Water Mass Analysis Of The North-West Iberian Ocean Margin

by Hendrik M. van Aken

Netherlands Institute for Sea Research (NIOZ)

ABSTRACT

In the first year of the OMEX II programme the physical oceanography department has assembled a historical set of hydrographic data with emphasis on the European ocean margin. Hydrographic data from the recent OMEX II cruises have been processed and quality control has been performed. Based in the historical date set the applicability of quasi-conservative nutrient tracers for multi-parameter water mass analysis has been evaluated. Preformed nitrate and phosphate gave more independent information than Broeckers "PO" and "NO" en are further used in the quantitative water mass analysis. The analysis of the deep and intermediate water mass in the north-eastern Atlantic Ocean has resulted in an identification and description of the source water types which set up this water mass. The analysis of the central water in the permanent thermocline is ongoing.

HISTORICAL DATA (Task II.1.1)

In order to be able to interpret the observations of the water mass near to north-west Iberian ocean margin in a larger scale context, a historical data set has been assembled for the area between 31 and 53°N, and east of 21°W. This data set mainly covers the period from 1897 till present. The data originate from several British, German, and Dutch WOCE Hydrographic Program cruises (WHP areas AR7E, AR12 and AR16), pre-WOCE cruises available from the Scripps Institution of Oceanography (web-site L. Talley), and from the ICES oceanographic data base in Copenhagen. Because of the emphasis of the OMEX programme, the assembled historical data focus on the European ocean margin.

The historical data sets consists of two parts, CTD(O_2) data and hydro-chemistry data. The latter contain records of pressure, temperature salinity and dissolved oxygen, phosphate, nitrate, and silica data. When assembling the data care was taken that all concentrations were expressed in similar units (µmol/kg). Quality control was carried out in order to obtain an internally consistent data set. Evidently outlying values were removed. The presently (May 1998) available hydrographic stations are shown in figure 1. Spanish hydrographic data from the Galicia and Morena projects have recently been submitted to BODC and will be incorporated in due time into this historical data set.

OMEX DATA (Task II.2.1)

The hydrographic data collected on board RV Pelagia have been processed at NIOZ. In co-operation with BODC, which collects, processes and archives all hydrographic data from the different OMEX cruises, quality control has been carried out. It appears that although the precision of the CTD data is within the limits set by BODC, salinity still contains spikes of the order of 0.005 to 0.010. This may limit the applicability of these data for the analysis of the deep water masses below 3 km depth. The data flow of hydro-chemical data (oxygen and nutrients) is slow, and about 50% of the data from 1997 have not yet reached BODC. Because of the low number of available hydro-chemical data no thorough quality control has been applied yet, but a first comparison with historical data indicates that the data are within the expected range and hydrographic structure.

CONSERVED NUTRIENT TRACERS (Task. II.4.2)

As a measure of the oxygen content, independent of the temperature dependent solubility, the apparent oxygen utilization (AOU) is used, defined by:

$$AOU = O_{2sat} - O_2 \qquad (1)$$

where O_2 is the dissolved oxygen concentration, and O_{2sat} is the saturation concentration in equilibrium with the atmosphere (Broecker and Peng, 1982). Whereas salinity and potential temperature behave conservative, the concentration of e.g. dissolved oxygen is not conservative and will decrease due to ageing of sub-surface water masses while AOU and nutrient concentrations will increase. We can consider such changes of non-conservative parameters as a qualitative measure for ageing, only indicating the characteristic direction of the flow of a water mass from "young" (low AOU) to "old" (high AOU).

For the study of the large-scale slow circulation and mixing of water masses use of conservative or quasi-conservative parameters may be advantageous when performing a multi-parameter water mass analysis, while the study of a tracer with a known decay rate may be a means to determine the transport rate and flow direction of water masses. Because the oxygen consumption rate is not well known, and may vary strongly in the vertical and horizontal direction (Johnston, 1977), equivalent changes in AOU in a water mass do not necessarily imply equivalent ages in years, nor equivalent transport rates of the water mass.

