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Water mass census in the Nordic seas using climatological and observational data sets

S. Piacsek(1), R. Allard(1) and J. McClean(2)

(1) *Naval Research Laboratory, Stennis Space Center - MS, 39529, USA*
(2) *Scripps Institution of Oceanography, University of California - San Diego La Jolla, CA, 92093, USA*

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Summary. — We have compared and evaluated the water mass census in the Greenlend-Iceland-Norwegian (GIN) Sea area from climatologies, observational data sets and model output. The four climatologies evaluated were: the 1998 and 2001 versions of the World Ocean Atlas (WOA98, WOA01), and the United States Navy's GDEM90 (Generalized Digital Environmental Model) and MODAS01 (Modular Ocean Data Assimilation System) climatologies. Three observational data sets were examined: the multidecadal (1965-1995) set contained on the National Oceanographic Data Center's (NODC) WOD98 (World Ocean Data) CD-ROM, and two seasonal data sets extracted from observations taken on six cruises by the SACLANT Research Center (SACLANTCEN) of NATO/Italy between 1986-1989. The model data is extracted from a global model run at 1/3 degree resolution for the years 1983-1997, using the POP (Parallel Ocean Program) model of the Los Alamos National Laboratory. The census computations focused on the Norwegian Sea, in the southern part of the GIN Sea, between 10°W-10°E and 60°N-70°N, especially for comparisons with the hydrocasts and the model. Cases of such evaluation computations included: a) "short term" comparisons with quasi-synoptic CTD surveys carried out over a 4-year period in the southeastern GIN Sea; b) "climatological" comparisons utilizing all available casts from the WOD98 CD-ROM, with four climatologies; and c) a comparison between the WOA01 climatology and the POP model output ending in 1997. In this region in the spring, the fraction of ocean water that has salinity above 34.85 is $\sim$ 94%, and that has temperatures above 0 °C is $\sim$ 33%. Three principal water masses dominated the census: the Atlantic water AW, the deep water DW and an intermediate water mass defined as Lower Arctic Intermediate Water (LAIW). Besides these classes, both the climatologies and the observations exhibited the significant presence of deep water masses with T-S characteristics that do not fall into the "named" varieties, *e.g.*, Norwegian Sea or Greenland Sea deep water (NSDW, GSDW). The seasonal volumetric changes for the Atlantic (AW), intermediate (LAIW) and deep waters (DW) in the GIN Sea are in reasonably good agreement between the climatologies, and with the results of hydrographic census surveys. Typical seasonal changes (spring-summer) involve about $30 \times 10^3\,\text{km}^3$ of AW increase and $33 \times 10^3\,\text{km}^3$ of LAIW decrease, and a decrease of about $32 \times 10^3\,\text{km}^3$ of DW between spring and autumn.

PACS 92.05.Df – Climate and inter-annual variability.
PACS 92.05.Fg – Diurnal, seasonal and annual cycles.
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PACS 92.10.Dh – Deep ocean processes.

1. – Introduction

In this paper we have set out to examine, compare and verify certain derived data sets, namely water mass census based on different data bases. The motivation was to 1) furnish an additional metric for verifying the accuracy of the mixing and transport processes of ocean models, 2) provide an additional tool for the scientific budget studies of these processes, and 3) provide synoptic data for the initialization, boundary and/or surface forcing for ocean models. This study has also led us to point out the strengths and deficiencies of the climatological fields and archived CTD data sets, upon which the models rely for these functions.

1·1. *Motivation: Use of climatologies in ocean modeling.* – Since synoptic 3D temperature and salinity fields are generally not observed over the extent of a whole ocean basin, most basin-scale ocean models are initialized with climatological temperature and salinity fields, and many also include a restoring term during the time integration that relaxes the temperature and salinity fields back to climatology over a certain period and/or a certain subregion. Often this restoring is confined to the surface, but in other cases (as in the case of Arctic simulations) it includes portions of the three-dimensional ocean volume, albeit with different time constants [1-5]. Similarly, at open boundaries one is often constrained to use fluxes derived from climatology.

Climatological temperature and salinity fields are also needed for supplemental information when creating synoptic oceanographic data sets for assimilation/forecasting purposes, as basin-wide sets of synoptic 3D temperature and salinity observations are very rarely available. The climatologies serve as useful first guess fields in the assimilation procedure.

An understanding of the processes of water mass transformations can shed light on the dominant thermodynamic and dynamic processes of a given region [6, 7]. This is especially important in high latitude seas that are covered with a seasonal or permanent ice cover, where the addition of brine during freezing periods and the excessive winter cooling introduce strong buoyancy effects and mixing, and in general lead to a complex series of water mass transformations.

1·2. *Background: Watermasses.* – A classic method of characterizing the properties of an oceanic region is to classify its water mass types, their spatial distribution and temporal variability. Based mostly on the well-known T-S (temperature-salinity) relation, the thermohaline structure of a given ocean can be conveniently described by only a few water mass types. The tendency toward permanence of the water mass distributions testifies to the quasi-permanent and repetitive nature of the processes that maintain this structure, namely air-sea interaction, convective and double diffusive mixing, and transports in and out of the respective region [8].

The export of certain water masses out of their basin of production is of great interest in climate studies, as the associated heat and salt advection forms one of the main components of the global thermohaline circulation. In particular, the advection of intermediate and deep waters out of the GIN Sea Basin, where it is formed by various mixing processes, has a global significance, since these outflows influence the formation of deep water in the Atlantic Basin.

Because water mass distributions are relatively stable and highly characteristic of a given oceanic region, they can be a useful tool for evaluating the output of models that aim to describe the thermohaline structure and its seasonal variability. A thorough study of the water mass distributions in the Greenland and Iceland Seas was made by Carmack and Aagaard [9], and Swift and Aagaard [10]. Petersen and Rooth [11] analyzed radioactive tracers to study the mixing processes in the Greenland Basin. These studies included deep water production as well as the transformations between other water masses. They were mainly confined to cruise data during the summer and winter seasons, but in the climatological studies we shall include all four seasons. More recently, consecutive cruises over an eight-year interval (1986-1993) have been carried out by the SACLANT Research Center in the Norwegian Sea and the Iceland-Faroe frontal areas [12-14]. Piacsek *et al.* [15] utilized the cruise data to make a corresponding water mass analysis for the area.

1·3. *Scope of present paper*. – We have compared and evaluated five climatologies: the 1982, 1998 and 2001 versions of the Levitus climatology [16], hereafter referred to as LEV82, and World Ocean Atlas WOA98 and WOA01 [17-19]; also two Navy climatologies: the Generalized Digital Model (GDEM, 1990 version) [20], and the Modular Assimilation System (MODAS, 2001 version) [21]. These will be hereafter referred to as GDEM90 and MODAS01.

The census computations, especially for comparisons with the hydrocasts, focussed primarily on a sub-region of the GIN (Greenland-Iceland-Norwegian) Sea where CTD data was found relatively "abundant" [10°W-10°E, 60°N-70°N].

All these climatologies carry out their analyses of the hydrographic data on fixed level surfaces, on the so-called "standard" hydrographic depth levels (33 levels to 5500 m). Actually, the MODAS01 climatology adds two more surface levels at 5 m and 15 m.

More recently, Lozier *et al.* [22] have prepared a climatology of the North Atlantic based on analyzing measurements on isopycnal surfaces. This procedure eliminates the artificial mixing introduced by averaging neighboring water masses on a level surface. Since the northern limit of their analysis is 65°N (the large σ_t values of the Greenland Sea are not found in the North Atlantic in general), and since the main focus of the current study is the GIN Sea and Arctic waters north of 60°N, we have not included it here, but will include it in a follow-up study.

It should be noted that this same kind of artificial mixing of water masses also occurs in fixed-level ocean models [1, 23], in contrast to mixing in isopycnal ocean models [24, 25]. Since climate-related ocean model studies have been using predominantly level type models during the last two decades, it was considered worthwhile to prepare a water mass census of the Levitus, GDEM and MODAS climatologies, to provide some check on their "thermodynamic performance". Recent advances in higher horizontal and vertical resolutions of the models (say 1/4° to 1/32°, with 40-60 vertical levels) will produce, in any case, much smaller artificial mixing than the climatologies with 1.0, 0.5 or even 0.25° resolution and 33 levels. A comparison of the 1.0° LEV82 and the 0.5° resolutions GDEM90 climatologies was performed by Teague *et al.* [20], employing the computed dynamic heights.

We have considered a water mass census in the Nordic seas a risky venture from the outset, knowing the sparsity of data that went into building the climatology, but felt nevertheless that an effort in this direction should be made to help evaluate and pinpoint the climatic drifts that all long-term numerical integrations inevitably suffer when forced with external atmospheric forcing functions. Climate-related long-term global simulations including the Arctic are becoming more numerous, and the representation of water mass change processes is an important guide to the correctness of thermodynamic ocean models. The census can also serve to point out the need for more deep-cast CTD data to delineate the deep water masses, and the preparation of new climatologies for future climate-related work.

We have also realized that these climatologies differ in their grid resolution [WOA98: 1×1 deg, GDEM90: 0.5×0.5 deg, WOA01: 0.25×0.25 deg, MODAS01: 0.125×0.125 deg], the hydrographic data bases utilized, and the interpolation and smoothing procedures employed, and that these factors will be the main causes of the differences of the census results. So besides comparing the different census obtained for the climatologies, we have also made some limited comparisons to census derived directly from hydrographic data, in order to establish some of the valid and deficient aspects of these climatic data sets. These evaluations have included two studies of "seasonal" comparisons with census derived from six extensive hydrographic cruises with many deep casts, and "climatological" comparisons with all available hydrocasts from the World Ocean Database 98 CD-ROM (hereafter referred to as WOD98(1)).

