WORLD CLIMATE RESEARCH PROGRAMME

WORLD OCEAN CIRCULATION EXPERIMENT

# Report of the WOCE-AIMS Tracer Workshop

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**University of Bremen, Bremen, Germany**
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# 1. PREFACE

As one of the topical workshops arranged by international WOCE to structure the data evaluations during WOCE-AIMS and possibly beyond, the WOCE-AIMS Tracer Workshop was held at the University of Bremen, 22–26 February 1999. More than 70 people from 8 countries attended (see Appendix 1), and, with few exceptions, all groups active in ocean tracer observations and in tracer modelling were represented. As planned, the workshop started with a number of invited talks (see Appendix 3), which were meant to assess the various aspects of the WOCE tracer data and their evaluation with the aim to structure the subsequent discussions. This was followed by working group and plenary discussion meetings (see Appendix 2). Individual scientific projects were presented as posters (see Appendix 4), many of which were also briefly presented in plenary meetings.

The tasks of the workshop had been defined as follows:

1. to further the oceanographic interpretation of the WOCE tracer data sets
2. to encourage the synthesis, compilation and dissemination of tracer data sets
3. to establish mechanisms for the production of data products (gridded and derived) for the use of a broader community
4. to identify strategies to facilitate assimilation and incorporation of tracer data into models.
5. to initiate collaboration and interaction between tracer geochemists and modellers

These and the layout of the meeting had been set up by a planning group, consisting of:

Wolfgang Roether, University of Bremen, Germany (co-Chair);

Scott Doney, National Center for Atmospheric Research, Boulder, USA (co-Chair);

William J. Jenkins, Southampton Oceanography Centre, Southampton, UK;

Yukata Watanabe, Ibaraki, Japan;

William M. Smethie, Lamont-Doherty Earth Observatory, Palisades, USA;

Claus Böning, University of Kiel, Germany;

Matthew England, Centre for Environmental Modelling and Prediction, Sydney, Australia;

co-ordinating with WOCE SSG and WOCE IPO. Of the planning group members, Y. Watanabe of Japan was unable to attend and C. Böning had to cancel his participation on short notice due to illness. The workshop began with a welcome reception the night before the meeting started. The reception and an evening at a local art museum during the week provided a hospitable environment for the workshop.

Discussions during the workshop were lively, and there was a consensus that the workshop was timely, providing a good basis for meeting the targets of WOCE-AIMS. It was felt that the compilation and initial interpretation of the WOCE tracer data set is well underway and that considerable scientific progress is to be expected with the completed WOCE data set now in hand. The working groups were specifically tasked to address four issues: the status of the WOCE tracer data set and its evaluation; the scientific achievements of the WOCE era tracer work to date; current questions/limitations and future directions for the work. There were four major working groups addressing: physical oceanographic issues and tracers (WG1), biogeochemical issues and tracers (WG2), model data interaction (WG3) and tracer data issues (WG5). A smaller group dealt with tracer data assimilation and other modelling issues of a more general character (WG4). A working group had also been envisaged to deal with future developments of the field, but this topic was actually discussed in plenary meetings. The outcome of this discussion and several issues contributed by the various working groups were combined into a number of recommendations (see next section) by the planning group members and a subset of the workshop participants.

## 2. WORKSHOP RECOMMENDATIONS

1. Complete the WOCE tracer data synthesis for both the primary analysis (basin and global scale merging, quality control and inter-calibration) and the calculation of appropriate second order statistics and synthetic data products (e.g. basin inventories, sampling error estimates, gridded fields, and time adjusted isopycnal surface distributions). It is imperative for the success of the overall WOCE synthesis and modelling effort that the WOCE tracer data and related data products be made publicly available through the WHPO as soon as possible.

2. Quantify and reduce major sources of uncertainty for tracer analysis and modelling. On-going numerical modelling progress requires further refinement of surface and, for regional models, lateral tracer boundary conditions, quantitative estimates of mesoscale tracer sampling error, and estimates of the representativeness of the WOCE tracer data with respect to seasonal and interannual variability.

3. Combine the WOCE tracer data synthesis with historical and contemporaneous non-WOCE tracer observations by identifying the relevant data sets, providing broad access through the WHPO when possible, and encouraging collaborations on the scientific interpretations of the data. Critical data gaps in the WOCE tracer observations, such as in the western South Pacific or Southern Ocean, have been identified and should be redressed either through analysis of available of non-WOCE data or specifically targeted cruises.

4. Encourage co-operation between the tracer modelling and observational communities to interpret field observations, evaluate model skill and diagnose model behaviour. Specific activities include promoting the incorporation of tracers into high-resolution modelling and data assimilation efforts, the public distribution of model results (e.g. simulated tracer data on all WOCE sections), and the development of integral measures for comparing observations and models such as basin and water mass inventories and meridional transports (e.g. silica transport constraints of Robbins and Toole, 1997).

5. Promote synthesis and modelling research on multi-tracer and multi-variable approaches for evaluating ocean general circulation model skill and behaviour (e.g. property-property plots) and for improving our understanding of specific oceanographic processes through a hierarchy of traditional data analysis methods, conceptual models, inverse techniques and ocean general circulation models.

6. Enhance the legacy of the WOCE tracer data set as a benchmark for future ocean change research through the linking of the WOCE data to long term ocean observational programmes and renewed efforts on international oceanographic chemical reference standards, both to maintain existing efforts (e.g. for CFCs, inorganic carbon) and to develop new ones (e.g. for nutrients).

The following recommendation goes beyond the specific scope of WOCE:

7. Explore future scientific applications of ocean tracers to process studies. Natural tracers and in particular tracer release experiments (TREs) have been and will continue to be key elements for hypothesis driven process studies in ocean physics (e.g. diapycnic and lateral mixing, convection), chemistry (e.g. gas exchange) and biology (e.g. iron fertilisation). A detailed discussion, in the form of a white paper, for future opportunities in this area is required that addresses the expanding spectrum of scientific issues, the rapid technological developments (e.g. autonomous sensors, moored water samples, new chemical tracers) and the role of process level modelling.

Moreover the group sees a need for action on the following items and urges the WOCE SSG to endorse these items and to help to translate them into action:

8. Provide resources for national and international scientific synthesis activities for the WOCE tracer data beyond the construction of the basin and global calibrated and quality controlled data sets.

9. Promote strong interactions with relevant, external oceanographic communities. The WOCE ocean tracer observations form a natural bridge between WOCE and existing and emerging physical (CLIVAR, polar programmes) and biogeochemical programmes (JGOFS, SOLAS), and joint higher level synthesis and modelling activities should be actively pursued.

10. Develop a strategic plan outlining the transition to a long-term ocean tracer and hydrographic observational programme. Standard analysis techniques and numerical models, both in the forward and inverse senses, demonstrate a compelling need for on-going, long-term tracer measurements building on the WOCE data. The workshop recommends the speedy formation of a committee to draft a white paper, addressing in detail issues of scientific objectives, implementation, sampling strategies (e.g. time series, repeat sections), and technological developments (e.g. sensors, platforms).

## 3. ACKNOWLEDGEMENTS

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The HWK, main sponsor of the meeting, also supported the evening programme and helped with the local organisation. The HWK organises and funds meetings and hosts fellows in order to support research in the region Oldenburg-Bremen focusing on oceanography and climate research, neurosciences and social sciences/social policy.

Thanks are also due to the many people from the University of Bremen who helped with the local organisation.

The organisers also thank Roberta Boscolo and the WOCE IPO for producing the final version of this report.

# 4. REPORTS OF WORKING GROUPS

## 4.1 Working Group 1: Physical Oceanography Applications and Processes
William M. Smethie, Chair

### 4.1.1 Achievements

Tracer oceanography has made significant contributions to our understanding of the oceanic circulation and internal water mass structure. It is appropriate to begin a discussion of future challenges and projects by reviewing the progress made through contributions from the tracer community.

Deep ocean overturning time

Prior to the measurement of $^{14}C$ in the ocean, the overturning time of the ocean was not known, but was thought to be as long as several thousand years. From $^{14}C$ measurements made during the GEOSECS study, Stuiver et al. (1983) determined the mean deep water residence time to be about 500 years for the Pacific Ocean and about 250 years for the Atlantic and Indian Oceans.

Importance of lateral vs. vertical mixing for thermocline ventilation

Tracer observations have led to the conclusion that lateral processes are primarily responsible for thermocline ventilation. Striking images of the horizontal penetration of bomb tritium in the Pacific by Suess (1975) and later by Fine et al. (1981) in the Pacific are a graphic demonstration of this. Observation of the penetration of tritium into the North Atlantic main thermocline indicated a small diapycnic-mixing rate (Rooth and Ostlund, 1972). Later, studies of the relationship between tritium and $^3$He in the Sargasso Sea placed an upper limit of 0.1 to 0.2 $cm^2/s$ to this value (Jenkins, 1980). These results were dramatically confirmed by tracer release experiments (Ledwell et al., 1993; 1998). Meanwhile, estimates of isopycnal advection and mixing rates (e.g., Jenkins, 1987; 1991; 1998) lead to the ultimate conclusion that thermocline property distributions are controlled predominantly by isopycnal processes.

Determination of the diapycnic mixing rate in the thermocline

Indirect estimates (i.e. budget calculations) imply sizeable diapycnic transports in the upper ocean (Walin, 1982; Niiler and Stephenson, 1982; Speer and Tzipermann, 1992; Speer, 1997). However, microstructure-based estimates of the diapycnic diffusivity indicate very weak mixing at thermocline depth in the ocean interior where the internal wave field is at background intensity (Gregg, 1989; Toole et al., 1994). Ledwell et al.'s North Atlantic Tracer Experiment (NATRE) beautifully demonstrated that diapycnic mixing in the thermocline is weak (of the order of 0.1 $cm^2/s$) (Ledwell et al., 1993;1998) and a recent ocean GCM study of McWilliams et al. (1996) found, contrary to previous analyses, that good balance and structure of the tropical/subtropical hydrographic fields and surface fluxes could be achieved with lower, more realistic diapycnic diffusion of 0.25 $cm^2/s$.

Lateral dispersion on the 1–10 km scale greater than previously thought

NATRE also documented the rate of lateral dispersion as a function of the spatial scale. One result was wider-than-expected tracer streaks approximately six months into the experiment. This implies a far more efficient lateral dispersion mechanism at the 1 to 10 km scale than predicted from internal wave shear dispersion by Young et al. (1982) (Sundemeyer and Price, 1998).

Magnitude of thermocline ventilation greater than the Ekman pumping rate

Tracer observations have shown that the magnitude of the thermohaline ventilation is greater than previously thought. In a seminal paper, Sarmiento (1983) demonstrated that the observed inventory of tritium in the North Atlantic thermocline exceeded by a large factor (2–4 times) that which would arise by Ekman pumping alone. This indicated that thermocline ventilation occurs not just by direct Ekman subduction of water into the subsurface flow, but by lateral induction (e.g., Woods, 1985; Federiuk and Price, 1984; Huang and Qiu, 1995). This has been subsequently affirmed by tritium-$^3$He measurements (Jenkins, 1987, 1998). Tracer-tracer relationships (Jenkins, 1988a) and the temporal evolution of tracer ages (Robbins and Jenkins, 1998) show a “low Peclet number” behaviour to thermocline ventilation, reinforcing the dominant role of advection over small-scale isopycnic or diapycnic mixing.

### Documentation of Pacific waters in the Indian Ocean upper thermocline

Tritium and CFC observations have shown that Pacific waters enter the Indian Ocean thermocline from the Indonesian throughflow (Fine, 1985). The throughflow is dominated by two components: one of well ventilated, low salinity water from the North Pacific thermocline via the Makassar Strait, and the other more saline South Pacific lower thermocline water via the eastern Indonesian Seas. There are seasonal variations in the ratio of these components perhaps modulated by El Niño conditions (Gordon and Fine, 1996).

### Discovery of new water masses and ventilation pathways

CFCs and tritium enter the ocean at the surface and thus tag recently formed subsurface water masses. This has lead to the discovery of new ventilation pathways and water masses and allowed the spreading pathways of recently formed subsurface water masses to be determined by mapping the CFC and tritium fields. In the North Atlantic the extensive vertical maximum in CFCs and tritium in the 4–5°C potential temperature range throughout the western subtropics and tropics (Jenkins and Rhines, 1980; Weiss et al., 1985; Olson et al., 1986; Fine and Molinari, 1988; Smethie, 1993; Rhein et al., 1995; Andrie et al., 1998) lead to the discovery of a new water mass, Upper Labrador Sea Water (Pickart, 1992), which overlies the denser Classical Labrador Sea. The ventilation pathway for this water mass is winter convection extending to a few hundred metres near the south-west margin of the Labrador Sea where eddies of this water become entrained and absorbed into the DWBC (Pickart et al., 1996; Pickart et al., 1997). Another example of a new ventilation pathway is North Pacific Intermediate Water. High CFC concentrations in the $26.8–27.2s_{\theta}$ density horizon in the North Pacific extend into the interior from the Northeast Pacific margin adjacent to the Sea of Okhotsk. Since this density horizon does not outcrop at the surface in the North Pacific, this is strong evidence that dense water formed in the Sea of Okhotsk by air-sea and sea-ice interaction during winter ventilates this layer (Warner et al., 1996). In addition, Smythe-Wright et al. (1996) have used CFC-113 to show that eddies originating in the Brazil Current can cross the South Atlantic to the Agulhas Retroflection region.