The consumption of oxygen in sub-surface water masses due to the mineralization of organic matter is connected, with nearly constant ratios, to the production of dissolved inorganic phosphate and nitrate (Redfield et al., 1963). This fact enables us to construct quasi-conservative bio-geochemical parameters, in order to study the mixing of deep water masses, by a linear combination of oxygen concentration (or AOU) and either dissolved inorganic nitrate or phosphate. One category of such parameters are the pre-formed nutrients, constructed from the linear combination of AOU and nutrient concentrations (Redfield et al., 1963). The other category are the parameters like "NO" and "PO" from a linear combination of dissolved oxygen and nutrients introduced by Broecker (1974), and used by Pérez et al. (1993) for the study of water masses off the Iberian Peninsula. Pérez et al. (1993) have clarified that there exists a simple physical relation between e.g. pre-formed nitrate and NO.

Both categories of quasi-conservative parameters have advantages and disadvantages in hydrographic research. Generally the NO and PO are highly correlated with temperature, because of the temperature dependence of the oxygen solubility. This correlation may obscure independent information from the nutrient distributions. The pre-formed nutrients are hard to interpret in terms of properties of source waters since both the deep waters of the Norwegian Sea and the Weddell Sea emerge with a marked oxygen under-saturation (Johnston, 1977). The latter are however generally less well correlated with (potential) temperature than NO and PO, and are therefore preferred, since they supply a more independent water mass tracer next to potential temperature and salinity.

The ratio of the bio-geochemical tracers involved in the mineralization of organic matter can be quantified by stochiometric ratios $-\Delta O_2:\Delta NO_3:\Delta PO_4$ (Redfield et al., 1963). Pérez et al. (1993) obtained, from a linear regression of oxygen and nutrient anomalies in the waters off the Iberian Peninsula, the ratios $-\Delta O_2:\Delta NO_3:\Delta PO_4 = 163:16.3:1$ without a clear depth dependence, not significantly different from the ratios for the North Atlantic Ocean obtained by other authors. We will use the stochiometric ratios given by Pérez et al. (1993) to determine the pre-formed phosphate PO_4^o and pre-formed nitrate NO_3^o, defined as:

$$PO_4^o = PO_4\text{-}AOU/163 \qquad (2)$$

$$NO_3^o = NO_3\text{-}AOU/10 \qquad (3)$$

For dissolved silica no precise stochiometric ratio with oxygen and the other nutrients can be expected because the ratio in living phytoplankton varies regionally, and dissolution of biogenic silica in diatom frustules occurs in a process, different from the process of mineralization of organic matter. However it can be expected that when a water mass ages while AOU, nitrate and phosphate increase due to mineralization of organic mater, also the silica concentration will rise due to the extended effects of dissolution and sediment-water interaction. Pérez et al. (1993) have determined an empirical $-\Delta O_2:\Delta Si$ ratio of 15 for the thermocline waters of the Iberian Peninsula, but also mention lower ratios in deep waters because of the strong downward decrease of the re-mineralization of organic matter. Analogous we have determined the linear regression coefficients of Silica with both NO_3 and PO_4 for the deep water masses. Combined with the $-\Delta O_2:\Delta NO_3:\Delta PO_4$ ratios, these gave an empirical ratio $-\Delta O_2:\Delta Si = 1.72:1$ for water samples below 2000 m depth. With this ratio a parameter Si^o is defined, analogous to (2) and (3), as:

$$Si^o = Si\text{-}AOU/1.72 \qquad \text{(depth > 2000 m)} \qquad (4a)$$

$$Si^o = Si\text{-}AOU/15 \qquad \text{(depth < 500 m)} \qquad (4b)$$

At intermediate levels the empirical ΔO_2:ΔSi ratio appears to vary continuously with depth. This prevents the use of a quasi conservative Si^o tracer for the analysis of intermediate water masses.

Because of the fact that the AOU in the newly emerging deep waters is generally above zero (Johnston, 1977), and since these waters, before descending to deep levels, were effected by higher ΔO_2:ΔSi ratios, Si^o in the deep water masses according to (4a) cannot directly be interpreted as the concentration of dissolved silica during the formation of source waters. In the deep waters of the Northeast Atlantic Si^o defined according to (4a) even obtains negative values. In the local context of our water mass analysis Si^o will be considered as simply a quasi-conservative tracer.