In sect. **2** we will give a brief description of the climatologies. In sect. **3** we discuss the analysis approach, including maps of the computational regions and the decomposition of the T-S diagram for census purposes (with a special figure for the deep water subclasses), outline the hydrographic data bases on which the census comparison will be based, and discuss special depth level and seasonal concerns. In sect. **4** we present the census results, give comparisons and relate them to observations. In sect. **5**, we make a summary of the results, and some conclusions and recommendations for future studies.

2. – Description of climatologies and methodologies

2·1. *The Levitus climatologies: LEV82, WOA98, WOA01.* – The first version of this climatology, hereafter referred to as LEV82, was published in 1982 [16], and used all observations available in the National Oceanographic Data Center (NODC) station data files up to 1978. It was prepared on a 1.0° by 1.0° grid, on the standard 33 hydrographic depth levels (for the depth values see table I). The data was divided into four seasons, with winter being February-April, spring May-July, summer August-October, and fall November-January. They were further sorted into latitude-longitude bins on a 360×180 grid where the boundaries of the grid boxes are the one degree latitude-longitude lines. The resulting temperature and salinity fields were obtained with the objective analysis scheme of Cressman [26], based on iterative difference-corrections. The final data points were located at the center of the 360×180 grid boxes, in effect on the half-degree lines of latitude and longitude.

WOA98(2) has followed the 1982 procedure to some extent, with 3 important differences: 1) the seasons were shifted to winter being January, February, March, etc.; 2) additional data was included that was obtained over the next 17 years by NODC projects and by the Alfred Wegener Institute for Polar and Marine Research of Germany; and 3) the improved analysis scheme of Barnes [27] was used, which required only one successive correction with a smoothing length scale of 771 km. Some additional smoothing was included by running median and mean filters. LEV82 prepared only an annual climatology for depths exceeding 1500 m, but WOA98 and WOA01(3) have deep values on a seasonal basis as well.

(1) WOD98: World Ocean Profile Data 98: contact NODC.services@noaa.gov.
(2) WOA98: World Ocean Atlas 98: See refs. [17] and [18].
(3) WOA01: World Ocean Atlas 2001: See ref. [19].

TABLE I. – *The* 33 *Standard Depth levels of five climatologies: LEV82, WOA98, WOA01, GDEM93 and MODAS (the last one has two extra levels inserted near the surface, at* 5 m *ad* 15 m*, respectively, for a total of* 35*). Table also includes the* 32 *depth levels of the* $POP_{1/3}$ *global model grid.*

STANDARD	POP
level 1—0.0 m	level 1—12.6 m
level 2—10.0 m	level 2—37.9 m
level 3—20.0 m	level 3—63.7 m
level 4—30.0 m	level 4—90.3 m
level 5—50.0 m	level 5—118.0 m
level 6—75.0 m	level 6—147.0 m
level 7—100.0 m	level 7—178.0 m
level 8—125.0 m	level 8—212.0 m
level 9—150.0 m	level 9—248.0 m
level 10—200.0 m	level 10—289.0 m
level 11—250.0 m	level 11—334.0 m
level 12—300.0 m	level 12—387.0 m
level 13—400.0 m	level 13—447.0 m
level 14—500.0 m	level 14—519.5 m
level 15—600.0 m	level 15—607.0 m
level 16—700.0 m	level 16—714.0 m
level 17—800.0 m	level 17—847.0 m
level 18—900.0 m	level 18—1010.0 m
level 19—1000.0 m	level 19—1210.0 m
level 20—1100.0 m	level 20—1450.0 m
level 21—1200.0 m	level 21—1710.0 m
level 22—1300.0 m	level 22—1990.0 m
level 23—1400.0 m	level 23—2280.0 m
level 24—1500.0 m	level 24—2580.0 m
level 25—1750.0 m	level 25—2880.0 m
level 26—2000.0 m	level 26—3180.0 m
level 27—2500.0 m	level 27—3480.0 m
level 28—3000.0 m	level 28—3780.0 m
level 29—3500.0 m	level 29—4080.0 m
level 30—4000.0 m	level 30—4380.0 m
level 31—4500.0 m	level 31—4680.0 m
level 32—5000.0 m	level 32—4980.0 m
level 33—5500.0 m	

2˙2. *The GDEM90 climatology.* – A complete description of the methodology used to prepare the GDEM climatology is beyond the scope of this paper. A published description of it is given in Teague *et al.* [20], where also comparisons are made with the Levitus climatology concerning dynamic heights. Recently, an electronic publication has appeared on a web site (in connection with the new US-Russian Arctic Ocean Atlas) that describes the version of GDEM used here, denoted by GDEM90, in a concise way (`http://ns.noaa.gov/atlas/html/met/met-int.htm`). Here we give a brief synopsis of the method, outlining the key steps but omitting the mathematics.

The GDEM90 climatology is prepared on $0.5° \times 0.5°$ squares, on the usual standard hydrographic depth levels as Levitus (table I). Seasonal variations are included at all depths. There is no horizontal smoothing as such (other than grid-box averaging), but there is horizontal interpolation. In the GDEM version used here, the data utilized by the computations included all the public data from NODC up to 1986, as well as restricted data of the US Navy. For GDEM the seasons are defined in the more customary manner, as in WOA98. Sea surface temperatures are in fact available at monthly intervals.

The first step in preparing the GDEM climatology was the determination of a set of analytical curves that represent the mean vertical distributions for grid squares. This was accomplished by averaging the coefficients of functional expressions chosen to represent the vertical profiles of the individual data casts. Three sets of functions were chosen to represent shallow, mid-depth and deep depth ranges, to minimize the number of parameters required to yield a smooth mean profile. Temperature and salinity determinations were done independently. In the top 400 meters, eight coefficients in a nonlinear least-squares method were used for temperature, and five-degree orthogonal polynomials for salinity. In the mid-depth range, seven-degree and five-degree polynomials were used for the temperature and salinity, respectively. Finally, the deep profiles were fitted with quadratic polynomials. In view of the nonlinear nature of the functions, the average coefficients are not the same as the coefficients of the averaged data. For further details the reader is referred to Teague *et al.* [20] and Davis *et al.* [28].

The second step was the determination of the horizontal grid onto which the polynomial coefficients were to be interpolated using minimum curvature splines. This was chosen to be a grid three times coarser than the final grid on which the digital data was to be published. By choosing such a coarser grid, the number of grid cells without data points, or with very few in it, were minimized.

The third step was the fitting of the coefficients onto this coarse grid using the minimum curvature splines [29, 30]. This step helps reduce the effect of aliasing due to data-void and data-poor grid cells. By using both published and restricted data, the number of such cells were very few.

Finally, the coarse grid values are interpolated onto the desired, final grid using cubic splines, and the actual digital temperature and salinity values are synthesized from the polynomial coefficients.

2˙3. *The MODAS climatology*. – MODAS has been designed to assimilate remotely sensed and *in situ* measurements, with the help of model-derived first guess fields, to prepare daily synoptic ocean states for environmental nowcasts as well as input to forecast models [21, 31]. Some of the elements of this system have also been used to generate climatological ocean fields: it is these latter fields we will discuss in this paper. A detailed description of the "static" climatology is given in Fox *et al.* [21], and we can only give a brief synopsis here. In many ways, it follows the procedure of Levitus and Boyer [32]. Noteworthy to mention are the facts that only profiles with cast/bottom depth ratios > 0.5 were kept, and in regions with bottom depths > 600 m, casts shallower than 300 m were rejected. The observations were binned into bi-monthly intervals, and care was taken not to "mingle" close observations in physically distinct regions. The climatology is stored on a variable grid that ranges from $1/8°$ near land, to $1/4°$ on shelves and $1/2°$ in the ocean basins. Monthly, a $1/8°$ global climatology was also generated: we refer to this as MODAS01, and it was used in the present calculations.

2˙4. *Preparation data bases*. – Both GDEM90 and MODAS01 have utilized observational data bases in preparing the climatology that have included restricted data from the Navy. For the time being, these climatologies have to be verified with available published data such as WOD98 (included in the data used in preparation), and with the WOA98 climatology, noting that both WOD98 and WOD01(4) are public data sets. To understand how closely a climatology represents the data base from which it was derived, was not the main object of this paper. To evaluate the interpolation algorithms, it is necessary to have exactly the data that went into it. However, to estimate the usefulness and validity of these climatologies for modeling purposes, comparisons with data bases that include only part of (or are different from) the "preparation data base", as well as with climatologies derived from known data bases, should be sufficient and certainly useful.

2˙5. *The global POP model.* – The set-up of the global ocean model, the results of which were used in this study, is described in detail in McClean *et al.* [5], so only the salient details are discussed here. The model is the Los Alamos National Laboratory's Parallel Ocean Program POP [33, 34]. The domain is fully global and is configured on a displaced pole grid whereby the North Pole is rotated into Hudson Bay to avoid a polar singularity [35]. The grid is eddy-permitting: it has an average resolution of 1/3° and 32 levels. A blended global bathymetry was created from Smith and Sandwell [36] and ETOPO5(5) in the Antarctic and Arctic. All important sills and channels were checked and modified to facilitate correct flow. The Large *et al.* [37] mixed layer parameterization, K-Profile Parameterization (KPP), was active. The model was initialized from the annual WOA94 (Levitus 1994) potential temperature and salinity climatology, and was spun-up for 30 years. During the spin-up it was forced with a daily climatology of momentum, heat, and freshwater fluxes formed from 1979-1993 European Centre for Medium Weather Forecasts (ECMWF) daily reanalysis (ERA) fields. To limit model drift, surface restoring to monthly climatological potential temperature and salinity with a time scale of six months was used. In the polar regions this surface restoring provides, to a certain degree, the climatological effects of ice on the model hydrography. No active ice model, however, was coupled to the ocean model. Since the oceanic signal examined in this study originates in the North Atlantic and passes almost entirely through year-round ice-free waters, the effects of not using an active ice model are likely to be small.