### Circulation pathways of recently formed deep and bottom waters

Circulation pathways of newly formed deep and bottom water have been clearly shown by CFC and tritium distributions. NADW components are transported from their source regions equatorward in the DWBC, enter the interior in recirculation gyres in the subtropical and Guiana basins, and flow eastward along the equator and southward across it (Jenkins and Rhines, 1980; Weiss et al., 1985; Olson et al., 1986; Fine and Molinari, 1988; Smethie, 1993; Doney and Jenkins, 1994; Rhein et al., 1995; Andrie, 1996; Andrie et al., 1998; Plähn and Rhein, 1998; Smethie et al., 1999). The circulation pathways of classical Labrador Sea Water that formed during the cold winters of the early to mid 1990s was shown to consist of three limbs, one entering the Irminger Sea, one entering the Northeast Atlantic (Sy et al., 1997) and one entering the subtropical Atlantic in the DWBC (Pickart and Smethie, 1998), corroborating the hydrographic observations. Flow paths of AABW from the Antarctic nearshore regions into the Atlantic Ocean (Smythe-Wright and Boswell, 1998; Rhein et al., 1998), the Indian Ocean (Haine et al., 1998; Boswell and Smythe-Wright, in press) and the Pacific Ocean (Orsi and Bullister, 1996) were also identified by mapping CFC distributions. The high CFC concentrations in deep water at the base of the Antarctic continental slope in the Indian and Pacific sectors of the Southern Ocean clearly revealed that there were major bottom water formation regions in addition to the Weddell Sea (Orsi and Bullister, 1996; Orsi et al., 1999).

### Distinguishing between spreading speed and velocity field

Integral spreading rates, defined as the effective propagation speed of a property anomaly, have been estimated from the transient tracer data. For deep waters formed in high latitude regions as part of the large-scale thermohaline circulation, the equatorward spreading rates have been estimated to be about 1–2 cm/sec from both northern and southern sources (Weiss et al., 1985; Smethie, 1993; Doney and Jenkins, 1994; Rhein et al., 1995; Haine et al., 1998; Smethie et al., 1999; Boswell and

Smythe-Wright, in press). However direct current measurements have revealed year long mean speeds in the DWBC to be 5–10 cm/sec. The tracers clearly reveal that newly formed water does not advance into the ocean at the speed of the DWBC, but moves at a slower rate due to exchange with the interior of the ocean basins caused by recirculation and mixing. Doney and Jenkins (1994) have estimated from tritium observations that water in the DWBC in the North Atlantic is completely replaced every 2500–4000 km by recirculating waters.

### Circulation pathways of mid-depth water in the Pacific Ocean

As part of the WOCE tracer work, the deep (>1000 m depth) helium field has been mapped in considerable detail for all of the major oceans. These deep helium data are a unique data set which provide strong constraints on the deep circulation, especially in certain regions where there are strong inputs of mantle $^3$He from hydrothermal venting. To first order, the amount of excess $^3$He in each of the major ocean basins varies in concert with the spreading rate of the mid-ocean ridges. For example, the Atlantic Ocean has the slowest spreading ridge system and has the smallest helium excess, while the ultra-fast spreading ridges in the Pacific are responsible for deep water masses with 30–40% excess $^3$He. In the Pacific, a descriptive analysis of the deep helium field shows that the deep regional circulation is clearly defined in certain regions where strong helium plumes are produced by intense hydrothermal venting. These include plumes at 2500 m depth extending eastward from the eastern Pacific in the eastern Pacific, a plume at 2000 m depth in the northeast Pacific near the Juan de Fuca Ridge, and a plume at 1100 m depth emanating from Loihi Seamount on the flank of Hawaii (Lupton, 1996; 1998). Similar descriptive analysis could also be applied to the deep helium distribution in the Indian Ocean. Recent work has shown that even in the Atlantic, where the primordial $^3$He source is far smaller, the resulting deep plumes can be mapped (Rüth et al., 1999). Ultimately, the greatest benefit from the deep helium data will be derived by comparison with forward tracer models, or by assimilation of the helium data into inverse models. For example, Farley et al. (1995) have incorporated helium data into a global GCM with some success, and there are plans to incorporate the helium field into inverse models for the Pacific Ocean and for the global ocean (Paul Robbins; Reiner Schlitzer, pers. comm.).

### Biogeochemical tracer constraints on thermohaline circulation

Boswell et al. (in press) show that diagenetic release from sediments is an important contribution to the silicate signal of Antarctic Bottom Water in the south-west Indian Ocean. Diagenetic release anomalies exceeding 25 micromol/kg, equivalent to 20% of the measured concentration, have been observed in the Crozet-Kerguelen Gap while remineralisation from falling biological debris contributes only 10% to the dissolved silicate signal. Results indicate substantial spatial variability, necessitating caution when using silicate as a quantitative tool in the south-west Indian Ocean or, for that matter, in any other ocean region, since diagenetic/remineralisation effects are most likely not restricted to the region where the observations were taken. Despite such uncertainty in the ocean’s silica budget, even very loose constraints on silica flux divergences place significant limits on the ocean’s velocity field, in particular the overturning circulation. Large concentration differences exist between upper ocean waters and the deep and bottom waters of the Pacific and Indian Ocean. Consequently, meridional overturning circulations in these basins effect a sizeable silica flux divergence. Constraints on the possible flux divergence of as large as ±100 kmol/s (1/3rd the total estimated global source and global sink of silica) has the effect of determining the overturning rate to plus or minus a few Sverdrups (Robbins and Bryden, 1994; Robbins and Toole, 1997). The biogeochemical budget thus sets severe constraints on the size of the overturning in individual basins.

### Water mass formation rates

Tritium-$^3$He dating measurements in the North Atlantic subtropical gyre have been used to obtain absolute velocities in the main thermocline to an accuracy of 0.1 cm/s, and to estimate subduction rates (Jenkins, 1987; 1998). The rates thus observed are seen to significantly exceed Ekman pumping for isopycnals that outcrop in regions of prominent latitudinal gradient of mixed layer depth as discussed previously. Transient tracer inventories in a water mass directly reflect the formation rate of this water mass during the time of the transient tracer input. Estimates of the formation rates for NADW based on CFC inventories suggest a rate of about 20 Sv (Smethie and Fine, 1999). Orsi et al. (1999) estimate a rate of 8 Sv for Antarctic Bottom Water. These estimates are unique in that they are integrated formation rates over the time of the tracer input and such integrated formation rates cannot be determined by any other means. Transient tracer distributions have also shown a decrease in the bottom water formation rate in the Greenland Sea (Bönisch et al., 1997). Recent measurements suggest that slow ventilation of the Greenland Sea Bottom Water is now occurring predominantly by vertical mixing (Visbeck and Rhein, 1999).

Identification of fresh water sources in high latitudes

The importance and characteristics of fresh water sources in high latitudes have been made evident by tracer data. Starting in the 1980, stable isotopes of water, in combination with salinity and nutrients, were used to determine the fractions of the individual freshwater components (river run-off, sea ice meltwater, Pacific inflow through Bering Strait) contributing to the strong stratification of the surface waters in the Arctic Ocean (Ostlund, 1982; Ostlund and Hut, 1984). This work was extended into the central Arctic Ocean during the late 1980s and the 1990s in the framework of the first extensive hydrographic work performed from icebreakers (Schlosser et al., 1994, Bauch et al., 1995, Schlosser et al., 1999). This work allowed us to identify pathways of freshwater and opened the way to calculations of inventories of the individual components in the water column. The $^{18}O$ field compiled from the individual cruises provides a valuable target for simulations of the freshwater distribution by a variety of GCMs. In the Southern Ocean, stable isotopes of water and $^{4}He$ provide information on the contribution of glacial meltwater to the freshwater balance (Weiss et al., 1979; Jacobs et al., 1985; Schlosser, 1986; Schlosser et al., 1990; Weppernig et al., 1996). Additionally, these isotopes can be used to estimate melting rates of glacial ice underneath the floating ice shelves (Schlosser et al., 1990).

### 4.1.2 Open Questions and Future Work

Return of water and materials to the ocean surface

The return of water and materials to the ocean surface is not a well constrained or understood phenomenon. This is an important unknown not only from the perspective of physical oceanography (particularly in long term climate behaviour of the oceans via SST feedback) but also for long term controls on biological productivity. The fluxes estimated on the basis of geochemical tracers (e.g., Jenkins, 1988b) exceed that achievable via “traditional” pathways, such as diapycnic and epipycnic mixing, by nearly an order of magnitude. Identifying and quantifying the mechanisms responsible (such as that suggested by McGillicudy and Robinson, 1997) should be a high priority in future research.

What controls property distributions in the thermocline

The issue of what controls the property distribution in the permanent thermocline is still not resolved. Subduction of surface layer water into the subtropical ocean interior has been thought responsible for property and stratification characteristics of the main thermocline. Rudnick and Ferrari (1999) recently presented observations of density compensated lateral temperature-salinity variability in the surface mixed layer. Tomczak and Pender (http://www.es.flinders.edu.au/~mattom/STF/fr1098.html) show similar observations from the Subtropical Front, the source region of subducted water, which show density compensation in the frontal zone to 300 m depth. Such variability is not commonly observed in the ocean interior within the main thermocline. This implies an unknown efficient mixing mechanism in the upper ocean that can remove density-compensated thermohaline variability. Schmitt (1999) suggests double diffusive processes (salt fingering) as the mixing agent. Tomczak and Gu (1987), on the other hand, show that in the equatorial Pacific Ocean the main thermocline is richly structured into regions possibly controlled by double diffusive mixing and other regions more likely controlled by turbulence. There are also methodological problems in evaluation of the relative roles of the two mixing processes (Tomczak, 1999). Whatever mixing mechanism is responsible, this mixing appears to be a key link between the mixed layer waters and those of the subtropical main thermocline.

Intergyre exchange

Much of the water in the ocean resides and circulates in major oceanic gyres such as the subpolar and subtropical gyres. A significant fraction of the oceanic transport of heat and other properties occurs by exchange of water between these gyres and thus it is important to understand and quantify this exchange process. These waters are tagged to a different degree by different tracers and tracer distributions provide information on the exchange pathways and timescales. The extensive WOCE tracer data set should provide a wealth of information on intergyre exchange.

### Deep convection and overflow entrainment

The input of transient tracers to the subsurface ocean is controlled not only by small scale processes that control the flux across the air-sea interface, but also by the mechanisms of deep water formation. For CFCs, much of the surface ocean is in near equilibrium with the atmosphere, but in regions where surface waters sink, more often than not the water is not in equilibrium. In regions of deep convection, the degree of equilibrium with the atmosphere will vary from tracer to tracer and is dependent on the depth of convection, the time period over which convection occurs, and the nature of the tracer surface boundary condition in particular the air-sea gas exchange rate (Doney and Jenkins, 1988). For CFCs, saturation as low as 60% have been observed. For dense waters that flow over sills or off continental shelves, often several water types are involved that have interacted with the atmosphere at a different location some time in the past. Tracers are very useful for sorting out these formation mechanisms and studies are needed for the formation of the North Atlantic Deep Water components as well as the Antarctic Bottom Water components. These studies will not only lead to a better understanding of the mechanisms themselves, but will provide the information needed to interpret tracer data downstream of the formation regions using various types of data analysis techniques and numerical models.

### Rates of subsurface water mass formation

Inventories of tracers that enter the ocean at the surface directly reflect the formation rate of subsurface water masses. As discussed, CFC inventories have been used to estimate formation rates of North Atlantic Deep Water and Antarctic Bottom Water. The WOCE provides a much greater data set with which such calculations can be done. This is essentially a tracer budget technique and similar techniques can be applied to tritium and radiocarbon data. Comparison of rates from radiocarbon and transient tracers will provide a contrast on vastly different time scales and insight into temporal variability on the century time scale. These rates will also be useful targets for OGCMs.

### Exchange between the Deep Western Boundary Current and the interior

Exchange processes between deep western boundary currents and the oceanic interior (lateral mixing, recirculation) have to be quantified. Some progress has already been made using tracer data (see achievements) and further advances will be possible using the WOCE data set. However, there are extended regions in the deep ocean into which transient tracers are just beginning to enter (Roether and Putzka, 1996). Since the build-up of tracer concentrations in these regions can give information not obtainable in any other way, observations must be planned to observe these regions repeatedly. A repeat period of about one decade is probably sufficient to document the tracer build-up in the ocean interior, but more frequent observations (perhaps every 2 years) will be required to document the tracer evolution in the deep western boundary currents. The details of the recirculation paths in the oceanic interior are also poorly known and can be established through such a programme.