WATER MASS ANALYSIS (Tasks II.1.5, II.2.1, II.2.2, and IV.1)

The water mass analysis till now focused on the description of the wider north-eastern Atlantic Ocean, but with emphasis on the European ocean margin. Multi-parameter analyses of the deep and intermediate water masses has been carried out, and an analysis of the thermocline water mass in underway. In the course of the OMEX II programme, when more recent data from OMEX cruises become available, we will focus in on the west Galician margin.

The deep water mass in the Northeast Atlantic (NEADW) can be described adequately with a four endpoint linear mixing model. Iceland-Scotland Overflow Water (ISOW) from the Iceland Basin, Labrador Sea Water (LSW), Mediterranean Sea Overflow Water (MSW), and Lower Deep Water (LDW) of Antarctic origin form the source water types (Fig. 2). Analysis of conservative and non-conservative bio-geochemical parameters (e.g. Fig. 3) reflect the importance of ISOW for the deep water mass, and support a cyclonic re-circulation of ISOW and LDW in the mid-latitude eastern north Atlantic, as proposed by van Aken and Becker (1996). Re-circulation of ISOW and LSW in the NEADW core extends southwards from the Iceland Basin to the Madeira Abyssal Plain. The observed southward and eastward increase of AOU and nutrients in the NEADW core at about 2500 m is explained for a large part by the meridional variation of source water type contributions due to mixing, but actual ageing due to mineralization of organic matter cannot be excluded in the NEADW core. A meridional oxygen trend is observed in the near bottom LDW water mass with the highest AOU and nutrient concentrations over the northern Porcupine Abyssal Plain. This trend cannot be attributed to mixing with overlying water masses, and must be due to ageing during the flow of LDW to the north. From the open ocean towards the European continental slope at NEADW levels the influence of both LDW and MSW increases, probably due to slope bound diapycnal mixing. Additional to this trend at NEADW and LDW levels an increase of AOU and nutrients towards the continental slope is observed. This probably reflects an increased input of organic matter into the deep water masses near the European ocean margin. A manuscript describing the deep water mass has been submitted for publication (van Aken, 1998a).

At intermediate levels the different water masses are characterized by maxima or minima in the salinity or potential temperature profiles (Fig. 4). By the use of conservative and quasi-conservative tracers the distribution and approximate pathways can be unravelled (see e.g. Fig 5). The sub-surface salinity minima below the permanent thermocline represent water masses formed in various regions. Over the northern Porcupine Abyssal Plain Sub-Arctic Intermediate Water (SAIW) is found, origination from the sub-arctic gyre. This water mass is characterized by the lowest salinities at intermediate levels. Further south the sub-surface salinity minima appear to derive their water from winter convection in the Porcupine Sea Bight and northern Bay of Biscay. Both water masses are characterized by relatively low AOU and nutrient values. Over the Seine Abyssal Plain off north-west Africa the sub-surface salinity minimum appears to be maintained by pole-ward advection of Antarctic Intermediate Water (AAIW) characterized by high AOU and nutrient values, especially silica. Entrainment of the latter water mass is required for the formation of MSW by mixing with water from the Alboran Sea in the Gulf of Cadiz. The density range of both SAIW and AAIW overlap the density range of MSW. This ensures that lateral mixing with MSW is possible, which restricts the meridional extent of the MSW core. Due to mixing with the MSW core as well as with the overlying permanent thermocline (either diapycnal or isopycnal) salinity in the sub-surface salinity minima increases. After formation in the Gulf of Cadiz, two MSW cores can be discriminated along the west Iberian ocean margin extending to the latitude of Cape Finisterre. Further from the source these separate cores decay and form a single MSW core. MSW, especially at the level of the upper MSW core, is characterized by relatively low AOU and (preformed) nutrient concentrations, due to its origin from the oligotrophic Mediterranean Sea, despite the entrainment of AAIW during the formation of MSW. Between 1700 and 2000 dbar the LSW core is found over the Porcupine Abyssal Plain and in the western Bay of Biscay, and occasionally of the western Galician margin. There it is characterized by a deep salinity minimum. In the eastern Bay of Biscay the anti-cyclonic circulating LSW is modified by diapycnal mixing with the overlying MSW and the underlying NEADW. This results in the destruction of the deep salinity minimum. The occasional presence of deep salinity minima related to the LSW core off western Galicia suggests in that region a southward transport of LSW from the Porcupine Abyssal Plain below the pole-ward MSW under-current. An un-published manuscript describing the intermediate water masses is available (van Aken, 1998b).