3. – The analysis approach

We approached our census studies from two perspectives: to compare the climatologies in regions of modeling interest, *e.g.*, the GIN Sea, and to evaluate the climatologies against available data in both "data rich" (WMO Squares 1600 and 7600), and "data poor" (WMO Squares 7700, 1700) regions, respectively (fig. 1).

The census approach was also guided by the highly smoothed and averaged nature of the climatological temperature and salinity fields, where the close T-S relations found in individual casts become dispersed due to the averaging and interpolation during preparation of the climatology (except in data sparse areas where individual classes and tracks can be detected). We have therefore adopted the simple approach utilized in past studies for such census, by subdividing the T-S area into rectangular sub-regions, whose boundaries correspond more or less to the T-S limits that are used to define some "known" or

(4) WOD01: World Ocean Database 2001: Ocean Climate Laboratory, NOAA, NODC Internal Report #16, March 2002.
(5) ETOPO5: global 5° topography at `http://www.ngdc.noaa.gov/mgg/global/etopo5.html`

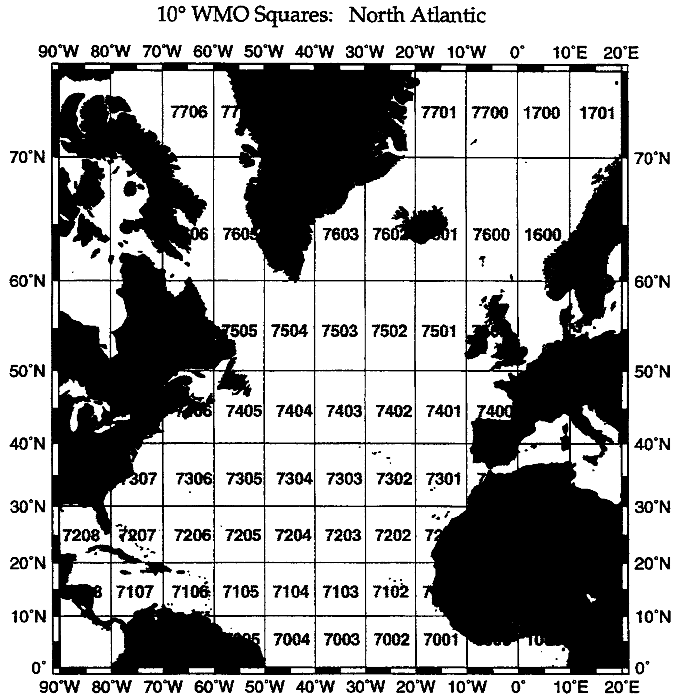

Fig. 1. – WMO Ten-Degree Squares arrangement in the GIN Sea, part of the census region (from [41]). The reduced GIN Sea domain, also referred to as the Norwegian Sea domain, consisted of WMO Squares 1600 + 1700, to make up the region 10°W-10°E, 60°N-70°N.

"named" water masses. These were usually defined by earlier researchers to facilitate the identification of water masses and transformation processes, based on some clustering of points in the T-S diagram. In particular, we will base our watermass classifications on the works of Carmack and Aagaard [9] and Johannessen *et al.* [38].

3·1. *The census regions.* – Altogether four census regions were considered, that correspond with the four WMO (Marsden) $10° \times 10°$ squares: 1600, 7600, 7700, and 1700, encompassing the region (10°W-10°E, 60°N-80°N). Because of modeling interests, we looked at the whole GIN Sea basin (20°W-20°E, 60°N-80°N). To compare with data, we focused on the squares 1600 and 7600, based on data density found in WOD98 ($\sim$ 5000 casts in the spring season of years 1965-1995), and on the fact that this was the region in which the SACLANT Center from Italy has carried out 7 extensive CTD surveys over the 4-year period 1986-89 (730 bottom-reaching casts).

3·2. *Division of the T-S domain.* – Previous studies of volumetric census in this region [9, 10] divided the T-S region into small intervals of 0.2°C and 0.02 psu, and then found the depth interval over which a given range extended. The depth intervals were then multiplied by the surface area associated with each station. Exactly how the area of representation was determined for each station was not discussed. They have also prepared T-S scatter diagrams from all the individual casts. The points in the diagram fell into "condensed" regions which were approximated by boxes; the major boxes then were found to correspond to the well-known water mass types of the region.

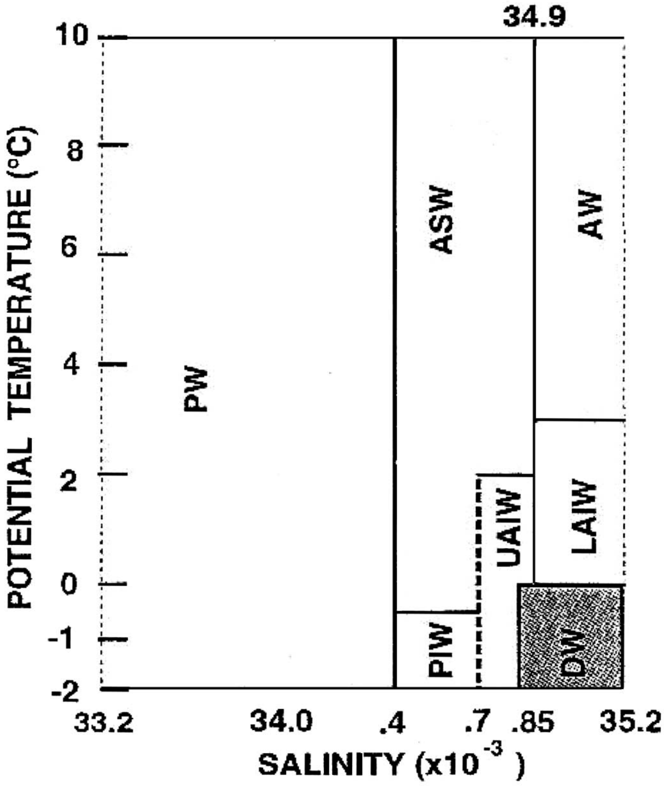

Fig. 2. – Primary decomposition of the T-S diagram into seven major classes. Here AW is Atlantic water, PIW is polar intermediate water, UAIW is upper arctic intermediate water, LAIW is lower arctic intermediate water, and DW is deep water (after [10]).

In this study we will use box volumes centered on the standard hydrographic depths used in all the climatologies (for depth values, see table I), and adopt a water mass classification based on fig. 13 of Carmack and Aagaard [9], and table 1 of Johannessen *et al.* [38]. The choice of the crude depth intervals is somewhat justified when we consider the ultimate purpose of the study, namely the evaluation of thermodynamic models employing even cruder vertical resolution.

A modification of the deep water class was performed by Piacsek *et al.* [15] with the establishment of additional deep water sub-classes. We found that in addition to Norwegian Sea, Greenland Sea and Arctic Ocean Deep Waters (commonly labeled NSDW, GSDW and AODW, respectively), the Arctic and its marginal seas contained various amounts of 6 more deep water classes, with seasonal percentages ranging from 1 to 14. Among these classes (see fig. 2), DW7 contains as a subset Canadian Basin Deep Water (CBDW), defined by Aagaard *et al.* [39] as water with limits $-0.5°\mathrm{C} < T < -0.25°\mathrm{C}$ and $34.94 < S < 34.95\,\mathrm{psu}$, and AODW contains Eurasian Basin Deep Water (EBDW), with limits $-0.9°\mathrm{C} < T < -0.6°\mathrm{C}$, $34.92 < S < 34.93\,\mathrm{psu}$.

Hopkins [12] and Johannessen *et al.* [38] define NSDW having salinity in the range $[34.90 < S < 34.94\,\mathrm{psu}]$, which would include the class AODW, defined by Swift *et al.* [40] as water having a salinity range of $[34.92 < S < 34.94\,\mathrm{psu}]$. We will separate

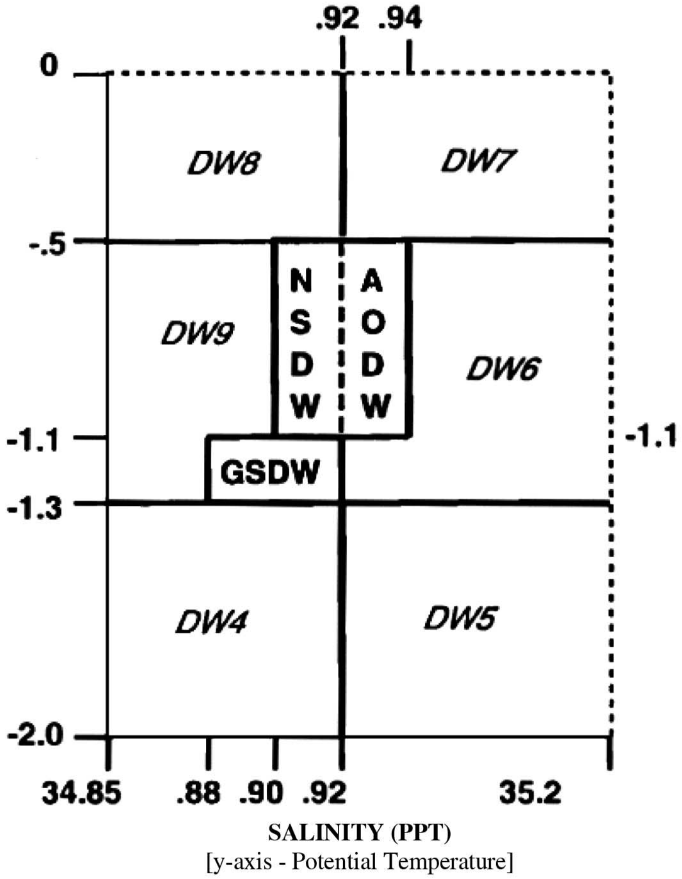

Fig. 3. – Secondary decomposition of the T-S diagram for deep water (DW) into nine sub-classes (after [15]): Greenland Sea Deep Water (GSDW), Norwegian Sea Deep Water (NSDW), Arctic Ocean Deep Water (AODW), and 6 other classes, defined typically as cooler or warmer, and saltier or fresher, than GSDW and NSDW; they are denoted as DW4 through DW9, respectively.

these classes, assigning NSDW the range [$34.90 < S < 34.92$ psu], and AODW the range [$34.92 < S < 34.94$ psu], in order to enhance the differences in the climatologies, between the GIN Sea and the Arctic, and the seasons.