### Relate tracer derived water mass ages to physical concepts

The concept of tracer age is not well defined and only loosely linked to physical concepts. More theoretical work is required to exploit the full potential of this method. Tracer ages are often calculated using simple assumptions which often lead to misinterpretations of the physical processes producing the tracer distributions. It has been shown (Robbins and Jenkins, 1998) that even in a steady-state flow field the tracer age field evolves with time due to mixing and the non-linearity of the source function (see also Roether, 1989). The calculated tracer ages are a result of mixing of waters from a variety of sources each with its own tracer age history. Attempts have been made to deconvolute this mixing through the concept of “age distributions” (Putzka et al., 1998; Putzka, 1999). Doney et al. (1997) found good agreement between tritium-$^3$He and CFC tracer ages for the eastern North Atlantic thermocline with approximately a 1:1 relationship below an age of 15 years and a tendency for lower tritium-$^3$He ages beyond that point. Further work should focus on combining a variety of tracers and their calculated ages to attempt to further constrain the underdetermined problem of calculating tracer age distributions. Other methods like combining multiparameter hydrographic analysis (e.g. OMP, Tomczak et al., 1994) and repeat sections may also prove useful in relating tracer ages to physical processes. The use of inverse models to determine the average concentration and its change with time within different densities in regions of the ocean should also be investigated.

### Distribution of fresh water sources and its effect on stratification

Studies in the northern high latitudes should focus on identifying the extent to which freshwater from the Arctic influences the surface waters of the Greenland and Labrador Seas (combined observational and modelling studies). $^{18}$O and tritium are well suited for this. Additionally, repeat observations are needed to study the variability of the individual freshwater components in the surface waters of the Arctic Ocean and how this variability affects stratification in regions of deep water formation outside the Arctic Ocean. Better knowledge of the transport of ice and freshwater out of the Arctic Ocean in the East Greenland Current and through the Canadian Archipelago is needed. In the Southern Ocean emphasis should be placed on determining the $^{4}$He and $^{18}$O distributions in the Pacific and Indian Ocean sectors to identify and better understand the role of glacial meltwater in the formation of bottom water and to improve models dealing with sub-ice shelf circulation and off shelf flow.

### Circulation pathways

Much progress has been made in determining the circulation pathways of subsurface water using tracers, but we should learn a great deal more from the extensive WOCE tracer data sets. The data sets are now extensive enough to allow mapping on density surfaces throughout the water column. The transient tracer fields will show the penetration of waters formed during the past 4 decades and the deep radiocarbon and $^{3}$He should reveal more about the pathways of deep water flow, including regions of vertical flow.

### Three-dimensional distribution of diapycnic and epipycnic mixing rates

The ocean's time averaged (low frequency) flow field depends critically on the diapycnic diffusion of buoyancy (Welander, 1968; Bryan, 1987). In addition to advection, the spread of tracers (and potential vorticity) depends on lateral (isopycnic) dispersion. To improve estimates of ocean models and of the ocean's three dimensional circulation in general, better knowledge of the spatial distribution of diapycnic and epipycnic mixing is needed. On climate time scales, mixing rates may change in response to modifications in the surface wind and buoyancy forcing as well as the three-dimension ocean baroclinic structure. Deliberate Tracer Release Experiments (TREs) are particularly well suited to studying sub-mesoscale and mesoscale dispersion rates. Understanding the causal mechanisms responsible for the mixing is therefore the key to understanding its spatial distribution for the present and for the future.

### Temporal variability

The degree of temporal variability and its impact on steady state estimates has to be quantified. This relates in particular to: (a) Changes in the ventilation of the permanent thermocline: Climatic changes in subtropical/subpolar mode waters and thermocline ventilation rates have been documented using tracers (e.g., Jenkins, 1982; Doney et al., 1998), although it is often complicated to separate changes in circulation and ventilation from evolution of tracer distributions arising from intrinsic tracer properties (Robbins and Jenkins, 1998). Such responses to changing climate forcing are an important observable in future climate studies, particularly when coupled with evolving climatic indices such as NAO and ENSO. Aside from the potential for feedback from the oceans to the atmosphere via SST and fresh water fluxes on long time scales, oceanic ventilation/circulation rates and features may prove to be sensitive accumulators of changes in forcing. Understanding these linkages is a critical step in improving coupled ocean-atmosphere modelling. (b) Deep Water formation, and how variations of North Atlantic Deep Water formation affect the global circulation: While tracer distributions represent average conditions since tracer addition to the ocean started, deep water formation is variable (rates, properties, final depth horizon reached, etc.). This must be taken into account when interpreting tracer distributions. Repeat observations are very important since the evolution of the transient tracer signals will contain information on variability, particularly on the decadal scale. It is also very important to determine and compare formation rates for the last few decades based on transient tracers to formation rates based on natural radiocarbon to determine variability on century time scales which affect the earth's climate.

### 4.1.3 Requirements for Methods and Techniques

Tracer input functions

To fully utilise the tracer data that have been collected during WOCE and other programmes, an understanding of the input of these tracers to the ocean is required. For CFCs the time history is well known, as are the solubilities which are functions of temperature and salinity. Much of the surface ocean is close to equilibrium with the atmosphere so the CFC concentration in the surface ocean can be readily calculated. However, in regions of deep and bottom water formation, equilibrium with the atmosphere is not achieved due to deep convection and/or ice cover. For tritium, source functions are available for certain oceans but a coherent global source function (with error bars) is still outstanding. Apart from a concentration source function, a flux boundary condition can be given (e.g. Weiss and Roether, 1980; Doney et al., 1993) and may in fact be more appropriate to describe input into the ocean. The time and space variability of tritium in precipitation is reasonably well constrained (Doney et al., 1992), and largest outstanding questions regard the magnitude of tritium vapour deposition (Koster et al., 1989; Doney et al., 1993). The disequilibrium between surface water vapour and rainfall tritium levels should be explored more thoroughly in atmospheric GCMs, and historical reconstruction of atmospheric water vapour and surface water tritium concentrations should also be pursued. This will enable modellers to perform simulations jointly for CFCs and tritium. To determine the time history of tracers in the waters actually replenishing deep water masses, an understanding of the formation mechanism is needed to develop the appropriate conceptual models to calculate the time history. Process studies will be required in some deep water source regions and the tracer data will provide valuable information on the deep water formation mechanisms. Tracers will also provide constraints on how deep and bottom waters are formed in OGCMs. The deep helium field, if combined with numerical models and with the proper boundary conditions, has the potential to yield critical information about the deep circulation of the oceans. However, in order for this to be successful, it is necessary to have an accurate description of the source function for $^3$He in all of the deep ocean basins. Except for a few hydrothermally active seamounts, most of the mantle helium is introduced by hydrothermal venting distributed along the global mid-ocean ridge system. Ideally, we would like to have complete knowledge of the distribution of hydrothermal sources from surveys conducted along the axis of the mid-ocean ridge system. These surveys could either be water-column plume studies or direct observations of the seafloor using submersibles or ROVs. Unfortunately, such surveys have been conducted on only a small fraction of the mid-ocean ridge system, namely in the Northeast Pacific, on portions of the East Pacific Rise, and on portions of the northern Mid-Atlantic Ridge (see Baker et al., 1995, and references therein). Furthermore, because of the considerable expense and shiptime involved, it is unlikely that a large fraction of the total mid-ocean ridge system will be surveyed for hydrothermal activity during the next decade. However, representative ridge-axis surveys have been completed on ridges spreading at a variety of rates. Baker et al. (1995) found a linear relationship between the percentage of ridge axis covered by hydrothermal plumes and spreading rate which holds for the slow spreading Mid-Atlantic Ridge up to the ultra-fast spreading southern East Pacific Rise. These studies suggest that, on broad temporal and spatial scales, the incidence of hydrothermal venting and the rate of helium input is proportional to the spreading rate. Thus, by carefully synthesising existing data without any additional survey work at sea, it should be possible to generate a reasonable first-order helium input function. This source function would consist of a line source located above the axis of active ridges the strength of which is proportional to the spreading rate. In certain cases where more detailed information is required for comparison with or assimilation into various models, then additional survey work may be necessary.

Chemical stability of tracers

CFCs and $CCl_4$ have been measured in the ocean for the past 2 decades and it will be possible to measure the evolution of these tracer profiles for at least another 5 decades. Carbon tetrachloride is not chemically stable in warm water (Wallace et al., 1994) and may undergo slow degradation in cold water. Although the degradation rate is too great to use $CCl_4$ quantitatively in warm water, it has great potential for cold deep water because the much earlier release of $CCl_4$ into the atmosphere relative to the CFCs allows us to study longer timescales of ocean ventilation. The $CCl_4$ degradation rate for cold water, if any, should be determined. In the purposeful tracer experiment in the Brazil Basin, the depth of the core of the $SF_6$ plume has moved to deeper depth and higher density water. The reason for this is not known, but could be explained by absorption and release from fine particles settling through the water column. Although there is no evidence to support such a mechanism, it should be investigated since any particle scavenging and redistribution of $SF_6$ would affect the results of tracer release experiments.

### Water mass analysis

Further development of multiparameter analysis techniques promises additional insight into ocean dynamics. The use of potential vorticity as an additional tracer can introduce an element of circulation dynamics into the mixing concept and should therefore be encouraged where it is feasible. The capability of the method to discriminate between diapycnic and isopycnic mixing has already been demonstrated (Tomczak, 1981; Tomczak et al., 1994; Klein and Tomczak, 1994), although a rigorous application may require new dedicated data sets of high vertical resolution. It is also possible to extend the use of the method by minimising the residuals through variation of the source water properties. This will change the system from an over-determined to an underdetermined problem and will therefore require computing resources on a different scale, but it will open the way for monitoring changes of water mass properties in the formation regions. This aspect is discussed in more detail in the section on inverse models. Progress will be documented on the OMP User Group web site http://www.ifm.uni-hamburg.de/~wwwro/omp_std

### Moored water samplers and in situ sensors

The ocean is a fluid in turbulent motion which is not adequately resolved by the present density of observations. As our understanding of the complexity of oceanographic processes has increased, the need for more dense measurements in space and time has increased. A tremendous increase in the information provided by tracers could be achieved by making these measurements at finer space and time scales. In situ measurement with a rapid response sensor is the ideal method of measurement and this may be possible for some tracers (oxygen, nutrients, $CO_2$, some halogenated compounds, some dissolved organic compounds). For other tracers ($^{14}C$, tritium, helium isotopes, CFCs, oxygen isotopes, noble gases) this does not appear to be possible, but greater temporal resolution could be achieved by collecting water samples from moorings. Both technologies should be vigorously pursued.

### Inverse techniques for extracting information on circulation and mixing from tracer data

Inverse techniques exist for using time dependent data such as transient tracers, but they are technically and computationally demanding. This is discussed in some detail in the reports of the modelling working groups 3 and 4.

### Technique for measurement of $^{39}Ar$ in the oceans

$^{39}Ar$ has tremendous potential for revealing information about ocean circulation and mixing and for constraining OGCMs because of its simple well known input function, its chemical inertness and its half-life of 269 years which is ideally matched to circulation time scales for the ocean below the thermocline. However, it is extremely difficult to measure and only about 100 ocean water samples have been analysed. But the field of analytical chemistry is a rapidly evolving one and new more sensitive techniques are being developed for many substances. If a technique is developed that allows $^{39}Ar$ to be measured on reasonably sized samples, this should be done in the future. Also, there are between 400 and 500 archived extracted gas samples from the Atlantic Ocean that could be analysed for $^{39}Ar$ if a technique were available.

## 4.2 Working Group 2: Role of Tracers for Ocean Biogeochemistry
Douglas Wallace and James Orr, co-Chairs

Working Group 2 sought to identify the range of issues relating to ocean biogeochemistry that have been addressed using tracers. In most cases, the tracers have been used to determine rates of processes in-situ, often to obtain basin-scale estimates for processes that are spatially and temporally variable and thus difficult to measure directly. Examples identified by the Working Group included:

| Issue | Timescale |
|---|---|
| Dissolved gas and nutrient cycling (incl. trace metals) | Diurnal to Seasonal |
| Apparent oxygen utilisation rates | Interannual to Decadal |
| Anthropogenic $CO_2$ uptake | Longer |
| Natural halocarbon production/degradation | Longer |
| Methane production and oxidation | Longer |
| Nitrogen cycling (incl. denitrification and nitrogen fixation) | Longer |
| Particle dynamics and scavenging | Longer |
| Redfield ratios | Longer |
| Nutrient remineralisation rates | Longer |
| Hydrothermal inputs to ocean chemistry (geochemical cycling) | Longer |

### 4.2.1 Accomplishments

The Working Group then proceeded to identify specific achievements that tracer studies have contributed significantly to the overall field of ocean biogeochemistry:

1. Gas exchange rates ($^{14}C$, $^{222}Rn$, dual tracers) (Broecker et al., 1986; Smethie et al., 1985, Wanninkhof 1992; Watson et al., 1991)
2. Ocean inventories for bomb $^{14}C$ (Broecker et al., 1995)
3. Anthropogenic $CO_2$ uptake, both model and data-based estimates (Maier-Reimer and Hasselmann, 1987; Sarmiento et al., 1992; Quay et al., 1992; Gruber et al., 1996; Gruber, 1998; Sabine et al., 1999)
4. Geochemical Constraints: $O_2$ production and utilisation rates (Jenkins and Goldmann, 1985; Jenkins and Wallace, 1992); Denitrification and nitrogen fixation (Howell et al., 1997; Gruber and Sarmiento, 1997); Methane oxidation (Rehder et al., 1999)
5. Tracers in corals (e.g., $^{14}C$, $^{13}C$, $^{18}O$) (Druffel, 1997)
6. Constraints from $^{14}C$ on cycling of DOC and POC (Druffel et al., 1992)
7. Particulate scavenging using Pa and Th (Murnane et al., 1994) and sediment $^{210}Pb$
8. $SF_6$ for biogeochemical manipulative experiments for Fe fertilisation (Coale et al., 1996)
9. Hydrothermal alterations to ocean chemistry

### 4.2.2 Challenges

A significant amount of discussion focused on challenges confronting the applications of tracers for specific scientific problems. These are listed according to scientific question:

Data-based estimates of anthropogenic carbon concentrations

The Working Group felt it essential to improve regional estimates of systematic errors associated with the methods used to estimate anthropogenic $CO_2$ concentrations, as calculated from inorganic carbon and other tracer data (Wanninkhof et al., 1999). Specific areas of research requiring further attention from the tracer community include:

1. Evaluation of the appropriateness of respiration corrections using specific and constant values of the Redfield ratios for $TCO_2$/AOU.
2. Regional evaluation of errors associated with assumption that the sea-air $CO_2$ difference ($pCO_2$) has remained constant over time. This is of particular concern in the Southern Ocean and other regions with rapid exchange between the surface and deep ocean.
3. Where is it safe to assume that the concentration of anthropogenic $CO_2$ in the oceans is negligible?
4. Most techniques to estimate anthropogenic $CO_2$ do not work well using summertime data collected in seasonally-perturbed upper layers of the ocean. There is a need to develop approaches suited to this region of the water column.
5. Exploration of the empirical anthropogenic $CO_2$ techniques in global biogeochemical models.