The analysis of the North-East Atlantic Central Water (NEACW) in the permanent thermocline has just begun. Similar to the water in the sub-surface salinity minimum, isopycnal analyses indicate that the thermocline waters off Galicia are formed in the northern Bay of Biscay, where they enter the permanent thermocline by subduction. This requires a southward transport mechanism in the eastern North Atlantic.

The hydrographic analyses performed till now all indicate an enhanced diapycnal mixing near the ocean margin in the Bay of Biscay at intermediate and deep levels. This boundary mixing is probably driven by breaking internal waves of tidal origin. Off the west Iberian margin enhanced diapycnal mixing is less evident, possibly masked by a more complicated hydrographic structure. Enhanced knowledge of the internal wave statistics and turbulent regime as planned in WP II may clarify this.

REFERENCES

BROECKER, W.S. (1974) "NO", a conservative water-mass tracer. Earth and Planetary Science Letters, 23, 100-107.

BROECKER, W.S., AND T.-H. PENG (1982) Tracers in the Sea. Eldigo Press, New York, pp. 690.

JOHNSTON, R. (1977) Some thoughts on the age and descent of the waters of the northeast Atlantic Ocean. In: A voyage of Discovery (M. Angel, ed.), Pergamon Press, pp. 121-145.

PÉREZ, F.F., C. MOURINO, F. FRAGA, AND A.F. RIOS (1993) Displacement of water masses and remineralization rates off the Iberian Peninsula by nutrient anomalies. Journal of Marine Research, 51, 869-892.

REDFIELD, A.C. B.H. KETCHUM, AND F.A. RICHARDS (1963) The influence of organisms on the composition of sea-water. In: The Sea, 2, M.N. Hill (ed.), John Wiley and Sons, New York, pp. 26-77.

VAN AKEN, H.M., AND G. BECKER (1996) Hydrography and through-flow in the north-eastern North Atlantic Ocean: the NANSEN project. Progress in Oceanography, 38, 297-346.

VAN AKEN (1998a) The Hydrography of the mid-latitude Northeast Atlantic Ocean: The deep water masses. (submitted to Deep-Sea Research)

VAN AKEN (1998a) The hydrography of the mid-latitude Northeast Atlantic Ocean: The intermediate water masses. (unpublished manuscript)