Figure 2 shows the primary decomposition of the T-S diagram area into seven major categories: polar water (PW), polar intermediate water (PIW), Atlantic water (AW), arctic surface water (ASW), upper arctic intermediate water (UAIW), lower arctic intermediate water (LAIW), and deep water (DW). Swift and Aagaard [10] have further subdivided the polar and arctic surface waters into two classes: PW1, PW2 and ASW1, ASW2, respectively. PW1 includes all water with salinities less than 34.0 psu (*e.g.*, the Norwegian coastal current).

Figure 3 shows the decomposition of deep water into the three known types (NSDW, GSDW and AODW) and into 6 additional classes, all but one of which (Class 5) were found in abundance in the Arctic Basin and in significant amounts in the GIN Sea. Only traces of the heaviest water Class 5 was found, but all other sub-classes (DW4, DW6-DW9) exhibited significant percentages, up to 5% for DW7 and up to 14% for DW8.

The T-S boundaries of these six deep water classes were determined partly based on considerations of computational ease, and partly as possible extensions of the other water masses.

3˙3. *Seasonal considerations*. – An examination of the WMO Squares in the GIN Sea region revealed similar distributions of the number of observations across the seasons: the highest numbers are found in the spring, followed by slightly lower summer numbers, and tailed by comparable fall/winter numbers that are 1/5 to 1/3 of the spring numbers. To perform the "data-rich" comparison, we used the WMO Squares 1600 and 7600 in the spring, with over 5000 casts. Also the SACLANT Center cruises have clustered in the spring and fall months. We have lumped the May 1987, June 1986 and June 1989 SACLANTCEN cruise data into a "spring" set, and the September 1987, October 1989 and November 1988 cruise data into a "fall" set.

3˙4. *Depth considerations*. – The three climatologies used the same depth levels (see table I), except for the additional surface levels of 5 m and 15 m in MODAS. Since very few locations reach 4000 m in the GIN Sea, and moreover, since very few CTDs went below 3000 m (or bottles for that matter), we have decided to confine our studies to a depth of 3000 m only. For the SACLANTCEN data sets we have also made water mass census using 10 m intervals, and compared them with the census obtained from the data set on the standard levels.

We have chosen to utilize information concerning the maximum depth for each cast as found in WDO98. In this way, it was easy to assign the same depth limits to the climatology profiles during the volume computations (*i.e.* when the climatology profiles were interpolated to the ctd locations). Another useful, in fact necessary, procedure involved the "filling" or "extension" of the climatological profiles below the bottom via Empirical Orthogonal Functions (EOF's), so that during interpolation no trouble arose when near land points.

The layer thicknesses for volume computations were computed using the mid-points between the depth levels of table I. In this study we have focused our presentations on the relative percentages in which the various water masses contribute to the volume of a given ocean region. The volumes themselves, though they had to be computed carefully to do the percentage analysis, were found not to be suitable for comparison, since the topography and hence the total volume associated with each climatology differed considerably due to the different horizontal resolutions. *E.g.*, the total volume computed for a "reduced" GIN Sea area (10°W-10°E, 65°N-80°N) is $4.14 \times 10^3\,\mathrm{km}^3$ for LEV82 (1×1 deg), and $3.87 \times 10^3\,\mathrm{km}^3$ for GDEM (0.5×0.5 deg).

3˙5. *Profile selections*. – A much bigger concern was the failure of many hydrocasts to reach near to the ocean bottom, thus missing out on information concerning deep water masses. The mean (cast depth)/(bottom depth) ratio R_{cb} for the 5000 spring 1966-1995 casts from WOD98 is about 0.50, whereas this ratio is about 0.87. We have decided to keep track only of casts for which R_{cb} is > 0.70. To more properly weight the deeper waters, we have also omitted casts whose depth was < 200 m.

We have rejected profiles which contained 4 or more consecutive, or 6 in total, missing depth values in either T or S. It was found to be difficult to use interpolation to fill missing values for those occurrences.

4. – Results and discussion

We commence the discussion of the results with three "validation" or "evaluation" studies. Strictly speaking, we will not do "validation" in the sense of the usual model validation studies, since then we would have to have access to all the data and analysis techniques involved in preparing the various climatologies. Rather, we do "evaluations" to yield a qualitative and/or a semi-quantitative overview of the water mass structures in the GIN Sea and the differences in their census. Some questions that have arisen are: 1) does the census performed on 295 ten-meter levels of a CTD survey vary much from one extracted from the same data set on the standard 28 depth levels (down to 3000 m)? 2) Does a census derived from 456 bottom-reaching CTDs spread over 4-week spans in each of 3 successive years (120, 167, 169 CTDs, respectively) approximate well the seasonal census derived from the various climatologies? 3) How does the watermass census derived directly from the individual observation profiles differ from one derived from the analyzed fields? 4) Which water mass classes are most affected by a change in the low-temperature limit of AW definition, $T_{\mathrm{AW}} = 3\,^{\circ}\mathrm{C}$, to a value of $2\,^{\circ}\mathrm{C}$? 5) How large are the differences in water mass volumes and percentages obtained by climatologies utilizing: a) different analysis techniques, b) significantly more or different data sets; and c) non-uniformly distributed (locally dense and spare) data sets?

The next 5 sections will try to answer, at least partially, each of the above questions, and at the same time give a general insight into the water mass structures, their depth dependence and geographical distribution in the GIN Sea. For the most part, we will be presenting percentages, *i.e.* volume fractions, which the various water masses occupy in a given region. But during our discussion of seasonal variations, we will present some volumes figures (in units of km^3) as well.

Test regions include 1) the CTD tracks of the May 1987 SACLANTCEN cruise, used to calculate depth level dependence of the census; 2) the CTD tracks of the 3 spring (1986, 1987, 1989) and 3 fall (1987, 1988, 1989) cruises, covered by the two WMO squares 1600 and 7600 [10°W-10°E, 60°N-70°N], 3) the "data-dense" regions of the GIN Sea in WOD98, WMO squares 1600, 1700, 7600 and 7700 [10°W-10°E, 60°N-80°N]; 4) the GIN Sea itself, 20°W-20°E, 60°N-80°N.

4·1. *Validation computations.* – Three types of "validation" studies were made, comparing census derived from individual CTD profiles and from the analyzed climatological fields: a) the first one, referred to as the "synoptic" comparison, utilized the near-bottom reaching CTDs of the May and September 1987 SACLANTCEN cruises (fig. 4). This study was mainly interested in establishing the accuracy of representing the water mass census on 28 standard levels down to 3000 m, by checking against the census obtained on the 295 ten-meter intervals of the cruise data, down to 2950 m depth.

b) The second one, referred to as the "seasonal" comparison, uses the results of 6 extensive CTD surveys (3 spring, 3 fall) made by the SACLANT Center from 1986 to 1989. The tracks covered parts of the Norwegian and Icelandic Seas area: two WMO 10-deg squares 1600 and 7600 [10°W-10°E, 60°N-70°N] —see fig. 1. For a cumulative display of cast locations see fig. 4. Most SACLANTCEN CTDs had cast depths of 80-90% of the bottom depth, many even went to 2950 m depth. As mentioned above, the mean cast depth to bottom depth ratio R_{cb} for these casts was .87. The cruises in June 1986, May 1987 and June 1989 were lumped into a "spring" data set, and the late September 1987, November 1988 and October 1989 data into a "fall" data set. The census was computed on the standard levels, and then compared to the spring and fall climatologies of WOA98,

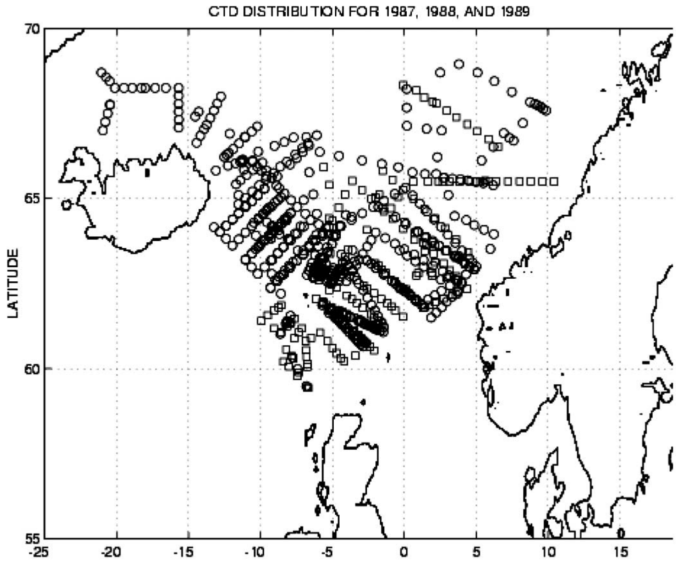

Fig. 4. – Locations of the CTD tracks taken in the six SACLANTCEN cruises 1986-1989.