Long-term variability of apparent oxygen utilisation in the deep ocean

Temporal changes in the respiratory oxygen deficit of deep waters would complicate the use of atmospheric ($O_2/N_2$) ratios to infer the relative magnitude and interannual variability of oceanic vs. terrestrial sinks for $CO_2$. Data and interpretative approaches for placing limits on such changes are required.

Horizontal tracer transport

Inter-ocean and inter-hemispheric transports of nutrients and $CO_2$ using hydrographic transport estimates and inverse modelling approaches promise to reveal the distribution of large-scale sources and sinks. Use of tracers as constraints for such inverse calculations requires further consideration.

Nutrient dynamics in the ocean

Two major issues are the remineralisation of nutrients in the deep ocean and re-supply of nutrients to the upper ocean. These issues are critical for ocean biogeochemistry but have proven resistant to direct observation. Tracer studies hold promise for making progress in this area (e.g. use of sub-euphotic zone $^3$He /$NO_3$ correlation); additionally, focused experimental studies may be required.

Nitrogen cycle

The ocean nitrogen cycle is complex and poorly characterised even in terms of measurements of all relevant chemical species (e.g. dissolved organic nitrogen). Tracers will continue to play a key role towards improving our understanding of two fundamental questions: Are there long-term changes in fixed nitrogen inventories in the ocean? What are the regional patterns of sources and sinks for fixed nitrogen?

Ocean margin and open-ocean exchange

The rates of biogeochemical cycling in the coastal ocean are amplified considerably over that of the open ocean, and there is considerable interest in the global role of the coastal ocean and terrestrial fluxes of iron, nutrients etc. In particular, better tracer based estimates of ocean-margin material exchange fluxes (e.g. Ra isotopes) and particle scavenging rates (Th, Pa isotopes) are required.

Standards – Geochemical work increasingly requires global datasets of high accuracy

Standards must be developed and used in order to ensure intercomparibility of data collected by different groups at different times.

### 4.2.3 Future Work

Based on the challenges and in consideration of current questions concerning ocean biogeochemical cycles, the following recommendations for future work were made:

New emphases for tracer studies

The tracer community must adapt and be forward-looking. There is a need to develop new tracers and new tracer interpretation approaches for new questions. For example there will be increasing requirements for:

1. Short-lived tracers for studies of nutrient cycling, gas exchange, in the context of upper ocean dynamics.
2. Tracers of open-ocean/continental margin exchange.
3. "Tracers from below" for studying upwelling and mixing of nutrients into the euphotic zone.

Anthropogenic carbon studies

Multi-tracer approaches have the potential to assess the validity of assumptions involved in estimating anthropogenic $CO_2$ concentrations from inorganic carbon data. High-resolution models and targeted measurement programmes should be applied, in particular, to examining the fractionation of tracers with different gas exchange timescales during water mass formation. Measurement of variability in "preformed values" for nutrients, oxygen, $TCO_2$, AOU and alkalinity is required in key regions. This monitoring could be achieved by a combination of multiparameter water mass analysis of time-series data immediately "downstream" of formation regions and collection of winter-time data.

Tracer Release Experiments

Deliberate Tracer Release Experiments (TREs) are a potentially important new avenue for studying ocean biogeochemical processes. Inert tracers such as $SF_6$ have been used to efficiently tag and track specific water parcels over the course of the experiment. To date the major applications have involved short duration (a few days to a week or two) upper ocean deployments, and future challenges will be develop the tracers and sensors to expand the domain of TREs.

General technologies and standards

Standards: The field of ocean biogeochemistry is a global science and measurements must therefore be directly comparable from one part of the ocean to another and over time. This requires, at minimum, that reference materials be regularly analysed by the tracer and geochemical community so that measurements made at different times, in different locations, by different measurement groups using different techniques can be compared against a common reference. Reference standards for inorganic carbon parameters have greatly improved the usefulness of ocean carbon data sets. Adoption of similar reference materials is urgently required for nutrients (including organic nutrients), organic carbon, oxygen, etc.

New Technologies: There is an increasing trend towards the use of autonomous and remote measurement technologies in the field of physical oceanography. Ocean biogeochemical studies share the need to acquire larger data sets in order to characterise variability and to reduce the overall cost per measurement. There is also a need to acquire data sets in locations and times that are difficult to reach with conventional ship-based sampling. The Working Group therefore recognised an urgent need for technological developments in four areas:

1. Sensors for existing or new tracers and biogeochemical parameters where feasible
2. Autonomous analysis systems suited for ship-of-opportunity work (e.g. surface layer analyses)
3. Moored water-samplers for collection of samples where in-situ analysis is not practical.
4. Inverse modelling and multivariate analysis

In interpretation of tracer and biogeochemical data, members of the Working Group recognised an increasing requirement for the application of inverse-modelling and multivariate analysis techniques.

## 4.3 Working Group 3: Two-Way Model-Data Interaction
## Matthew England, Chair

### 4.3.1 Working Group Overview

The scope of Working Group 3 discussions included the use of chemical tracers to assess/ improve ocean models and using ocean models (often conceptual) to evaluate the distribution of chemical tracers. Issues left to other working groups included biogeochemical tracer modelling (WG2) and the assimilation of chemical tracer data into ocean models (WG4).

The tasks set for this Working Group included describing the achievements and present status of chemical tracer modelling, detailing limitations and uncertainties, and making specific recommendations for future work and action items. The WG discussions in these three areas are synthesised below.

### 4.3.2 Achievements in Tracer Modelling

Chemical tracers used to assess/improve ocean models

Geochemical tracers are now widely used to assess the simulated circulation in ocean models. Tracers that have been used in this context include tritium, chlorofluorocarbons, natural and bomb-produced radiocarbon; and, to a lesser extent, oxygen, silicate, phosphate, isotopes of organic and inorganic carbon compounds and dissolved noble gases (e.g., helium and argon). Table 1 from England and Maier-Reimer (1999) includes a list of these tracers and their various applications and properties. Particular aspects of ocean models that have been assessed in this way include Deep Western Boundary Current (DWBC) flow rates (e.g., Redler, 1997; England and Holloway, 1998), thermocline ventilation (e.g., Jia, 1996; Jia and Richards, 1996; Dutay, 1998), water-mass formation in the Southern Ocean including AABW flow rates (e.g., England, 1995; Robitaille and Weaver, 1995; England and Hirst, 1997; Haine et al., 1998), and deep ocean overturning in the Pacific Ocean using radiocarbon (e.g., Toggweiler et al., 1989; England and Rahmstorf, 1999; Duffy et al., 1997). Geochemical tracers, especially tritium-helium dating, have also provided a direct estimates of thermocline ventilation rates, absolute velocities and subduction rates (Jenkins, 1998) and on the apparent Peclet number of thermocline flow (Robbins and Jenkins, 1998; Robbins et al., 1999).

Ongoing incremental model improvement

The above mentioned studies in ocean model assessment have contributed to a number of improvements in certain aspects of ocean GCMs. This is because model assessment using chemical tracers can give relatively unambiguous tests of model performance with regard to certain parameterisations or ventilation processes. The results of chemical tracer assessment studies then prompt certain model refinements, and in this way tracer data sets facilitate the process of ocean model improvement that is a key goal of WOCE. Examples include improved representation of subgrid-scale mixing effects (e.g., England, 1995; Robitaille and Weaver, 1995; England and Hirst, 1997; Duffy et al., 1997) and bottom boundary layer dynamics (Beckmann and Doescher, 1997). In addition, geochemical tracers have helped to reveal fundamental model limitations with respect to horizontal resolution (Redler, 1997), interior T-S restoring techniques (Toggweiler et al., 1989), and the spatial extent of open-ocean convection (England and Hirst, 1997). Coarse resolution models chronically exaggerate the spatial scales of open ocean convection and deep currents, while underestimating deep flow rates and diffusing downslope flows with excessive lateral mixing. Considerable advancements in tracer oceanography have occurred in the framework of conceptual or intermediate complexity models much simpler than a full 3-D numerical ocean general circulation models. Schematic models allow specific hypotheses to be posed in a clean fashion and provide an inexpensive method to quantitatively constrain rates of ocean dynamics given a limited set of observations. For example, Jenkins (1980) used a very simple two box model to demonstrate the dominance of lateral over vertical ventilation processes at Bermuda Hydrostation S with tritium-$^3$He data in a two box model. The application of lateral 1-D pipe models (e.g. Jenkins, 1998) and 2-D gyre models (Musgrave, 1990; Thiele and Sarmiento, 1990; Doney et al., 1997) to thermocline transient tracer data has generally supported the patterns proposed in the “ventilated thermocline” model though with subduction rather than Ekman pumping being the main driving force. Tracer pipe models have also been used to show the importance of lateral mixing and entrainment in

**Table 1. Chemical tracers used to assess ocean circulation models and/or those incorporated into biogeochemical models**

| *Tracer:* | *Chemical formula:* | *Main sources(s):* | *Properties:* | *Measurability:* | *Applications:* | *Key refrences:* |
|---|---|---|---|---|---|---|
| Radiocarbon | $^{14}C$ | Natural isotope and bomb-produced | 5730 year half-life | 0.250 litres | Natural and transient | *Toggweiler et al.* [1989a,b] |
| Tritium | $^{3}H$ | Bomb-produced radionuclide | 1243 year half-life | 2.5 litres | Transient (favours NH) | *Sarmiento* [1983] |
| Chlorofluorocarbons | $CCl_NF_M$ | Refrigerants, foams, solvents | Stable, inert | 0.030 litres | Transient | *England et al.* [1994] |
| Argon-39 | $^{39}Ar$ | Natural radioactive isotope of $^{46}Ar$ | 269 year half-life | 200-1200 litres | Model diagnosis | *Maier-Reimer* [1993b] |
| Helium-3 | $^{3}He$ | Seafloor volcanism. $^{3}H$ by-product | Stable | 0.100 litres | Deep water flows | *Farley et al.* [1995] |
| Silicon-32 | $^{32}Si$ | Natural radioactive isotope of $^{28}Si$ | 120 year half-life | 1000 litres* | Model diagnosis* | *Peng et al.* [1993] |
| Krypton-85 | $^{85}Kr$ | Bomb-produced radionuclide | 10.6 year half-life | 200-1200 litres | North Atlantic | *Heinze et al.* [1998] |
| Cesium-137 | $^{137}Cs$ | Bomb-produced, Chemobyl | 30 year half-life | 0.030 litres | Regional models | *Staneva et al.* [1998] |
| Sulphur Hexafluoride | $SF_6$ | Deliberate tracer release expts. | Stable, inert | 0.350 litres | Mixing estimates | *Ledwell et al.* [1998] |
| Oxygen-18 | $\delta^{18}O$ | Natural stable isotope of $^{16}O$ | T/state fractionation | 0.015 litres | Paleoceanographic | *Schmidt* [1998] |
| Carbon-13 | $\delta^{13}C$ | Natural stable isotope of $^{12}C$ | T/Prod. fractionation | 0.250 litres | Paleoceanographic | *Maier-Reimer* [1993a] |
| Phosphate | $PO_4$ | Naturally occurring nutrient | Biogeochemical | 0.010 litres | Carbon Cycle Models | *Maier-Reimer* [1993a] |
| Nitrate | $NO_3$ | Naturally occurring nutrient | Biogeochemical | 0.010 litres | Carbon Cycle Models | *Maier-Reimer* [1993a] |
| Silicate | $SiO_2$ | Naturally occurring nutrient | Biogeochemical | 0.010 litres | Carbon Cycle Models | *Maier-Reimer* [1993a] |
| Oxygen | $O_2$ | Naturally occurring nutrient | Biogeochemical | 0.010 litres | Carbon Cycle Models | *Maier-Reimer* [1993a] |

Chemical formulae indicate the modelled isotope, compound or ion. Chlorofluorocarbons cover a variety of species (CFC-11 [$CCl_3F$] and CFC-12 [$CCl_2F_2$] are the most common). NH refers to the Northern Hemisphere. Natural radioactive isotopes are created by cosmic rays in the atmosphere, then radioactively decay once dissolved in seawater. The stable isotopes ($\delta^{18}O$, $\delta^{13}C$) fractionation effects are dependent on temperature (T), changes in state such as precipitation, evaporation and ice formation (state) and/or productivity (Prod.). The measurability indicator is simply the required volume of seawater to detect the chemical tracer to reasonable levels of accuracy: it should be noted that some tracers require sophisticated equipment to make such measurements (#$^{32}Si$) is barely detectable to typical oceanic concentrations). Key citations listed are those that describe the method of including the various tracers into ocean models, normally the first reported use of the given chemical factor.

deep western boundary currents (Pickart et al., 1989; Doney and Jenkins, 1994). Initial estimates of the ocean uptake of anthropogenic carbon were completed in simple box-diffusion models (Oeschger et al., 1975), which were tuned based on natural and artificial transient tracer distributions, and zonal 2-D ocean thermohaline models are still used today to project the impact of climate change scenarios on the carbon cycle (Joos et al., 1999).