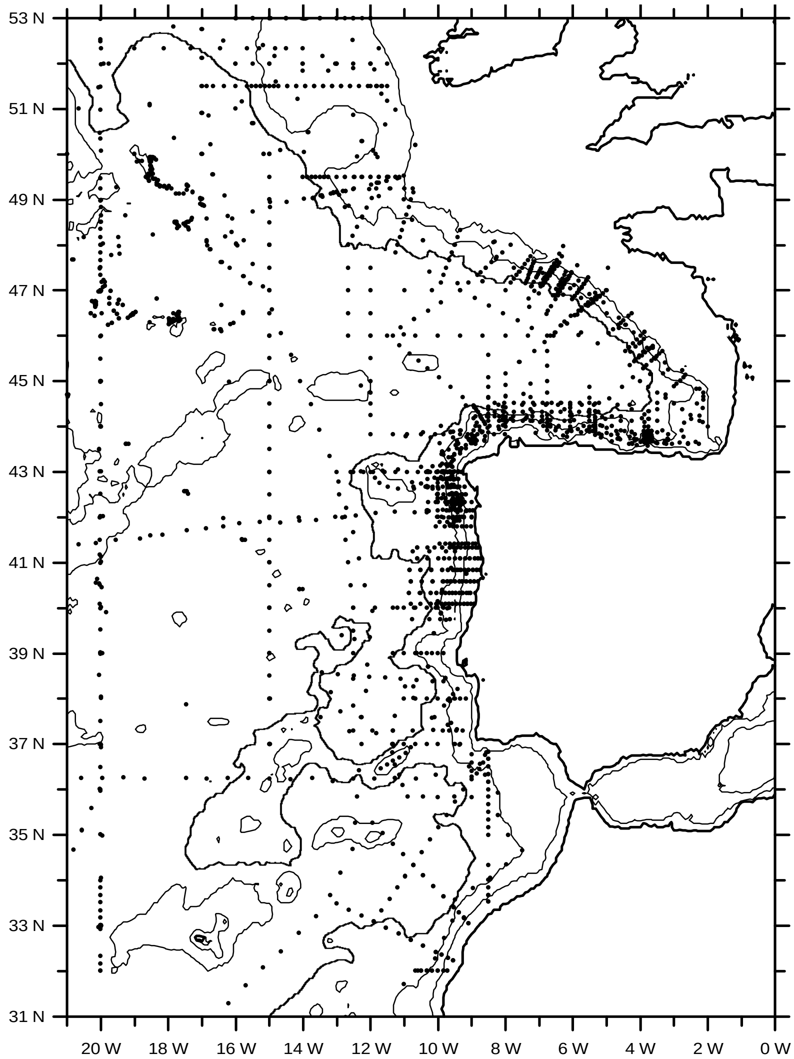

Figure 1. The distribution of the 2283 historical hydrographic stations available in May 1998.

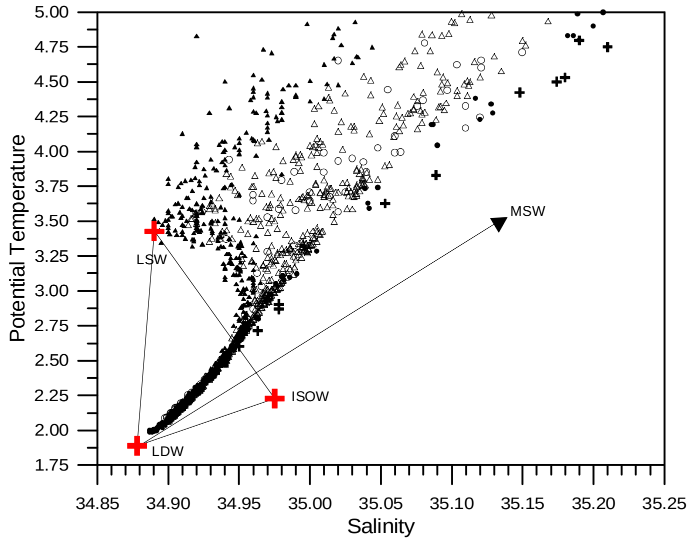

Figure 2. Potential Temperature-Salinity diagram for the deep water mass in the north-eastern Atlantic Ocean. The source water types are indicated with crosses.