GDEM90 and MODAS01. It is important to note that the census was prepared on the cruise track locations for BOTH the CTDs and the climatologies for a direct comparison.

c) The third, referred to as the "climatological" comparison, uses all suitable (depth/bottom ratio > 70%) hydrocasts found on the CD-ROM of the World Ocean Database 98 (WOD98) for the spring season, spanning the years 1965-1995. The area studied was the whole GIN Sea basin 20°W-20°E, 60°N-80°N (this includes WMO Squares 1600, 7600, 7700, 1700, see fig. 1).

We then continued the comparison studies with two bulk census on regular "model" or "analysis" grids in the Norwegian Sea and the complete GIN Sea regions. The first compared the census obtained from the four climatologies with different resolutions: WOA98 (1 deg), GDEM90 (0.5 deg), WOA01 (0.25 deg) and MODAS01 (0.125 deg). It also made a comparison with a census derived from all casts in the GIN Sea at their respective CTD locations, and included a study of seasonal variations. The second compared the WOA01 results with a census derived from global model output that stopped in 1997, in the area of the southern Norwegian Sea.

We are presenting our results in tables. The nature of the census, yielding percentages, is such that it is better served by presenting the results in tables. In particular, better quantitative comparisons are obtained for the small and close values of the deep waters.

4.1.1. The 1987 SACLANTCEN cruises: Effect of vertical grid on the census. Table II clearly shows a surprising result: there is very good agreement between the two census computed on the CTD 10 m and the standard climatology depth levels in the spring, but not so in the fall. In the spring, there is exact agreement in the two major water masses ASW and NSDW, an agreement to within 1% between the two largest water masses, AW and DW, with the only significant error in GSDW at 6.9%. In contrast, in the fall the corresponding errors for AW and DW in the fall are 33% and 9.4%, respectively. Considerable errors exist also at 33% for ASW, 4% for NSDW, and 25% for GSDW.

TABLE II. – *Water mass distributions in percentages, computed on* 10 m *observational depth levels, and on the standard hydrographic levels (see table* I*). Data from the May* 1987 *SACLANTCEN survey in the southern GIN Sea (*10°W-10°E, 60°N-70°N*). Maximum depth of computations is* 3000 m*:* 2950 m *for the* 10 m *CTD computations, and* 3000 m *on level* 28 *for the Standard Depth computations.*

	(a) SPRING		(b) FALL	
Wmass	CTD_10M	CTD_SL	CTD_10M	CTD_SL
PW	0.0	0.8	0.0	0.6
PIW	0.0	0.0	0.0	0.0
AW	**29.7**	**29.4**	**24.4**	**32.4**
ASW	1.9	1.9	4.5	2.7
UAIW	2.6	2.7	5.7	3.4
LAIW	11.7	11.4	10.8	11.7
DW	**54.1**	**53.7**	**54.4**	**49.3**
GSDW	7.2	6.7	5.6	4.2
NSDW	20.6	20.6	34.7	33.3
AODW	12.2	12.1	0.0	0.0
DW4	0.0	0.0	0.0	0.0
DW5	0.0	0.1	0.0	0.0
DW6	4.4	4.5	0.0	0.0
DW7	2.6	2.6	0.0	1.9
DW8	7.0	6.9	11.2	9.9
DW9	0.1	0.2	2.2	0.0

PW—Polar Water; PIW—Polar Intermediate Water; AW—Atlantic Water; ASW—Arctic Surface Water; UAIW—Upper Arctic Intermediate Water; LAIW—Lower Arctic Intermediate Water; DW—Deep Water; GSDW—Greenland Sea Deep Water; NSDW—Norwegian Sea Deep Water; AODW—Arctic Ocean Deep Water; DW4–DW9—deep water sub-classes (see fig. 3).

Of scientific interest is the strong spring presence of AODW (12%) and a deep water class DW6 (4.4%) in the CTD survey, and their complete disappearance in both depth computations in the fall. The strong increase of NSDW in the fall, from 20.6% to 34.7%, is also noteworthy.

In summary, there is little effect of the vertical resolution on the computed water masses in the spring, but a very large one in the fall. One likely reason for the large discrepancy in the AW percentage is the fact that in the fall the Atlantic waters extend much deeper, where resolution is much coarser. A follow-up study is needed of the exact vertical distribution and its seasonal variation of the water mass classes to understand this effect, but this is beyond the scope of the present paper.

4·1.2. The spring/fall census from the 1986-1989 SACLANTCEN cruises ([6]).

The approach here was to interpolate the climatological profiles to the CTD locations and to the mean period of the respective cruises (2-4 week durations). The monthly WOA98 profiles (0–1500 m) were appended with interpolated values from the seasonal files (0–5500 m) to prepare monthly files going down to 3000 m. For GDEM90 (seasonal) and MODAS01 (bi-monthly) simple time interpolation to the cruise periods was used for the whole depth range. The CTD census was performed on the Standard depths used by the climatologies.

([6]) ICES Data Base web reference: `http://www.ices.dk/ocean/`.

TABLE III. – *Water mass distributions (percentages) for the cumulative spring and fall SACLANTCEN surveys (*1986-1989*) in the southern GIN Sea, and for the WOA98, GDEM93 and MODAS01 climatologies computed at the CTD locations but on standard levels. The same terminology is used to denote the watermasses as in table* II.

(a) SPRING for CTD $(86+87+89)$ and for the 3 climatologies

Wmass	CTD	WOA98	GDEM93	MODAS01
PW	0.9	2.5	3.9	6.5
PIW	0.0	0.0	0.0	0.0
AW	**30.1**	**26.5**	**28.9**	**26.1**
ASW	2.0	0.7	0.4	0.8
UAIW	2.7	0.5	0.3	0.5
LAIW	11.3	18.5	22.9	16.2
DW	**53.1**	**51.6**	**44.0**	**50.0**
GSDW	6.7	9.6	7.5	6.9
NSDW	20.3	28.3	24.2	26.7
AODW	12.0	3.9	1.4	4.5
DW6	4.5	0.0	0.0	1.5
DW7	2.6	2.5	2.4	3.2
DW8	6.8	7.3	7.6	6.8
DW9	0.2	0.0	0.8	0.4

(b) FALL for CTD $(87+88+89)$ and for the 3 climatologies

Wmass	CTD	WOA98	GDEM93	MODAS01
PW	0.6	0.0	0.0	0.2
PIW	0.0	0.0	0.0	0.0
AW	**32.4**	**26.2**	**27.4**	**29.8**
ASW	2.7	2.7	1.6	1.6
UAIW	3.4	0.6	1.5	1.9
LAIW	11.7	20.3	32.0	16.2
DW	**49.3**	**50.3**	**37.2**	**50.6**
GSDW	4.2	5.3	2.7	2.7
NSDW	33.3	27.8	20.2	23.2
AODW	0.0	0.7		
DW6	0.0	0.3	0.3	1.0
DW7	1.9	2.2	4.9	1.2
DW8	9.9	13.9	8.0	13.5
DW9	0.0	0.0	0.2	0.3

The results are summarized in table III (a,b). The list of water mass abbreviations is found in table II. It is immediately clear from the tables that in this area in spring, only three major water masses appear: AW, LAIW and DW. Most noteworthy is the rather constant percentage of AW and DW exhibited by the climatologies, the total range of percentages being 26.1–28.9% in the spring, and 26.2% to 29.8% in the fall. However, the cruise data show values of 30.1% and 32.4%, with discrepancies from the mean climatology values of 11% and 16%, for spring and fall, respectively. For the LAIW, only WOA98 and MODAS01 are close with spring values of 18.5% and 16.2%, respectively. Cruise data shows a much lower value at 11.3%, and GDEM90 a much higher value at 22.9%.

For the deep water DW, the agreement is close between the cruise data, WOA98 and MODAS01, with spring values ranging from 53.1%, 51.6% and 50.0%, respectively, and with fall values ranging 49.3%, 50.3% and 50.6%. But GDEM90 shows large discrepancies with a spring value of 44.0% and a fall value of 37.2%.

Regarding the DW sub-classes in the spring, MODAS01 has excellent agreement with the cruise data on GSDW and DW8, the values being 6.7%, 6.9% and 6.8%, 6.8%, respectively. WOA98 and GDEM90 exhibit higher values for GSDW, these being 9.6% and 7.5% but show good agreement on DSW8 at the somewhat higher values of 7.3% and 7.6%, respectively. Concerning NSDW, only the CTD, WOA98 and MODAS01 census are somewhat close, with values of 30.1%, 28.3% and 26.7%, respectively. On DW7, the CTD, WOA98 and GDEM90 census are in good agreement with values of 2.6, 2.5 and 2.4, respectively. Only the CTD cruise data shows a surprisingly large amount of AODW (Arctic deep water) at 12%, which differs sharply from the much lower climatological values of 4.5% of MODAS01 and 1.4% of GDEM90.

In the fall, all the census differ sharply for NSDW, and none show the presence of AODW. But there is close agreement on GSDW between GDEM90 and MODAS01, albeit at the reduced amount of 2.7%, and between WOA98 and MODAS01 on DW8, the lightest DW class, with values of 13.9% and 13.5%.

Two interesting facets of the census are the very low value of 0.9% for PW exhibited by the CTDs, and its monotone increase in the climatological values with resolution: 2.5% for 1°, 3.9% for 0.5°, and 6.5% for 0.125°. A possible explanation for the first one is the difference of 3-year (1987-89) *vs.* multi-decadal (1965-1995) coverage of the observations going into the analyses. Polar water appears here only in the spring with very low salinity values, hinting at an origin involving melting ice, so the SACLANTCEN cruises in these years may have 1) encountered diminished transport of PW into their track areas (south of 70°N); or 2) there may have occurred increased amounts of melt and/or an earlier start in years before 1986 or after 1989, in the ice-covered zones; or 3) both events happened. A possible explanation for the second facet is the narrowness of the current which carries this water into the southern Norwegian Sea.