PWP models of upper ocean ventilation and gas uptake

Upper ocean models, most notably based on the Price-Weller-Pinkel formulation, have been used to simulate and diagnose seasonal and interannual variations in upper ocean dissolved gas concentrations. Used in conjunction with observations of dissolved noble gases, oxygen and nitrogen, these models have provided estimates of gas exchange and bubble entrainment rates, and set constraints on biological productivity (e.g., Spitzer and Jenkins, 1989).

### 4.3.3 Uncertainties and Limitations

There are a number of limitations and uncertainties in the process of using chemical tracers to assess ocean models, and models to interpret observed tracer distributions. These are summarised here.

Input functions and boundary conditions

There are a number of key areas of uncertainty in terms of forcing chemical tracer uptake in ocean models. These include the following:

1. Uncertainties in the parameterisation of the air-sea gas piston velocity k (Wanninkhof, 1992). Estimates of the dependence of k on wind speed vary by up to a factor of two for typical open ocean wind speeds. This can result in significant uncertainties in the estimation of model air-sea gas exchange, particularly over deep convective mixed layers. This is critical as the chemical tracer signature in the deep ocean is directly tied to the simulated saturation levels in the winter mixed layer. This is more important for the slow equilibration gases such as $CO_2$.
2. Uncertainties in the atmospheric histories of bomb-$^{14}C$, CFCs, and $CO_2$. Normally models assume some time history of tropospheric concentrations of bomb-$^{14}C$, CFCs, and $CO_2$, with a simple latitudinal dependence. The error bars on this assumption are probably relatively small. However, they are yet to be formally quantified.
3. Uncertainties in the input functions of tritium (Doney et al., 1993; Roether, 1989, see Working Group 1 report) and mantle helium (Farley et al., 1995). There remains some source of uncertainty in the various components of tritium input into the World Ocean. Global estimates of tritium input should include some estimate of possible uncertainties due to unknowns such as precipitation rates, marine vapour exchange and river run-off. Mantle helium sources are very difficult to quantify directly. Moreover, the utility of mantle helium in ocean model assessment remains fundamentally limited by the degree of uncertainty surrounding the mantle helium flux from seafloor volcanism (e.g. Farley et al., 1995).
4. Unknown error distributions in global climatologies of wind speed and sea-ice coverage (for forcing air-sea gas exchange). Air-sea gas fluxes of CFCs, $^{14}C$ and $CO_2$ depend on a knowledge of “climatological” wind speed and sea-ice. Yet these properties are poorly measured in some ocean regions, particularly in the Southern Ocean. Recent advances in remote sensing technology should improve these climatologies in the near future, although even then low-frequency climate variability might skew these estimates of global wind speed and sea-ice coverage.

Sampling errors and aliasing of temporal/spatial variability

WOCE and non-WOCE tracer fields contain unknown sampling error distributions – both spatial and temporal. To directly quantify model skill, for example, to reject a model solution because it is inconsistent with tracer data, requires some knowledge of the sampling error distribution associated with that data (Haine and Gray, 1999). This includes measurement error, which is perhaps often small, as well as errors associated with the aliasing of sub-grid scale spatial and temporal variability. Oceanic variability is ubiquitous and evident at many scales, both in space and time, so we can expect a degree of aliasing in the WOCE tracer data sets compared to what might be simulated in an ocean model.

### Assessing ocean models in climate studies

Ocean-only model assessment adopts climatological wind speed and sea-ice data to estimate air-sea gas fluxes. In coupled model studies, it is unclear whether model assessment should employ similar surface field climatologies or whether the internal model predicted winds and sea-ice are more appropriate. If the model fields are used, errors in the model generated sea-ice or winds could compensate for errors in the ocean circulation rendering the model validation inappropriate (as detailed by England and Maier-Reimer, 1999). On the other hand, in some instances, such as over a spurious polynya in polar waters, using observed sea-ice fields could alias errors in the model predicted ocean circulation. It seems that both techniques should be adopted to assess ocean models within climate prediction systems.

### Quantification of model skill, formulation of cost function

A range of different cost function definitions is required to identify the quantities that are most strongly constrained by tracer observations. These should include the best spatial and temporal fit to measurements and the best fit to model benchmarks (discussed below). Studies that seek to estimate quantities such as subduction rates, diffusivities and biogeochemical rates using inverse methods and tracer data are likely to be particularly fruitful (see also report to WG4).

### Accelerated integration techniques

The computational cost of computing the transport of additional passive tracers can be large both for global coarse-resolution models, where multiple millennial equilibrium solutions are desired, and in high resolution regional or global models, where the computational limits are already being pushed just in integrating with respect to T-S and circulation. It remains unclear to what extent the tracer integration can be optimised with regard to computational cost. Issues include:

1. Initialisation fields. Choosing an initial tracer solution that is close to the final equilibrated field (for tracers such as natural $^{14}C$) can minimise required computational costs (e.g., Aumont et al., 1998).
2. Off-line tracer modelling techniques. These normally require careful consideration of internal model dynamics not normally resolved in the mean T-S and u-v fields saved for the off-line model. This includes consideration of model variability in convection fields and in eddy behaviour. Some error will be introduced into off-line models, and necessarily this is difficult to compute.

### Transient tracer fields at open boundary conditions

Specifying boundary conditions for chemical tracers in regional ocean models can be problematic, especially for transient tracers. Even if a model domain is selected to have open boundaries that coincide with a WOCE hydrographic section, it is necessary to extrapolate the time-dependent transient tracer content at this open boundary, which requires assumptions about the long-term ocean circulation in particular regions. Examples of regional transient tracer modelling include that by Redler et al. (1998) and Barnier et al. (1997). High resolution multi-tracer modelling is an effective tool to determine the seasonality and interannual variability in water mass production and transport. However, the high computational demands of such models presently restrict them to limited regions of the world ocean. Several high resolution model studies are underway, the French CLIPPER project (Barnier et al., 1997; CLIPPER, 1998) and the German FLAME programme (Redler et al., 1998). These projects use a variety of model configurations covering both the whole Atlantic and various smaller subdomains, with open boundary conditions to treat the in- and outflow of T-S and tracers. For these boundaries reliable tracer data are needed at the Drake Passage, 30°E, 20°S, and 70°S to simulate the tracer signal in the model interior. For transient tracers such as CFCs, this requires an estimate of the temporal evolution of tracer at these sections from the 1930s to the present (Beining and Roether, 1996). The problem of regional transient tracer modelling is demonstrated in the North Atlantic model of Redler et al. (1998), wherein an open boundary exists at 18°S. While the high resolution model is able to reproduce observed CFC patterns in the DWBC quite well, it fails to show up features in the equatorial current regime like the eastward flow of CFC enriched water at depths around 2000 m. In the model, advection of water with low CFC concentration from the south dilutes the near-equatorial waters, and this is entirely a boundary condition effect. Redler et al. (1998) did not have adequate estimates of CFC content at the southern open boundary to properly address this question. Similar problems show up in a model covering the whole Atlantic with open boundary conditions in the Drake Passage and along 30°E (across the Agulhas Current). The CFC signal south of the equator is diluted if the inflowing CFC signal from the open boundaries is missing.

### Advection schemes: Problems, requirements, and solutions

The centred-time centred-space (CTCS) scheme, traditionally used in GCMs, features conservation of mass and variance of the field combined with low computational costs. However, it has the side-effect of numerical dispersion, a main drawback for tracer-modelling, as it causes ripples and negative concentrations as the field approaches zero. Thus, it violates the second law of thermodynamics. The simple and cheap upstream scheme is not dispersive and it conserves mass, but at the cost of inducing high implicit diffusion, which makes it unsuitable for most model applications. Second-order schemes like QUICK and QUICKEST reduce the noise considerably, but unphysical extrema are only little affected, while the costs are about three times those of CTCS. To achieve sufficient accuracy for biogeochemical tracers, flux-correction schemes such as FCT (e.g., Gerdes et al., 1991), a combination of CTCS and upstream, are required. Continuously differentiable advection schemes are required, however, so that tangent-linear and adjoint models can be formulated for inverse studies. Iterative schemes based on upstream schemes like MPDATA, which can preserve sign and produce smooth fields, would be ideal for tracers. To minimise the high costs of these schemes, “super-cycling” could be applied, i.e., a bigger timestep for passive tracers.

### Some specific chemical tracer issues

1. Radiocarbon: Normally modellers simulate radiocarbon as the deviation of the $^{14}C/^{12}C$ ratio from a standard atmospheric value. It is argued (Fiadiero, 1982) that this renders isotopic fractionation effects and biological conversion processes insignificant, so that radiocarbon is like a passive tracer which simply undergoes radioactive decay. However, as biological transport processes result in a more rapid cycling of carbon between the surface mixed-layer and the deeper ocean, ignoring these processes can systematically bias a model $^{14}C$ simulation. Recent modelling studies suggest an order 5–10 per mil difference between the abiotic case and the biotic case in deep/intermediate waters (Caldeira, pers. comm.). Another issue with radiocarbon is the separation of bomb-produced $^{14}C$ from natural $^{14}C$ in the observational data sets. Because radiocarbon was measured during GEOSECS as well as WOCE, some attempt should be made to quantify the time-dependent spreading of bomb-$^{14}C$ since the 1970s.
2. $^{39}$Argon: Being unaffected by biological processes and with a half-life of 269 years, $^{39}Ar$ would be an ideal constraint on intermediate and deep ocean circulation, and a natural complement to the longer time-scale tracer $^{14}C$. However, only around 100 measurements of $^{39}Ar$ have been made in the ocean, although most of these are in the Atlantic basin. Some modellers have used $^{39}Ar$ as a constraint on ocean simulations (e.g., Orr, pers. comm.), although the sparsity of measurements leaves this tracer more suited to simple model diagnosis, such as separating processes of water-mass conversion (e.g., Maier-Reimer, 1993).

### Uncertainties in derived data products

Whilst modellers seek derived data products, such as integral quantities, column inventories, tracer fields objectively mapped onto isopycnic surfaces, ‘age’ estimates, and so on, the “gapiness” of tracer data (exacerbated when transient) renders many of these derived products subject to unknown error. Modellers need some measure of this error in order to use the derived data products judiciously.

### 4.3.4 Future Work, Action Items, Recommendations

Modellers need tracer field error distributions

Estimates of the spatial and temporal variability of passive tracer fields are required for mapping profiles and sections and comparison of observations with model predictions. The sampling error introduced by surveys with measurements at WHP spacing is significantly greater than typical instrumental errors. In order to objectively estimate this sampling uncertainty the power spectrum of variability for each particular tracer is required. Current knowledge of these spectra is very poor and deserve attention in future. Preliminary work suggests that the spectra may depend only weakly on the tracer sources and sinks (Haine and Gray, 1999). If this is the case, there is a reasonable prospect that a universal passive tracer spectrum exists. This spectrum could be estimated directly on scales between 100 and 1000 km using observations. There is also scope to estimate the power at shorter scales using eddy-resolving circulation models. Such studies are encouraged.

Tests of model “consistency” with observed tracer data

Research that addresses whether, or not, passive tracer fields are consistent with tracer predictions from GCMs is preliminary to full-blown inverse studies using GCMs. The results from this work will identify the ways that tracer fields provide useful constraints on GCM circulation and mixing fields and will be helpful in guiding the future interpretation of tracer data. One theoretical way to approach this issue has been explored by Mémery and Wunsch (1990; tritium) and Gray and Haine (1999, CFCs) in the North Atlantic.

Need improved input functions

The use of chemical tracers in ocean models requires well-known input functions. Improved knowledge of tracer entry functions is required, foremost for mantle helium, surface tritium, and radiocarbon. Improved estimation of the air-sea gas piston velocity is also needed for tracers such as $CO_2$, CFCs and $^{14}C$.

