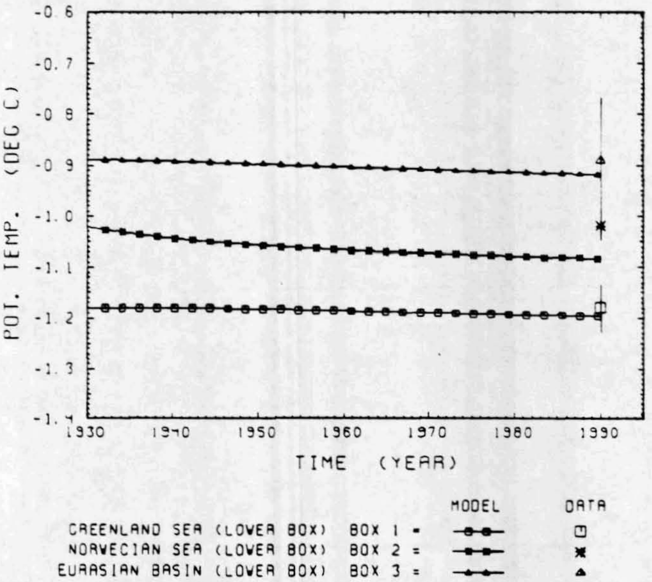


Fig.(3e)
Model functions
for deep waters,
potential temperature.

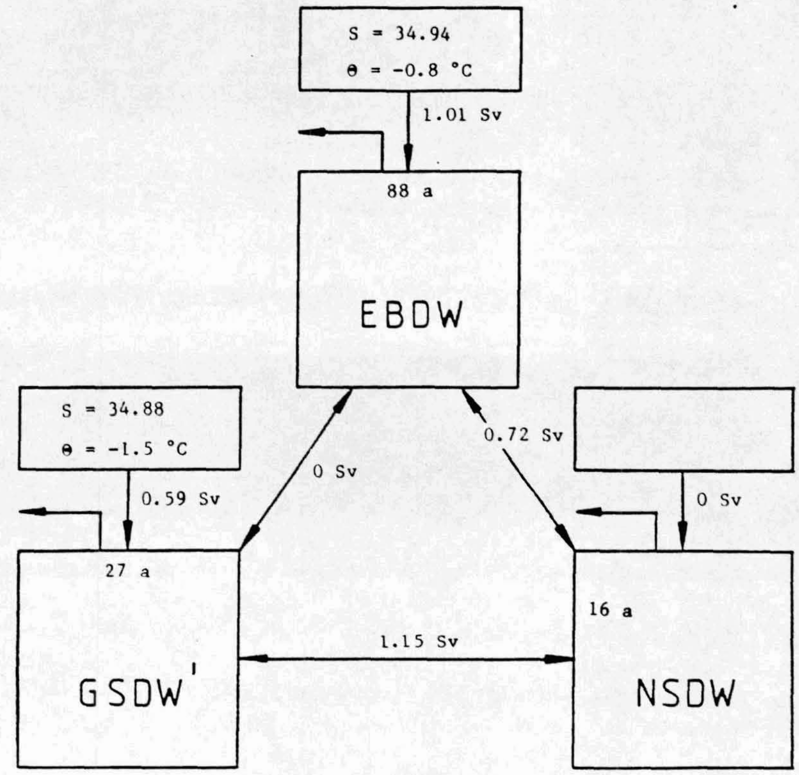


Fig.(4a) Case a. Exchange between NSDW ans GSDW′ at equal rates.

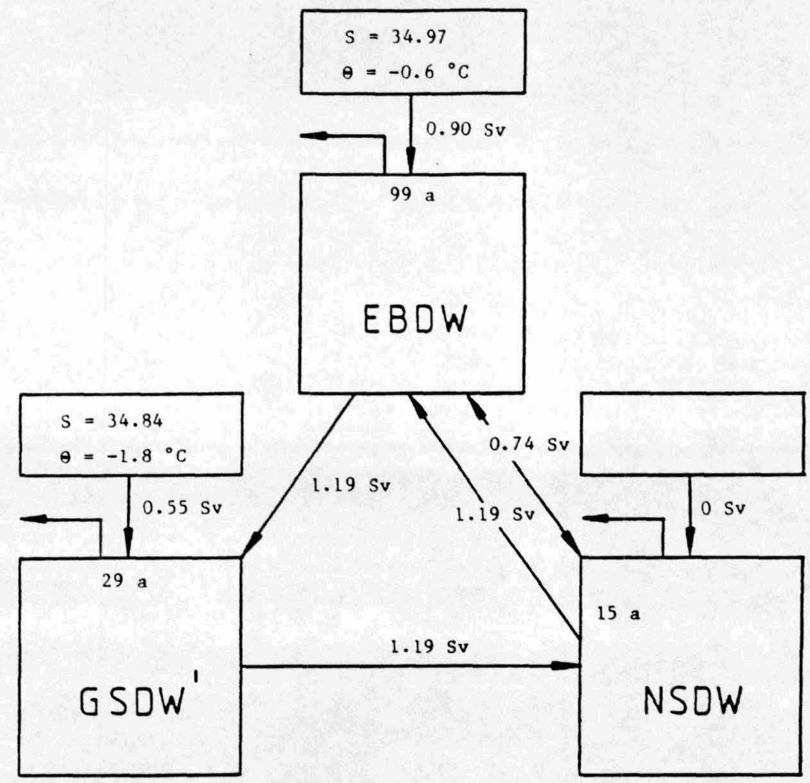


Fig.(4b) Case b. Internal circuit EBDW->GSDW′->NSDW->EBDW.