4˙2. *Comparison of climatologies on Atlas or model grids.* – In the previous subsections, we have always computed the census at the CTD locations. In this subsection, we will compute them on regular model grids in orthogonal coordinates, so as to make absolute volume figures more meaningful. Also, it's these census figures that interest us most, since the most frequent use of the climatologies today is model initialization, forcing (at boundaries usually) and verification.

4˙2.1. The complete GIN Sea. In this region (20°W-20°E, 60°-80°N) we have 800 grid points for WOA98, 6400 points for GDEM90, 12800 for WOA01, and 51200 points for the MODAS01 climatology. The results of the census computations are summarized in table IV. The census computed from the cumulative spring data set of WOD98 (1965-1995) are also included for comparison. As with other comparisons in this area, we have only the three major classes AW, LAIW and DW to consider.

In the spring season, for the Atlantic water AW the mean discrepancy error (in percentage) of the climatologies from their average is 12%, and from the CTD census 35%, though for WOA01 the CTD error is only 10%, but $\sim 50\%$ for the Navy climatologies. For LAIW these figures are 10.3% and 6.1%, and for DW 6.1% and 3.5%, respectively. We note the excellent agreements for GSDW between CTD data (WOD98) and WOA98, at 25.1 *vs.* 24.1, and for NSDW and DW4 between WOA98 and MODAS01 at 24.5 *vs.*

TABLE IV. – *Water mass distribution (percentages) in the complete GIN Sea Basin,* 20°W-20°E, 60-80°N, *for four climatologies: WOA98, GDEM90, MODAS01 and WOA01. The census computed from the cumulative spring data set of WOD98 (*1965-1995*) are included for comparison. The water mass terminology is the same as in table* II.

(a) Spring

Wmass	WOD98 (ctd)	WOA98 (1 deg)	GDEM93 (0.5 deg)	MODAS01 (0.125)	WOA01 (0.25 deg)
PW	0.0	0.6	1.4	1.1	1.0
PIW	0.0	0.3	0.3	0.2	0.5
AW	**12.1**	**15.6**	**17.7**	**18.8**	**13.3**
ASW	0.4	0.9	1.1	1.1	2.2
UAIW	3.4	2.0	3.4	2.0	1.6
LAIW	14.5	12.0	14.8	12.3	15.1
DW	**69.5**	**68.8**	**61.3**	**64.7**	**66.3**
GSDW	25.1	24.1	18.4	16.0	22.0
NSDW	9.3	24.5	19.2	24.6	31.5
AODW	2.7	5.6	1.4	5.0	3.5
DW4	7.3	4.6	0.3	4.9	1.3
DW5	1.4	0.0	3.2	0.0	0.0
DW6	9.1	2.6	2.4	2.9	1.3
DW7	0.9	2.7	5.3	4.0	2.2
DW8	3.8	3.0	6.7	4.8	2.8
DW9	10.1	1.5	1.7	2.4	1.7

(b) Fall

Wmass	WOA98	GDEM93	MODAS01	WOA01
PW	1.1	1.2	1.1	1.7
PIW	0.2	0.5	0.1	0.2
AW	**15.9**	**18.5**	**19.0**	**15.2**
ASW	1.7	1.6	2.5	3.1
UAIW	2.8	2.8	2.6	1.2
LAIW	10.1	13.2	12.6	12.6
DW	**68.3**	**62.2**	**62.3**	**65.9**
GSDW	27.7	21.1	17.2	24.0
NSDW	15.8	18.2	23.4	24.0
AODW	4.8	1.6	4.8	2.4
DW4	6.6	3.2	4.7	2.6
DW5	0.1	0.0	0.0	0.0
DW6	1.8	2.1	2.2	1.6
DW7	1.1	5.2	1.2	1.4
DW8	4.3	9.5	4.4	3.2
DW9	6.1	0.2	0.9	6.6

24.6, and 4.6 *vs.* 4.9, respectively. Somewhat troublesome is the very high value of 31.5 for NSDW in WOA01, and its very low value of 9.3 in the WOD98 CTD data census. In addition, if in WOD98 one adds the anomalous high value of 10.1 for the DW9 deep water class to the NSDW value of 9.3, one obtains a value of 19.4 for NSDW, which would be in excellent agreement with the GDEM90 value of 19.2. One justification for this addition to explain the above anomalies would be the fact that the water mass class DW9 lies next to the class NSDW in the DW TS-diagram (fig. 3), and a slight shift of 0.01–0.02 ppt of salinity, easily produced in the measurements or (more likely) in the analysis process, could achieve this result.

In the fall season, perhaps the most striking effect is the very close agreements between the Navy climatologies GDEM90 and MODAS01, and between the NODC climatologies WOA98 and WOA01, in regards to the values of AW and DW. The respective Navy census percentages are 18.5, 19.0 for AW, and 62.2, 62.3 for DW; whereas the respective NODC percentages are 15.9, 15.2 for AW, and 68.3, 65.9 for DW.

The main findings in this study were:

a) The errors are lowest for the cumulative deep water DW, and largest for the Atlantic water AW.

b) The mean discrepancy error between climatologies is larger than their mean deviation from data for the LAIW and DW, but smaller for AW.

c) The errors for the three major water masses (AW, LAIW and DW) are smaller in data-rich regions than data-poor regions. This also holds true for Norwegian Sea and Greenland Sea deep waters (NSDW and GSDW), but not for the other DW sub-classes.

Some explanations for these facts could be the following. Surface waters tend to be sampled much more than deeper waters, thus AW has the lowest errors associated with it. Water masses with large T-S domains (AW) or containing many sub-classes and clusters of points in T-S space (DW) will tend to hide the observational and analysis errors, thus again reducing the errors. The very large fraction associated with DW will make the relative errors look good, but the actual volume errors, which are sure to be important in studying water mass transformations, can still have large errors.

4˙2.2. Comparison of WOA01 climatology with POP in the Norwegian Sea. Table V presents the results for this study. Here we have encountered and studied some particular effects not encountered up to now. For example, the agreement between the AW mass percentages is mediocre (AW = 13.6% for the model and 18.4% for climatology), but deteriorates badly for the other water masses. Very large discrepancies occur for the intermediate and deep water masses, with POP/WOA01 ratios of 55.4/8.9 for LAIW, and 30.3/59.4 for DW. The excessive amount of model LAIW comes at the expense of both the AW and the DW masses. We also note the absence of polar water, PW, and the very small amounts of ASW and UAIW, 0.4% each, in the model results. Furthermore, most of the deep water in the simulation occupies the classes DW7 ($\sim$ 24%) and DW6 ($\sim$ 7%), with DW7 being the warmest and saltiest of the deep water classes. We also note the complete absence of Norwegian (NSDW) and Greenland Sea (GSDW) deep waters, both being fresher and cooler than DW7. There is a small amount of AODW at 0.5%. In general, the simulated waters are moderately warmer and somewhat saltier than those described by the climatology WAO01.

TABLE V. – *Spring season water mass distribution (percentages) in the reduced GIN Sea Area (*10°W-10°E, 60-70°N*), containing WMO Squares* 1600 *and* 7600 *computed for the WOA01 climatology and the output of the* $POP_{1/3}$ *global model. The water mass terminology is the same as in table* II.

WOA01		POP Model	
$\boldsymbol{T_{\mathrm{aiw}} = 3.00\,°\mathrm{C}}$		**3.00 °C**	**2.50 °C**
$T_{\mathrm{idw}} = 0.00\,°\mathrm{C}$		0.00 °C	**1.10 °C**
$T_{\mathrm{ubns}} = -0.50\,°\mathrm{C}$		−0.50 °C	−0.00 °C
$T_{\mathrm{lbns}} = -1.10\,°\mathrm{C}$		−1.10 °C	−0.80 °C
$S_{\mathrm{ubns}} = 34.90$		34.90	34.92
$S_{\mathrm{lbns}} = 34.92$		34.92	35.02
PW	7.6	0.0	0.0
AW	**18.4**	**13.6**	**17.5**
ASW	5.9	0.4	0.2
UAIW	0.0	0.4	0.4
LAIW	**8.9**	**55.4**	**22.2**
DW	59.4	30.3	**59.7**
GSDW	12.7	0.0	0.0
NSDW	**20.0**	**0.0**	19.7
AODW	11.0	0.5	0.0
DW6	6.5	6.6	10.0
DW7	3.9	**23.5**	**29.3**

T_{aiw}—temperature boundary between Atlantic and Lower Intermediate water masses; T_{idw}—temperature boundary between Lower Intermediate and Deep waters masses; T_{ubns}—upper temperature boundary of Norwegian Sea Deep Water mass; T_{lbns}—lower temperature boundary of Norwegian Sea Deep Water mass; S_{ubns}—upper salinity boundary of Norwegian Sea Deep Water mass; S_{lbns}—lower salinity boundary of Norwegian Sea Deep Water mass.

After an examination of the T-S diagrams (figs. 2 and 3) and the above results, we have decided to bring the WOA01 and POP water mass fractions closer to agreement by changing gradually the values of the temperature boundaries between AW and LAIW, T_{aiw}, and between LAIW and DW, T_{idw} (see notations in table V). The fraction of ocean water that has salinity above 34.85 is $> 98\%$ for the POP, and $> 94\%$ for WAO01. However, the water fraction in POP that has temperatures above 0 °C is $\sim 70\%$, whereas for WAO01 it is only $\sim 33\%$. Lowering the temperature boundary T_{aiw} by only 0.5 °C (to 2.5 °C) brings the simulated AW mass percentage closer to agreement, with WOA01 at 18.4.7 and POP at 17.5 (table V, columns 1 and 3). Whereas we set $T_{\mathrm{aiw}} = 3\,°\mathrm{C}$ in fig. 3, following Swift and Aagaard [10], Johannessen *et al.* [38] set $T_{\mathrm{aiw}} = 2\,°\mathrm{C}$.