Need gridded and derived tracer quantities for assessing model skill

Ocean model assessment using chemical tracers relies on the availability of quality controlled hydrographic sections and data sets. The tracer modelling community endorses the continued processing of WOCE tracer data to this end. Much can be learnt from WOCE tracer section comparisons and water-mass analyses (e.g., property-property diagrams). Tracer observationalists and modellers should also work together to develop new integral measures of model fidelity. As discussed above, these should include error estimates for tests of model ‘consistency’. An analogy in hydrographic data sets is the estimation of poleward heat transport to assess ocean models at WOCE transects. Recommended data products include integral quantities, column or water-mass inventories, and tracer fields objectively mapped onto isopycnic or geopotential surfaces. Where possible, normalised regional maps of transient tracer concentrations are also recommended. Modellers should liaise with tracer observationalists to target those products that are critical to capturing ocean climate processes. Where available, the use of time-differenced tracer fields (e.g., WOCE minus GEOSECS tritium and radiocarbon) is recommended in ocean model assessment. Such data products constrain ocean model solutions more than simple non-repeat hydrographic sections.

Need ongoing tracer measurements for assessing ocean models

Whilst the WOCE tracer data sets can be combined with other non-WOCE tracer data to develop some picture of low-frequency variability in ocean circulation, this is substantially limited. In order to assess the decadal-scale ocean circulation in models it is strongly recommended that a strategy be developed for measuring chemical tracers in the global ocean at selected times subsequent to the WOCE tracer measuring programme. This should ideally be done in consultation with the ocean modelling community so that key oceanic processes relevant for climate models are measured.

Models should be used to:

1. Estimate the spatial-temporal covariance functions of tracers (related to recommendation 1 above). High-resolution process-oriented models can be used to estimate the spatial and temporal scales of variability in tracer fields. This will improve our knowledge of tracer field sampling error distributions.

2. Extrapolate-interpolate WOCE data, both in space and time. Adjoint methods could be useful in filling out the data gaps in WOCE tracer fields, for example to facilitate the reconstruction of open boundary conditions for regional ocean models or to estimate basin-scale inventories for use in ocean model assessment.

3. Assess the validity of derived "age" data products. For example, modelled CFCs in combination with modelled age tracer fields can be used to test techniques for determining CFC-11/CFC-12 ages and to verify methods used to determine water masses and their relative contributions to the "age" value (e.g., England and Holloway, 1998).

4. Estimate meridional and air-sea fluxes of tracers. For example, model studies can be used to estimate air-sea fluxes of tracers over convective mixed layer regions where direct measurements are difficult to make. Also, global integral quantities such as the meridional transport of a tracer can be estimated in combination with hydrographic and modelling techniques.

5. Examine tracer flow dynamics in process studies (e.g., convection, bottom boundary layer). Modelling studies that investigate the processes of passive tracer transport in oceanic boundary layers and the ocean interior are required to guide the interpretation of field measurements. Preliminary progress has been made on the mechanisms of CFC stirring and mixing in ocean mixed layers by Haine and Richards (1995) and Haine and Marshall (1998). Future work should address the role of interior mixing on tracers with qualitatively different sources and sinks including derived tracer quantities such as tracer age.

Recommend multiple tracers in ocean model assessment

Because property-property analyses provide a more powerful assessment of ocean model skill, particularly when using properties that give relatively distinct information, multiple tracer modelling is recommended in ocean climate model assessment. A good example would be to simulate natural $^{14}C$, chlorofluorocarbons, tritium, and if a suitable input function is known, mantle helium.

Provide model output for tracer observationalists

Interactions between the tracer observing and modelling communities are often one-way, with modellers seeking tracer data without necessarily returning model output results and other diagnostics to tracer observationalists. In order to enhance the two-way interaction between tracer modellers and those that collect tracer data, it is recommended that model output be accessible through an interactive Web site, perhaps housed from a WOCE IPO location. Modellers would be encouraged to submit their output to the site along with a brief READ_ME file that describes their model configuration. The Web facility would then enable the plotting of WOCE and non-WOCE sections, calculation of tracer inventories and other products, such as air-sea fluxes, tracers on isopycnic surfaces, and mixed layer saturation maps.

## 4.4 Working Group 4: Tracer Assimilation and Inverse Studies

Tom Haine and Jens Schröter, co-Chairs

### 4.4.1 Goals

The goals of tracer assimilation and inverse techniques include: (i) State estimation of 4-D tracer fields, for example during the WOCE field phase. (ii) Improvement of ocean general circulation models by systematic and quantitative comparison of tracer measurements with predictions from models. Different tracers have different advantages, e.g., transient tracers provide information on gyre-scale ventilation, deliberate tracer releases often focus on small-scale mixing processes. (iii) Deduction of features of the ocean circulation and mixing that arise specifically from analysis of tracer data. (iv) Estimation of biogeochemical rates, for example oxygen utilisation rates. (v) Estimation of air-sea tracer fluxes. The particular goal of the inverse study determines the choice of objective function or cost function (beauty principle). For example, it is natural to want to reproduce spatial/temporal distributions of tracers. It is also interesting to estimate integral quantities, such as water-mass formation rates and net fluxes, which can be used in model comparison studies that do not otherwise directly include tracers. Ranges of exact and approximate methods exist to minimise the objective function which have various advantages and disadvantages. Almost all methods have a significant technical and computational requirement.

### 4.4.2 Current Achievements

There are few active groups in this field. The work of Schlitzer (AWI), Schröter (AWI), de las Heras (AWI), Follows (MIT) and Haine (Oxford) focuses on transient tracer inversions using GCMs. These studies have not yet generated a substantial number of publications (notable exceptions are Mémery and Wunsch, 1990; Gray and Haine, 1999; Schlitzer and de las Heras, 1999). We anticipate a significant expansion in this field during the AIMS phase. A larger number of workers have studied steady hydrographic section and box inversions following the pioneering work of Wunsch (1978, 1996). These researchers include: Robbins (SIO), Ganachaud (MIT), Wunsch (MIT), Holfort (Kiel), Peacock (LDEO), Schröter (AWI) and Sloyan (AWI). This work has established the usefulness of tracer data as constraints on the circulation and is also expected to grow (see: de las Heras and Schlitzer, 1999; Robbins and Toole, 1997; Schlitzer, 1996; 1999; Sloyan, 1998; Sloyan and Rintoul, 1999).

### 4.4.3 Limits and Uncertainties

Current difficulties that require development include:

1. Accurate advection schemes to reliably transport tracer in GCMs with the corresponding tangent linear and adjoint algorithms. The defects of advection schemes used currently in GCMs are often unavoidably exposed when tracers are included in the simulation. See also report on Working Group 3.
2. Accurate estimates of tracer boundary conditions and the corresponding uncertainties. Improvement is needed in particular tritium. It is possible to project all model error and all data misfit onto unknown boundary conditions but in this case the corresponding increase in knowledge will be poor (see Mémery and Wunsch, 1990; Gray and Haine, 1999).
3. Estimates of underlying tracer variability in order to judge the goodness-of-fit between model and data (see report on WG3).
4. Estimates of time variability in transport are required in order to permit linear box inversions using non-synoptic data. The role of internal waves, inadequate spatial resolution (including bottom triangle problems) and the accuracy of the thermal wind balance also require scrutiny. Also, the estimate of Ekman transport needs improvement through better estimates of wind stress, improved understanding of the validity of the Ekman theory, and estimates of correlation between tracer fluxes and wind stress anomalies. Results from ALACE floats are likely to help in the determination of the reference level transports. Work by Ganachaud (1999) has begun to address these issues, many of which have a scope extending beyond the specific field of tracer inversions.

5. The current techniques to perform hydrographic inversions assume a steady circulation and are not immediately suitable for transient tracer calculations where there is strong time-dependence in the tracer fields. Mémery and Wunsch (1990) have addressed the issue of consistency between the circulation and tracer distribution. However, it is not straightforward to directly constrain the hydrographic inversion using transient tracer data.

#### 4.4.4 Recommendations

The working group recommends a hierarchy of models to be used in inverse studies with tracers. This would span the range from very simple, analytically tractable, models (e.g., Rhein, 1994; Haine et al., 1998) to sophisticated 4-D assimilation systems with GCMs. We also require repeat measurements of tracers on key sections which promise to provide powerful constraints on the ocean circulation (e.g. Heinze et al., 1990; Schlosser et al., 1991; Bönisch and Schlosser, 1995). Specific recommendations are:

1. Tracer oceanographers needs to make a convincing case to the wider inverse/data assimilation community to include tracers in their studies. The advantages of both steady and transient tracers in this context are compelling. Since there has been very little prior work in this field a significant opportunity currently exists to combine tracers with models.
2. A method to easily include transient tracers in box inverse models is needed. This amounts to solving the problem of correcting non-synoptic transient tracer data to a common date (see working group 5 report).
3. The limits of the linear hydrographic inverse need to be established. Use of data from floats, current meters, ADCPs and altimeters is highly relevant in this context. The role of non-linear hydrographic inverse methods must also be explored.
4. Alternative, non-dynamical, approaches to inverse modelling of tracers are encouraged. For example, a simple linear mixing model which aims to explain tracer measurements as a product of a number of unknown source water masses should be considered (e.g., Tomczak, 1999). In general such a model can be used to estimate the number and types of source waters. Given tracer time series the source time histories may also be determined. These methods may also include the opportunity to remotely monitor changes in water mass formation conditions and air/sea fluxes.

## 4.5 Working Group 5: Tracer Data Products and Issues
### Chair: Jim Swift, co-Chair: Mark Warner

The tracer data products realistically feasible from the WOCE Hydrographic Programme (WHP) include, in ideal order of production (and following WOCE Data Products Committee (DPC) nomenclature):

1. **Zero order:**
    a. Original data
    b. Clean data
        (i) Bad values flagged
        (ii) Cast- and cruise-as-a-whole zero-order corrections
        (iii) Merged with other data from the same water samples
        (iv) Available in standard exchange format
2. **First order:**
    a. Basin-wide quality control
    b. Gridded data
3. **Second order**
    a. Derived quantities
        (i) "Age-corrected" concentrations
    b. Advanced plots and tools
        (i) Properties mapped onto neutral surfaces
        (ii) Calculated fields of tracer ages
        (iii) Water column inventories
        (iv) Water mass inventories

The WHP field programme minimum intended product is to complete the "zero order" work and to make these publicly available from the WOCE Archive. Individual data providers are responsible for items 1.a and 1.b.i. Items 1.b.iii and 1.b.iv are typically overseen by the WHP Office (WHPO) and are greatly facilitated by tracer data submissions which include the key identifying information EXPOCODE, station, cast, and sample (or bottle) number. Depth or pressure is explicitly to be avoided as an index for any water sample data, including all tracer data. The "standard exchange format" (1.b.iv) agreed to by WOCE investigators is the WHP format. Community efforts are sometimes required to complete item 1.b.ii, and this is underway or soon to be started as follows:

- CFCs – data repository maintained by John Bullister
- tritium/helium – data repository maintained by Peter Schlosser
- $^{14}C$ – data repository maintained by Bob Key
- $^{13}C$ – Paul Quay and Anne McNichol
- nutrients – data repository maintained by Bob Key
- plus ongoing JGOFS $CO_2$ community effort co-ordinated via Alex Kozyr.

There are also CFC and helium-tritium data examinations led by Wolfgang Roether for the South Atlantic and by Monika Rhein for the North Atlantic atlas. All these groups include 1.b.ii as a preliminary step to working on item 2, which is their minimum intended product. Some aspects of item 3 may be also addressed by some of these groups. There remains a possible issue as to whether these QC groups will deal with large changes differently than they do small changes, in terms of whether the result remains original data versus becoming a data product. The WHPO recommended that this be handled on a case by case basis, with the general guideline couched on a slightly different basis, namely that data changes made/approved by the original investigator could still be considered to be original data (if the original investigator thought that appropriate), but data changes made by "the community" should be considered a data product (typically of first order) and be stored separately from the raw data.

The Working Group discussed whether the WHPO should hold all data as they go through the QC process. J. Swift stated that due to the difficulty of assuring correct merging of data, that all tracer data should be provided to the WHPO for merging, and then provided back to the individual QC groups.

Swift promised high priority would be given to merging data sets identified as urgently needed by the QC groups. The WHPO repeated its pledge not to release proprietary data – including to the QC groups – without permission from the data providers. The Working Group felt that it was the responsibility of PI to not release data (make the data public) until reasonable confidence in QC had been reached.

Discussion held that documentation of the data should be so complete that, for example, the data used to prepare a manuscript as of a certain date should be able to be recreated from the present version plus the documentation of past changes. The WHPO was of the opinion that this practice of "reversibility" of data changes should be instituted, if possible, for all data changes made subsequent to the data for the parameter(s) in question becoming fully public. The WHPO must ensure that changes in data once public are detailed on the WHPO web site, and archived, including a file history, at the WDC-A WOCE Archive.

Participants were concerned – from their examinations of the WHPO web site – that the data reports sent in by PIs were not being integrated with the on-line documentation. Swift explained that he requested of the WHPO staff that first priority be given to making the greatest amount of data available, second priority into merging data, and third to adding and integrating the documentation. Thus there has been some delay in the last. Due to the varied nature of the submitted documentation, when feasible the added tracer documentation will be fit into the original .doc file, and the remainder will go into .pdf (and original, if feasible) format into separate file to be zipped with principal .doc file.