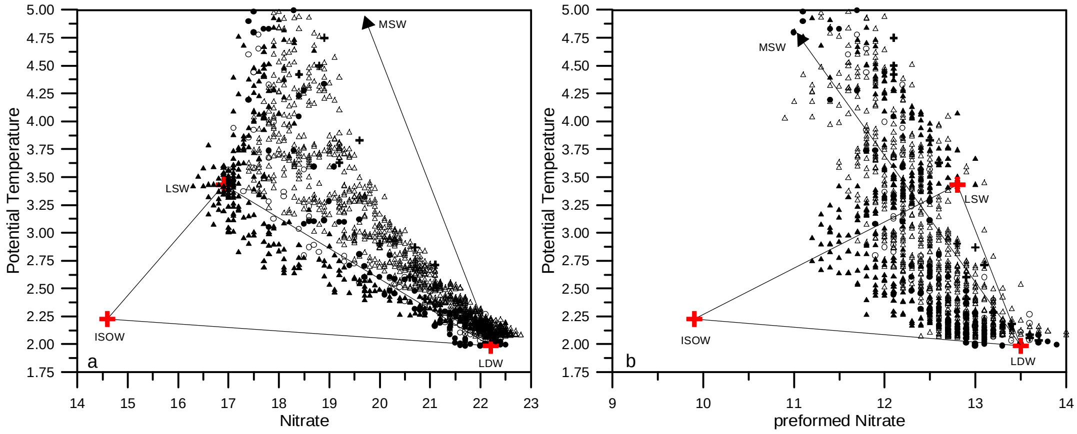

Figure 3. Plots of nitrate (a) and pre-formed nitrate (b) versus potential temperature for the deep water mass. The source water types have been indicated with crosses.

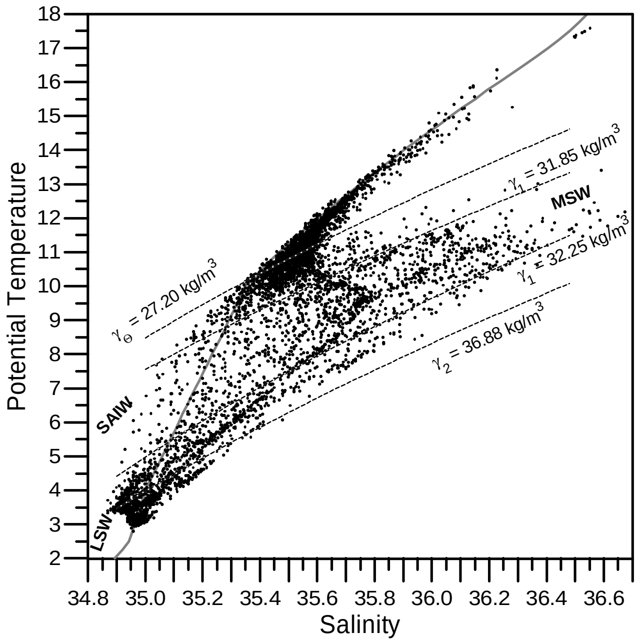

Figure 4. Potential temperature-salinity diagram for the intermediate water masses in the north-eastern Atlantic Ocean. Relevant isopycnals are indicated with lines, while the approximate position of the dominant water masses is indicated with the acronyms. The thick line indicate separate the waters of sub-arctic origin (SAIW and LSW) from the water masses from more moderate latitudes (MSW and the locally formed sub-surface salinity minima).

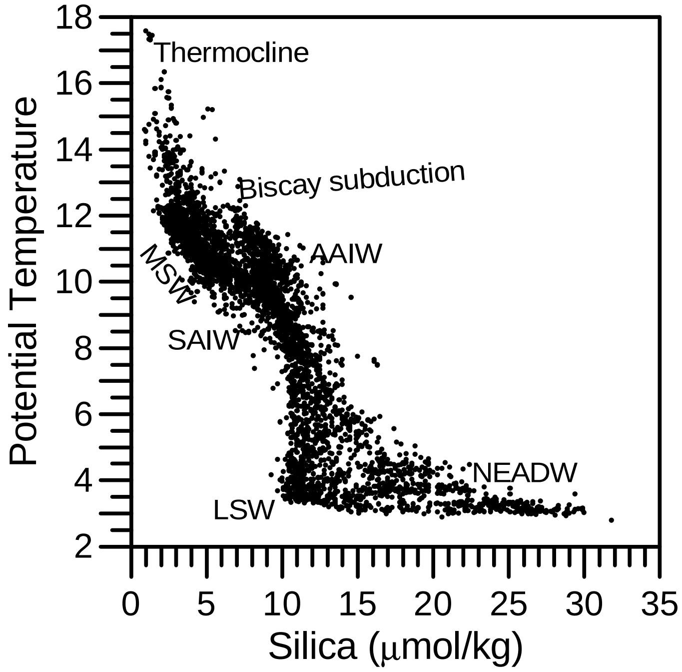

Figure 5. Potential temperature-dissolved silica diagram for the intermediate waters. The approximate position of the main intermediate water masses is indicated with acronyms.