It is more difficult to bring the excessively low model results for DW at 30.3 into agreement with climatology at 59.4. We have to increase T_{idw} (separating LAIW and Deep waters) by 1.10 °C. This change does help to bring the fraction for DW to an almost perfect agreement, with POP/WOA01 = 59.7/59.4, and it lowers the excessive LAIW fraction (along with the decrease of T_{aiw}) from 55.4 to 22.2. It is interesting to note that the sum of the climatological fractions for PW, ASW, UAIW and LAIW also equals 22.4, clearly indicating that these waters have been aliased by the model into LAIW, along with a large volume of DW and a small amount of AW.

We also have to tackle the most difficult problem of "finding" the named DW classes in the model results. In this paper, we will only do this for NSDW, the deep water for the region modeled, the southern Norwegian Sea. The upper and lower boundaries for temperature and salinity of NSDW are defined in the table V footnotes and in the schematic of fig. 3. We have found that by raising the upper boundary T_{ubns} from $-0.5\,^{\circ}\text{C}$ to $0.0\,^{\circ}\text{C}$, and S_{ubns} from 34.92 to 35.02, we get very good agreement with climatology, with POP/WOA01 = 19.7/20.0. Before these adjustments, most of the modeled deep water was sitting in the warmest and saltiest class DW7. The original model results do not have any water with $T < -0.8\,^{\circ}\text{C}$ and $S < 34.93$.

In trying to understand the source of the model discrepancies, we note that the model has only run with daily atmospheric heat fluxes for 14 years, and the correct adjustments of the lower deep layers will evidently need a lot more more simulation time. An examination of the last 11 years of the model simulation has shown the right trends concerning the DW volumes. In defense of the model results concerning PW, we must note that the SACLANTCEN CTDs also showed a presence of only 1% in this area (even with the 10m depth resolution!), and none of the climatologies in the GIN Sea analysis (table IV) showed more than 1.4%.

Finally, we must point out that the model results used here represent a "synoptic" picture of the ocean in 1997, whereas the average of at least 5–10 years of simulation should be used for comparisons with climatology. Such a study is being planned by using models with higher spatial resolution and longer simulation times.

4˙3. *Seasonal changes in the GIN Sea.* – To shed some light on actual volumetric changes associated with the water masses, we have tried to follow the seasonal changes in AW and DW, and when involved, the LAIW and UAIW masses, as well. We can convert any seasonal change in the percentages to seasonal change in volumes by multiplying the percentage changes with the total volumes.

For WOA98, we have found the first seasonal (spring to summer) increase $\Delta(\text{AW})$ to be about $30 \times 10^3\,\text{km}^3$, and a $\Delta(\text{DW})$ decrease of $8 \times 10^3\,\text{km}^3$. A second seasonal change (spring to fall) gave a $\Delta(\text{AW})$ of $23 \times 10^3\,\text{km}^3$, and a decrease of $\Delta(\text{DW})$ of $32\,\text{km}^3$. These seasonal changes are in reasonable agreement with Swift and Aagaard's [10] estimate of $30 \times 10^3\,\text{km}^3$ for this region, provided we use the spring-summer increase for $\Delta(\text{AW})$ and the spring-fall decrease for $\Delta(\text{DW})$.

For WOA01, the same computations give a spring-summer increase $\Delta(\text{AW}) = 33 \times 10^3\,\text{km}^3$, but only a spring-summer decrease $\Delta(\text{DW}) = -10 \times 10^3\,\text{km}^3$. We can only balance the transitions for WOA01 by invoking exchanges with other neighboring water masses, mainly LAIW and UAIW. We start by looking at the corresponding seasonal changes involving the water mass LAIW. The spring-summer change $\Delta(\text{LAIW}) = -33 \times 10^3\,\text{km}^3$ and the spring-fall change is $\Delta(\text{LAIW}) = -62 \times 10^3\,\text{km}^3$.

To have a balance between the three principal water masses, LAIW has ample volume to supply for conversion to AW. Some of these processes must also occur in the WOA98 census in the spring-summer transitions.

We also note an interesting fact about the sum of the WOA01 census percentages for AW and LAIW. For winter, spring, summer and fall, these are 27.8, 28.3, 28.2 and 27.8. How much of the Atlantic water AW is converted to intermediate water LAIW, or to deep water DW by first passing through LAIW, is difficult to deduce here because the precise path of transformations between AW, DW and LAIW may not be simple. For example, we note that AW is not anywhere in contact with DW in T-S space (see fig. 2). This problem certainly merits further study, but it is beyond the scope of the present paper.

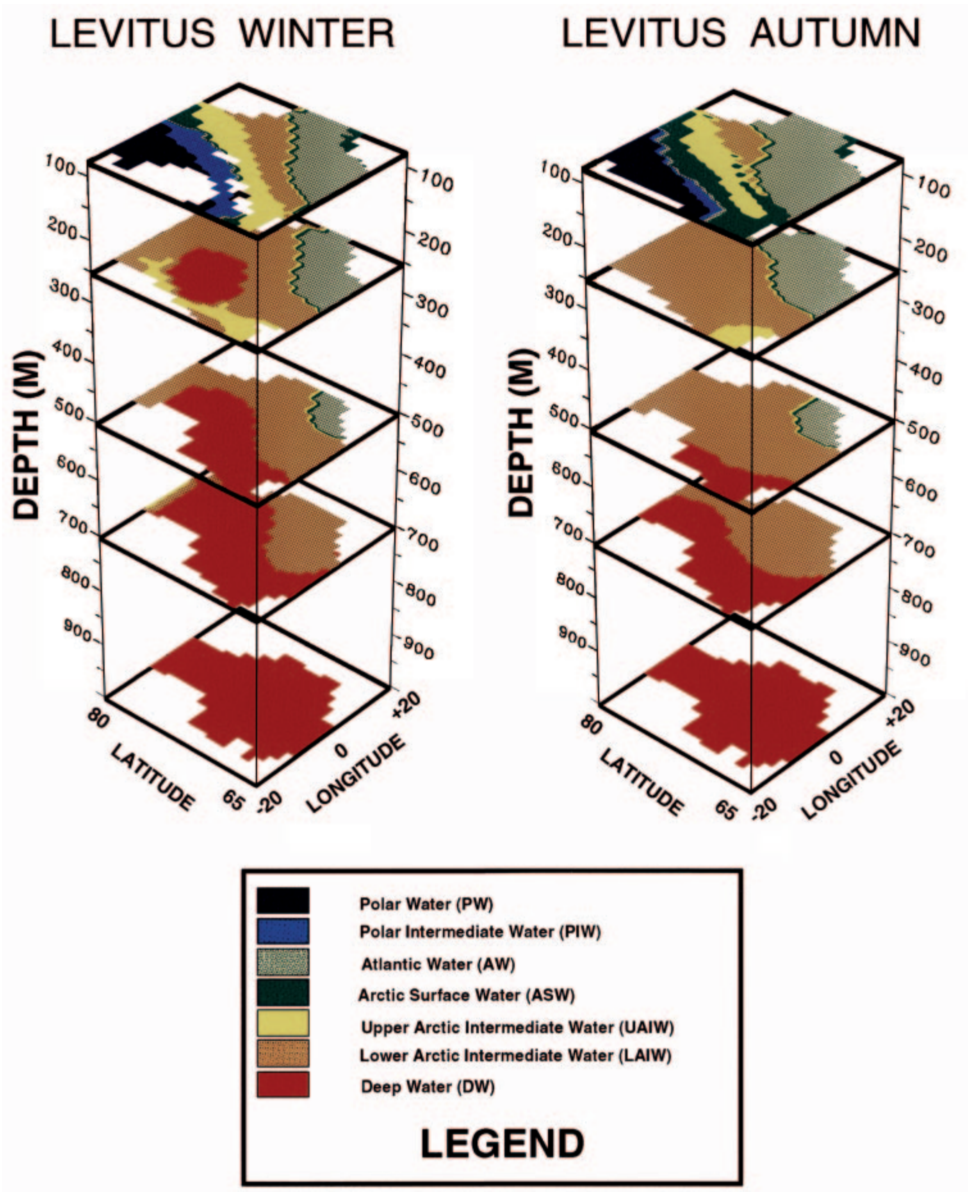

Fig. 5. – A 3D view of the water mass distributions in the GIN Sea for the Levitus climatology, in the spring (left) and the fall (right). The successive depth levels are at 75 m, 250 m, 500 m, 700 and 1000 m. The seven major classes presented here are PW (polar water), PIW (polar intermediate water), AW (Atlantic water), ASW (Arctic surface water), UAIW and LAIW (upper and lower arctic intermediate waters), and DW (deep water).