The Working Group felt that the WHPO should be more proactive in contacting data originators to see if/when their data could be made public. "Automatic" e-mailing was considered desirable.

The tracer community is concerned that atlas efforts may be going forward ahead of tracer community quality control efforts and of tracer community decisions about how the data are to be represented. (For example later discussion within the helium/tritium sub-group revealed that it could be two–three years before their quality-controlled data set is available with inter-laboratory adjustments.) This requires immediate co-ordination of effort with the present atlas groups. Discussion about whether atlases should use "corrected" (i.e. aged-referenced) data focused on clear desirability of this for maps. There was no clear decision on whether original or corrected data should be preferred in section plots made from observations from a single cruise by a single measurement group. Jim Crease pointed out that there is a WOCE atlas committee to which to refer such issues.

Which tracer data products should be held (and later archived) by the WHP Office? Alternatives include availability/responsibility by data product originator only; a link from WHP Office to the data product provider's web site would be an additional possibility during the lifetime of the WHP Office. The procedure will be that the individual tracer communities can recommend to WOCE DPC what products should be archived. The DPC should respond, and the WHPO will then act as needed based on the DPC recommendation, although in many cases the data products to be archived may be obvious and would not need the formal attention of the DPC. The Working Group recommended that 3-D gridding not be a standard product, but that gridding along sections could be considered a standard product.

Regarding standard exchange formats J. Swift reported that it is expected that a new standard exchange format for ocean profile data developed by the US NODC (WDC-A), in consultation with the WHP Office and others in the community, will become the community standard for exchanging profile data, including tracer data. The new format specification addresses many of the problems inherent in exchanging profile data, including provisions for metadata, and by virtue of its profile orientation (as opposed to the WHP format's cruise orientation), it is better overall suited for a wide range of end uses, similar to the way the old "SD2" format made it easy to exchange and work with routine hydrographic profile data. Adoption of the new exchange format will help ensure easiest use of WOCE data with non-WOCE data, and incorporation of the WOCE data in the profile database at NODC/WDC-A (as opposed to being available only from the WOCE Archive at NODC/WDC-A). The WHPO proposes that all non-WOCE tracer data feasible should thus be moved to this new format, and in addition to providing WHP data in WHP formats the WHPO should provide WHP data in the new format. One issue which arose in discussion that the WHPO investigate how this may fit into plans for the Distributed Ocean Data System (DODS) being developed by several US groups. DODS provides a hub and node system where exchange format software prepared for the user, providing a standardised yet distributed "medium of exchange".

The Working Group recommended that discussion of the implementation of the new format should be brought to the DPC.

The lack of citability of the WHP's official documentation is an ongoing concern for data providers. The present practice of encouraging data originators to publish their own reports, and then for the WHP Office to always include citation to those reports, was not regarded by some Workshop participants as an effective overall solution. The WHP Office does not have experience in preparing citable references for electronic documentation – at present all their documentation is electronic – and will seek advice from the DPC on methodologies appropriate to this task.

Another concern raised was the issue of how data are presented. This could be as simple as recommending that data be shown only in specific units, to references to an agreed-upon standard year for time-variant data, or agreement of reference to specified source functions, or even to specific recommendations about graphical representations. The individual tracer sub-groups were asked to examine this issue.

It was reported by R. Key that a group is examining WOCE nutrient data for cruise-to-cruise comparisons. Key strongly recommended that an expert panel, perhaps chaired by Andrew Dickson (SIO), who was leading this effort (or a similar one), but has not yet reported to WOCE, be convened ASAP to complete examination of the long-standing issue of the OSU versus SIO silicate methodologies, and that a recommendation for adjustment be made and implemented ASAP.

Concern was expressed that the large-volume sample data were not yet available from the WHPO web site. The WHPO also reported that, as a temporary measure, when only some of the parameters in a bottle data file were public, a "stripped" version of the file, containing only the public parameters was the only bottle data file available. The WHPO, however, will ASAP institute a simple solution of permitting multiple bottle data files on the web site when more than one is required. This should result in all LVS and tracer data being on line, though all proprietary data will be encrypted, as usual.

The WHPO reported that it expected to have completed all merging of tracer data held now (or received soon), plus have all files on line, prior to the April 1999 DPC meeting, at which time it expected to produce version 1.5 of its CD-ROM.

Sub-groups organised by tracer discussed the community QC process for each tracer. Summaries are as follows:

### 4.5.1 CFCs

J. Bullister reported on the three-year CFC community DQE/data product effort recently begun in the US, but including the entire WOCE CFC community (start 01/1999). The basins have been given to sub-groups. CFC-11 and CFC-12 will be examined. The first stage is assembling the data and looking at cruise-to-cruise consistency. Adjustments will be handled on a case by case basis. Proposed CFC data products include:

- air measurements
- age-corrected concentrations
- apparent ages (by sample)
- water column inventories
- water mass inventories
- (corrected/DQE'd) gridded sections (as opposed to "original" data)
- sections in basin atlases now underway
- maps (age-corrected) on neutral surfaces

Each data product will include documentation about the methodology used. These data products will be on the CFC consortium's web site. The WHPO noted that it will provide web space for data products, and moreover that the WHPO is the conduit for WHP-related data products which are intended for the WOCE Archive. W. Roether and M. Rhein reported on the German DQE efforts. They will lead the Atlantic efforts for the community CFC DQE. The responsibility for the Weddell Sea data will be transferred to the Southern Ocean lead investigator. Regarding standardised representation of the CFC data, the CFC community will co-ordinate with the atlas group for each basin to maintain standardised aspect ratios and colour schemes for official data products. The CFC basin sub-groups are asked to co-ordinate between themselves to work for standardisation of data products where appropriate. The CFC DQE groups for each basin will produce reference-suitable reports. Some problems of timing are anticipated, for example not all CFC data are ready for the first stage DQE this year.

### 4.5.2 Helium/tritium

A US-funded Helium/tritium global data quality control and data product group is expected to be funded soon. Specific issues of inter-lab methodologies and comparisons were discussed at the Tracer Workshop. This group is at an early stage. Workshop participants urged the helium/tritium group – and all others – to co-ordinate presentation of data products as far as practical (for example using neutral surfaces versus density surfaces, or using the same neutral surfaces where appropriate). A preliminary list of parameters to be reported to the WHPO by this subgroup include:

- ($^{4}$He) (the symbol pair "()" = "concentration")
- (Ne) (available for many of the WHP helium lines)
- $\delta^{3}$He ("del" = isotope ratio anomaly)
- $^{3}$H

Guidelines for uniform reporting standards and units were agreed upon. A work list for the laboratories was drawn up, including:

- Check ($^{4}$He) and (Ne) for consistency, within individual labs (data set consistency) and between all WOCE helium labs (inter-lab calibration and data set comparisons).
- Check $\delta^{3}$He for consistency. (Same as above.)
- Check ($^{3}$H) for consistency. (Same as above.) Also examine and correct for inter-laboratory differences in accounting for the cosmogenic contribution.

For intercalibration the group agreed upon preparation of standards and standard samples, with distribution to all the identified WOCE laboratories (WHOI, LDEO, PMEL, University of Miami, University of Bremen, University of Heidelberg, University of Paris, and SOC):

- $^{3}$H: 0 TU prepared by WHOI/LDEO, 0.2 and 2 TU prepared by University of Bremen. Obtain 5 TU standard from IAEA for absolute calibration against established reference (Peter Schlosser). Provide two 1-litre glass bottles of water to each laboratory.
- (He) and (Ne): same laboratories; provide two different sets of samples: high temperature and low temperature. University of Bremen: for Mediterranean cruise 1999, University of Heidelberg will send two boxes of copper tubes (48 tubes) to UB.
- Gas standard: check into availability of University of Heidelberg gas standard container.

The group agreed upon an investigation of the linearity of $^{3}$He measurements. First-order data products (list not yet finalised) may include:

- $\Delta$He ("Delta" = saturation anomaly)
- $\delta^{3}$He
- $\Delta$Ne
- ($^{3}$He)

Standard procedures for preparation were discussed.

Other, more interpretative or model dependent data products may include:

- terrigenic He
- ($^3$He) (in TU)
- ($^3$H) + ($^3$He) (in TU)
- $^3$H /$^3$He age

A request was made to the WHPO (or ODF/SIO) to arrange a short cruise (1 day; or participation on a short cruise already scheduled, ASAP) to collect multiple (3?) 30-litre Niskin samples at two (?) depths (a well-mixed upper layer and a ca. 1000 m or deeper layer) for multiple helium (copper tube) samples to be sent to all labs for a comparison exercise. J. Swift agreed to broach the matter to SIO. J. Lupton mentioned a fall-back plan for a possible summer 1999 chance to obtain the samples.

### 4.5.3 Radiocarbon

$^{14}$C concentration, bomb-$^{14}$C, alkalinity, total $CO_2$, and anthropogenic $CO_2$ will be archived by CDIAC and in the WOCE Archive. A US-funded group effort (contact: R. Key) is underway to carry out basin wide calibrations of the global data set, including DQE by cruise and by basin. The basin DQE may result in changes to the quality byte 2 in the data files. Data products (for each parameter) expected include gridded sections and a 3-D gridded data set (by basin). Bomb-$^{14}$C and anthropogenic $CO_2$ will have water column inventories and a table of recommended calibration adjustments. Alkalinities where not measured will be calculated and will have quality byte set to zero. Basin-wide nutrient examinations will also be done and will result in a table of recommended calibration adjustments.

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## PROGRAMME

**Sunday, 21 February**

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|---|---|
| 18.30 | Welcome Reception and Buffet dinner (end 22.00) |

**Monday, 22 February**

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| 9.00 | Introduction, welcome addresses |
| 10.00 | Review of tracer constraints in ocean circulation (*P.Schlosser*) |
| 10.45 | Coffee break |
| 11.15 | Review on tracer modelling (*M. England*) |
| 12.00 | Available tracer data and methodology (*W. Roether*) |
| 12.45 | Lunch |
| 14.00 | Poster presentations |
| 14.45 | Issues in upper ventilation and circulation (*W. Jenkins*) |
| 15.00 | Issues in intermediate and deep water formation (*W. Smethie*) |
| 15.45 | Coffee break |
| 16.15 | Diapycnal mixing in the ocean interior (*J. Toole*) |
| 17.00 | The role of tracers for ocean biogeochemistry (*D. Wallace*) |
| 18.00 | Adjourn |

**Tuesday, 23 February**

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| 9.00 | Poster presentations |
| 9.30 | Assimilation of tracers into models (*R. Schlitzer*) |
| 10.30 | Coffee break |
| 11.00 | Conceptual models vs GCMs in tracer oceanography: a false dichotomy (*S. Doney*) |
| 11.45 | General discussion, formation of working groups |
| 12.45 | Lunch |
| 14.00 | Poster presentations |
| 15.00 | Working groups meet |
| 16.00 | Coffee break |
| 16.30 | Working groups meet |
| 17.00 | Adjourn |
| 18.30 | Museum Weserburg: Reception, Dinner (end 22.30) |

**Wednesday, 24 February**

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| 9.00 | Future oceanographic developments and programmes (*plenary discussion*) |
| 9.45 | Working groups report and discussion |
| 10.30 | Coffee break |
| 11.00 | Working groups meet |
| 12.45 | Lunch |
| 14.00 | Poster presentations |
| 14.45 | Working groups meet |
| 15.45 | Coffee break |
| 16.15 | Working groups meet |
| 17.15 | Tracer data product needs and issues (*Mark Warner*) |
| 18.00 | Adjourn |

**Thursday, 25 February**

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| 9.00 | Working groups report and discussion |
| 9.45 | Working groups meet |
| 10.45 | Coffee break |
| 11.15 | Working groups meet |
| 12.30 | Lunch |
| 14.00 | Working groups meet |
| 15.30 | Coffee break |
| 16.00 | Final plenary |
| 17.30 | Adjourn |

**Friday, 26 February**

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| 9.00 | Writing jobs (workshop output), definition of joined projects, discussing tracer community future, special presentations, other workshop leftovers |
| 10.00 | Coffee break |
| 11.00 | Final meeting of Planning Group |
| 13.00 | Lunch |
| 14.00 | Planning group continued |
| 15.00 | End of Workshop |

# ABSTRACTS OF INVITED LECTURES

## REVIEW OF TRACER CONSTRAINTS ON OCEAN CIRCULATION – Peter Schlosser, LDEO, USA

Tracers have been used routinely in oceanographic studies since several decades. In this overview, the application of a variety of tracers to oceanographic problems is reviewed. The tracers discussed include transient tracers (CFCs, tritium, tritiogenic $^{3}$He), as well as quasi-steady state tracers ($^{14}$C, $^{39}$Ar, stable isotopes of water, helium isotopes). Case studies are used to illustrate the insight into oceanographic problems gained from tracer measurements. They cover a wide spectrum of spatial and temporal scales, ranging, for example, from global studies of the distribution of $^{14}$C in the deep ocean to regional studies of the temporal variability of deep water formation.