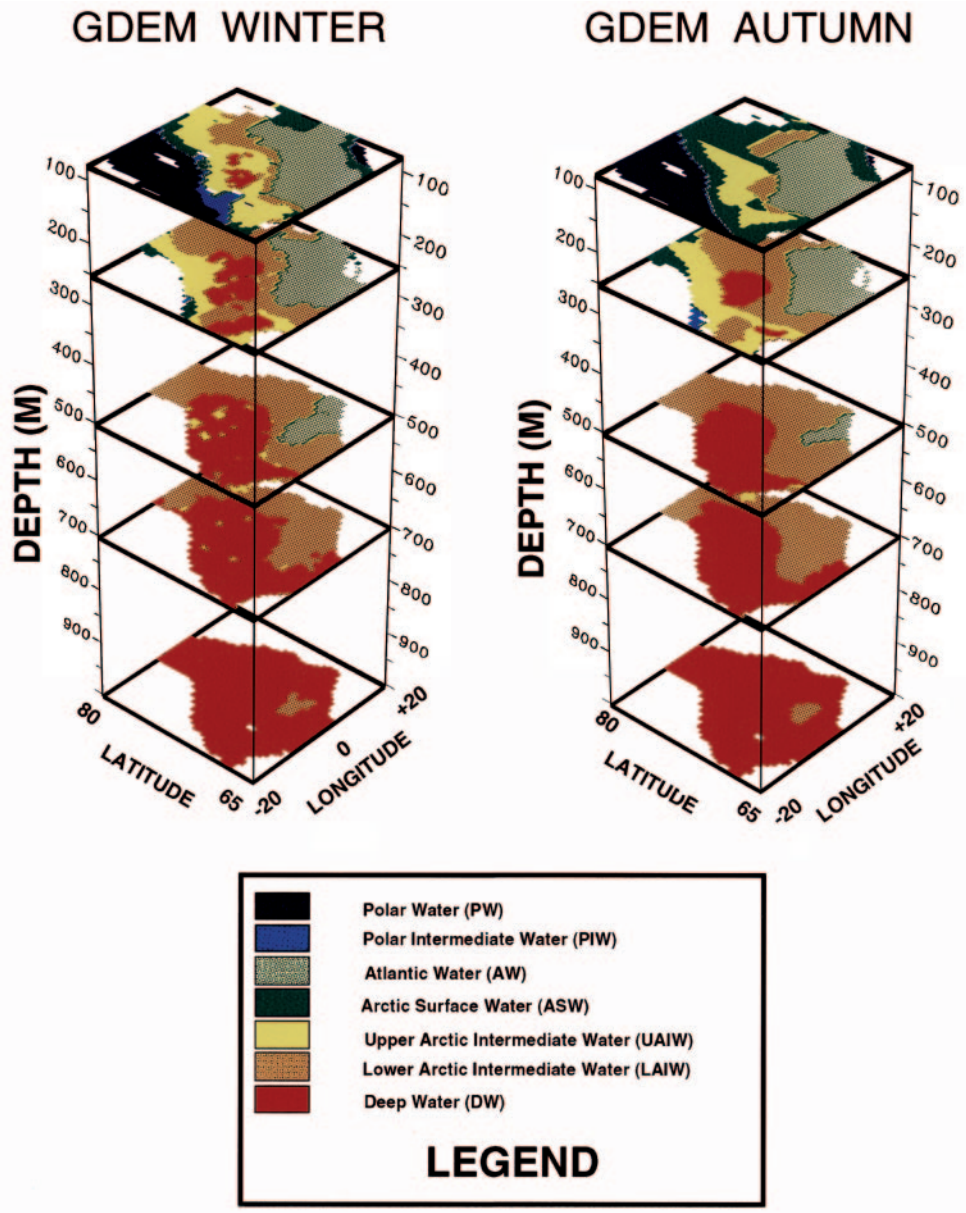

Fig. 6. – As in fig. 5, but for the GDEM climatology. Left, winter; right, fall.

We also note from figs. 5 and 6, and from the T-S diagram in fig. 2, that the domain of LAIW is adjacent to the AW domain at all depths, so that much of the lost AW has had to go into LAIW production, at least as an intermediate or temporary product, before any conversion to DW.

4·4. *Visualization of the GIN Sea.* – To give an insight into the depth-geography distributions of the water masses, we display 3D diagrams in figs. 5 and 6. These display simultaneous cuts at depth levels 75 m, 250 m, 500 m, 700 m and 1000 m, selected to display the most depth variation within the 5-frame constraint of the software package UNIRAS. Figure 5 depicts the winter and autumn seasons of Levitus (LEV82) and fig. 6 the same for GDEM (GDEM90). The first things we notice is that GDEM90 is somewhat "noisy", *i.e.* it has not undergone the heavy smoothing of the LEV82 climatology.

GDEM90 shows traces of deep water near the surface in winter, and this has been observed by towed chains by Johannessen *et al.* [38]. It also shows much more UAIW present at 75 m, and in contrast to LEV82, polar water further up the Greenland shelf under the ice. There is much more AW present in LEV82 in the fall, and also in the winter. One big difference is the absence of DW at 250 m in LEV82 autumn, and its greatly diminished presence at 500 m as compared to GDEM90; the latter is about half LAIW and half DW in the 500–700 m depth range. Also, the LEV82 autumn has almost no UAIW present at the 250 m level, except a small amount in the SW corner, whereas GDEM90 has a large banded structure east of the Greenland shelf.

5. – Conclusions and recommendations

We have compared and evaluated the water mass census of four climatologies: the 1998 and 2001 versions of the Levitus climatology (WOA98, WOA01), the US Navy's GDEM90 and MODAS01 climatologies. The census computations focused on the southern part of the GIN Sea, especially for comparisons with hydrocasts, but the whole GIN Sea Basin proper was also examined.

Validation computations included a "synoptic" comparison with a large CTD survey (CTD87 spring), "seasonal" comparisons using the results of 6 extensive CTD surveys (3 spring, 3 fall), with tracks covering parts of the Norwegian and Icelandic Seas area: 10°W-10°E, 60°N-70°N, and "climatological" comparisons with all available casts from the World Ocean Atlas 98 (WOA98 CD-ROM) in the complete GIN Sea area: 20°W-20°E, 60°-80°N.

We try to summarize some of the specific findings in the following points:

1) There is little effect of the vertical resolution on the computed water masses in the spring, but a very large one in the fall. A follow-up study is needed of the exact vertical distribution and its seasonal change of the water mass classes to understand this effect, but this was beyond the scope of this paper.

2) The seasonal volumetric changes for the Atlantic and deep waters in the GIN Sea are in reasonably good agreement between the climatologies, and with the results of hydrographic census surveys. Typical seasonal changes involve about $33 \times 10^3\,\mathrm{km}^3$ of AW increase from spring to summer, and about $32 \times 10^3\,\mathrm{km}^3$ of DW decrease between spring and autumn.

3) For the major water masses, the mean discrepancy error between climatologies was less than their mean disagreement with the hydrocasts for the mass AW, but greater for LAIW and DW.

4) The errors for the three major water masses (AW, LAIW and DW) are smaller in data-rich regions than data-poor regions. This also holds true for Norwegian Sea and Greenland Sea deep waters (NSDW and GSDW), but for the other DW sub-classes are poorly known. This has implications as to how well the analyzed climatological fields represent their respective ocean regions, at least in terms of their water masses.

6) Both the climatologies and the observations exhibited water masses with T-S characteristics that do not fall into the "named" deep water varieties, namely GSDW, NSDW, AODW. In the GIN Sea, the classes DW6-DW9 were all present at some time of the year.

7) In general, the simulated waters are moderately warmer and somewhat saltier than those described by the climatology WAO01. Relatively small increases of 0.5 °C to 1.0 °C, and 0.02 to 0.10 psu, in the temperature and salinity boundaries separating the water masses could bring them into alignment with climatology. In the present studies, only the season of the last model year 1997 was compared with climatology (based on data from 1965-1995), so the model results being warmer and saltier in the Atlantic Inflow region tend to follow the trends found in other observational and simulation studies.

Some explanations for these trends could be the following. Surface waters tend to be sampled much more than deeper waters, thus AW has the lowest errors associated with it. Water masses with large T-S domains (AW) or containing many sub-classes and clusters of points in T-S space (DW) will tend to hide the observational and analysis errors, thus again reducing the errors for the complete ocean volume. The very large fraction associated with DW will make the relative errors look good, but the actual volume errors, which are sure to be important in studying water mass transformations, can still have large errors. In addition, the errors associated with the many DW sub-classes are also likely to be large, as they are confined to narrow salinity intervals of 0.02 to 0.08 psu.

Experience with analysis of large volumes of hydrocasts in the GIN Sea (both synoptic and climatological) has led us to suspect that most of the errors attributed to observations (mainly for the intermediate waters and the DW sub-classes) are due to errors in the salinity field. A small change of 0.005 psu can easily shift a water mass between these classes, especially in the DW regimes.

We expect much of the errors associated with the interpolations to incur during the horizontal level averaging of neighboring water masses. These errors will be worst for the deep waters, where depth levels are separated by 500 meters and the actual oceanic mixing generally takes place along isopycnals.

Based on our findings, we would like to make the following recommendations:

1) The evaluation of the climatologies against observational data sets should continue, and should extend to all four seasons. The complete GIN Sea census should also include WMO Squares 1601, 1701 and 7601, 7701, with extensions to longitudes 20°E to 30°E, and 30°W to 20°W, respectively. A significant amount of AW also enters the GIN Sea between Iceland and Greenland, and exits into the Barents Sea between those limits.

2) The accuracies of the salinity measurements of all data should be reviewed. The maxima-minima of the measured or analyzed salinity values across all locations of the individual surveys, on a given depth level, should be computed. This has been helpful in the past to understand the source of some of the discrepancies for DW masses, especially the balance between all its subclasses.

3) For regions where at least a moderate hydrocast density exists, the complete volume percentages computed on both the ctd locations, as well as on the regular "model" grid covering that region, should be compared. This would give a better indication

for the validity of the regularly gridded climatologies. Comparisons only at the CTD locations may distort the larger picture of the water mass distributions of the region, favoring the "observed" region.

4) Studies should continue on the effect of the vertical resolution on the computed water masses, to explain an apparent seasonal effect (small in spring, large in fall). It should include a study of the exact vertical distribution of the water mass classes and its seasonal changes, which is most likely needed to understand this effect. Examples of these distributions on selected depth levels are shown in figs. 5 and 6.

5) To reduce the unphysical mixing errors incurred during horizontal averaging and smoothing of the neighboring water masses, Nordic climatologies should also be prepared on σ_t surfaces, and compared with the "level" climatologies. This has been done recently for latitudes lower than 65°N already in the North Atlantic [22]. However, the strong deep convection and other mixing processes in the GIN Sea and the Arctic might not favor the isopycnal approach.

* * *

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