## REVIEW ON TRACER MODELLING – Matthew England, The University of New South Wales, Australia

Geochemical tracers are now widely used to assess the simulated circulation in ocean models. Tracers that have been used in this context include tritium, chlorofluorocarbons, natural and bomb-produced radiocarbon; and, to a lesser extent, oxygen, silicate, phosphate, isotopes of organic and inorganic carbon compounds and certain noble gases (e.g., helium and argon). Table 1 includes a list of these tracers and their various applications and properties. This paper reviews the use of chemical tracers in assessing the circulation and flow patterns in global and regional ocean models. Elsewhere reviews are given of biogeochemical tracer modelling and chemical tracer assimilation into ocean GCMs. Crucial information can be derived from chemical tracers that cannot be obtained from temperature-salinity (T-S) alone. In fact, it turns out that a model with a good representation of T-S can have significant errors in simulated circulation, so checking a model's ability to capture chemical tracer patterns is vital. Natural chemical tracers such as isotopes of carbon, argon, and oxygen are useful for examining the model representation of old water-masses, such as North Pacific and Circumpolar Deep Water. Anthropogenic or transient tracers, such as tritium, chlorofluorocarbons, and bomb-produced $^{14}$C are best suited for analysing model circulation over decadal time-scales, such as thermocline ventilation, the renewal of Antarctic Intermediate Water, and the ventilation pathways of North Atlantic Deep Water and Antarctic Bottom Water. Tracer model studies have helped to reveal inadequacies in the model representation of certain water-mass formation processes; for example, convection, downslope flows, and deep ocean currents. They show how coarse models can chronically exaggerate the spatial scales of open ocean convection and deep currents, while underestimating deep flow rates and diffusing downslope flows with excessive lateral mixing. Higher resolution models typically only resolve thermocline ventilation because of shorter integration times, and most resort to high-latitude T-S restoring to simulate reasonable interior water-mass characteristics. This can be seen to result in spuriously weak chemical tracer uptake at high latitudes due to suppressed convective overturn and vertical motion. Overall, the simulation of chemical tracers is strongly recommended in model assessment studies and as a tool for analysing water-mass mixing and transformation in ocean models. A cost-effective approach is to simulate natural radiocarbon to assess long time-scale processes, and CFCs for decadal to interdecadal ocean ventilation. In addition, property-property analyses and the assessment of transient chemical signatures in key locations provide more stringent constraints on ocean models than simple comparisons of WOCE sections along selected lines. Natural radiocarbon provides the best test of deep model ventilation rates. It is relatively straightforward to simulate in ocean models, and by estimating radiocarbon as a ratio to $^{12}$C, rather than as an absolute concentration, isotopic fractionation and biological conversion processes can largely be ignored. However, long equilibration times are normally required to bring the model radiocarbon fields to steady state (up to 5000 years for a global model). Some techniques have been developed for accelerating this equilibration process in higher resolution models, such as adopting initialised fields from an off-line coarser grid model. The main three transient tracers simulated in ocean models are chlorofluorocarbons, bomb-produced radiocarbon, and tritium. Simulating anthropogenic radiocarbon involves extending a natural radiocarbon simulation by about 50 years, covering the nuclear bomb enhancement of the atmospheric concentration of this carbon isotope, which is reasonably well-known. Tritium input functions into the ocean are time-dependent and strongly favour the Northern Hemisphere, where most of the atmospheric bomb testing in the 1950s and 1960s occurred. This is because tritium enters the ocean primarily in rainfall, water vapour and river run-off, not in gaseous form.

The World Ocean entry function of tritium has been estimated by several researchers, though its certainty is not well-known. Chlorofluorocarbons are perhaps the simplest chemical tracers to include in ocean models as they have well-known source functions, no biological conversion, and only require short model integration times. Recent model assessment studies using CFCs have identified short-comings in the simulation of the Deep Western Boundary Current (DWBC) in the North Atlantic and the meridional overturn of water masses in the Southern Ocean. The DWBC is generally too broad and sluggish in coarse resolution models and typically only includes one CFC-laden core. In the Southern Ocean excessive open-ocean convection near the subpolar front contaminates interior CFC simulations unless realistic mixing schemes are adopted. Even then, time-scales of bottom water ventilation are generally unrealistic, even if reasonable T-S are captured by the model. There are a suite of other chemical tracers that are present in seawater and have the potential for use in ocean modelling studies. Examples include argon, mantle helium, and caesium, as well as radioactive isotopes of common tracers such as silicon and oxygen. There are generally fewer deep ocean observations of these tracers, particularly $^{39}$Ar. Nevertheless, they often have distinctive entry functions or radioactive decay rates, thereby giving different information to the more commonly used tracers. A key example is mantle helium, which enters the deep ocean in hydrothermal fluids in seafloor volcanism. It therefore tracks Deep Ocean spreading pathways and rates, although the exact entry distributions remain relatively poorly known. $^{39}$Ar decays with a radioactive half-life of 269-years, therefore providing a different view of deep ocean ventilation than that given by radiocarbon. There remain several sources of uncertainty in the inclusion of chemical tracers in ocean models and their comparison with observed WOCE data sets. These include source input functions, representation of air-sea gas exchange, spatial and temporal variability in the observed tracer data, open tracer boundary conditions for regional models, and uncertainties in derived data products. One of the working groups of the WOCE Tracer Workshop (WG3) has listed priority research areas to minimise these uncertainties in chemical tracer modelling.

## AVAILABLE TRACER DATA AND METHODOLOGY – Wolfgang Roether, Universität Bremen, Germany

The starting position of this workshop is that we are heir to the extensive oceanic tracer data set that the WOCE field programme has produced. The data provide unprecedented global spatial coverage compared to the more regional surveys available so far (e.g., SAVE), and at the same time a spatial resolution by far exceeding that achieved in the only previous tracer programme of a global scope, i.e., GEOSECS. In dealing with this data set, we have to address data issues and issues dealing with derived products and methodology. The data part includes:

- Spatial resolution: while along-track resolution is good, there are considerable distances between sections, making horizontal mapping problematic. One may compute tracer fluxes across sections, but more often tracer inventories are required. Isopycnal interpolation presumably is the best way to obtain the latter. Besides area gaps, one has also to consider seasonal gaps.

- Data precision: CFCs are best in precision and resolution (= detectable fraction of surface water concentration), but calibration, the corrections for non-linear detector response, and contamination may cause inconsistencies. Tritium and $^3$He lack the latter problem but have lesser precision in total. The data need to be accurate in the sense of precise and consistent intercalibration between all contributing laboratories.

- Boundary conditions: Concentration boundary conditions are rather straightforward for the CFCs and, naturally, also for tritiugenic $^3$He. Tritium is problematic; a globally coherent source function so far only exists for tritium flux but it of appreciable uncertainty. Ice-covered areas are problematic, and source rates of terrigenic He from the ocean floor have still to be assessed.

- Chemical stability: $CCl_4$ is known to be unstable in warm waters. Its limits of stability in cold waters and also those of CFC-11 and CFC-12 are unknown. CFC-113 appears to be problematic in the upper waters.

The data products, derived quantities, and methodology part includes:

- The data are non-synoptic on a basin scale. Some users want original data, but often correction to a common year is required, which cannot be done in a unique fashion.

- Commonly used derived quantities are equivalent partial pressures using published solubility functions, apparent saturation, and water ages (age = period since the ocean mixed layer was left). It must be kept in mind that all these products depend on certain assumptions (e.g., solubility equilibrium in the mixed layer).

- Tritiugenic $^3$He is determined as the excess over a natural background, which has a certain error margin; in the southern hemispheric there is little tritiugenic $^3$He so that to determine this property becomes a research issue.

When evaluating tracer observations by numerical models, or by conceptual models of various kinds, it is advantageous to use data for more than one tracer. To exploit differences between the distributions of different tracers in this way, however, requires that sufficiently numerous and precise data exist (including repeated observations preferably, but ocean variability must also be taken into account). Differences in distributions are due to differences in tracer boundary conditions in connection with ocean mixing, but one must note that the differences are mostly quite small and that well-conditioned situations have to be selected, because otherwise different tracers may yield rather redundant information only. Studies on this exist but further work is required. Several tracer ages can be calculated (concentration ages and tracer ratio ages, based on different tracers), which likewise show differences in the numerical values. One way to exploit these is the concept of age distributions. The number of degrees of freedom of the latter must be adapted to the information content extractable from the available tracer data, or from any other complementary information (e.g. generic concepts of ocean transport). By using transient tracer data, naturally, the age of waters older than at most several decades remains undefined. Of these tracers, $CCl_4$ extends the farthest into the past, information further back could only come from $^{14}$C or $^{39}$Ar data. Investigations have shown that a rather robust information is mean age versus percentage of the youngest fraction of the water. This represents an extension of the well-known tracer ratio dating which allows the determination of an old, tracer-free fraction. In principle, a numerical model can be tested against a tracer-based age distribution, i.e., without addressing tracer data directly. Tracer-based information such as an age distribution is complementary to the more common determinations of velocity fields and mass fluxes, in that it tells the strength and nature of internal recirculation of the waters.

## ISSUES IN UPPER VENTILATION AND CIRCULATION – William J. Jenkins, SOC, UK

Transient tracers have provided us with extraordinary insights into upper ocean processes of ventilation, circulation and mixing. These, in turn, have lead to equally remarkable progress in quantifying biogeochemical cycling within the upper ocean. The sophistication with which we interpret tracer observations has evolved, and there is an emerging recognition that their strength arises from interpreting such observations within the context of other data. We are faced with a number of challenges over the next few years, some of which are:

- The effect of small scale processes on tracer distributions: reflects on what optimal resolution of sampling is required, how representative of the “real field” are tracer observations, and how to parameterise tracer transport in models. What experiments can we do to evaluate these processes?

- How a limited knowledge of boundary conditions for tracers affects their utility. How do we improve our knowledge of these boundary conditions? What are the ultimate limitations?

- Where is the obverse of ventilation occurring? How do nutrients and AOU (and $^3$He) return to the ocean surface layer? These are important issue for understanding ocean productivity.

- How can we use transient tracers to evaluate climatic variations in ventilation? How do such variations affect our inferences of the “steady state”?

WOCE has provided us with a global-scale, broad-brush sketch of tracer distributions in the world ocean. It is very clear that in the post-WOCE era, carefully conceived and co-ordinated multi-tracer regional or process studies represent the optimal strategy to complement climate-motivated monitoring studies. Agreeing on and designing such efforts will require a lot of thought, introspection and a realistic assessment of resources and priorities.

## ISSUES IN INTERMEDIATE AND DEEP WATER FORMATION – William M. Smethie, LDEO, USA

Major oceanographic problems with respect to the deep ocean that can be addressed using tracer data are: mechanisms of deep and bottom water formation, rates of formation of deep and bottom waters, circulation and mixing of deep waters, and temporal variability in formation rates and circulation. Tracer data have been used to investigate deep water formation since the first measurements of $^{14}C$ in the deep ocean were made 4 decades ago and $^{14}C$ data from later studies such as GEOSECS provide one of the most reliable estimates of the overturning rate of the deep ocean. More recently, observations of transient tracers such as the tritium/$^{3}He$ pair and CFCs, have revealed the input pathways for newly formed deep and bottom water from North Atlantic and Southern Ocean sources as well as the time scale for water to move along these pathways. The formation rates of these deep waters have also been estimated from inventories of transient tracers. Observations of $^{3}He$, which emanates from the mid-ocean ridges, has revealed mid-depth flow patterns in the Pacific Ocean. These studies have been based mainly on local and regional surveys carried out over a couple of decades and have been limited by a lack of complete spatial coverage and, in the case of the transient tracers, by not being synoptic. The WOCE data set has great potential for expanding these studies and addressing the problems listed above. The methodology used in these previous studies such as mapping tracer concentration fields to determine circulation patterns, calculating tracer water mass ages to estimate flow rates, and performing box model budget calculations to estimate deep water formation rates and basin exchange rates will certainly be applied to this new data set as an initial step at interpreting the data. But to realise the full potential of the data, the data analysis must be more quantitative and include other types of data. Modelling will be one of the major techniques by which this will be done. There are some problems that must be addressed to fully utilise the tracer data for deep water investigations. One of the most important problems for any quantitative interpretation of the tracer data is knowledge of the input functions. For tracers entering the surface ocean from the atmosphere, this is complicated in deep water source regions by rapid deep convection and/or ice cover that prevent equilibration of the surface water with the atmosphere. Also, as waters descend to deep depths after being made dense at the surface, they often entrain adjacent water or mix with dense water from other sources. This problem cannot be addressed strictly with the WOCE data set and will require process studies to understand the mechanisms of deep water formation. For the deep $^{3}He$ signal in the ocean, the emanation rate from the mid-ocean ridges is needed. Ocean variability needs to be considered in interpretation of the WOCE data set. This is especially true for the North Atlantic data since the WOCE data set was taken at a time when the NAO index reached a very high level. This clearly affected the rate of formation of Labrador Sea Water and possibility other components of North Atlantic Deep Water. Both previous and future data sets will need to be combined with the WOCE data to address ocean variability problems. Careful planning will be required to determine where and when future observations will be made.

## DIAPYCNAL MIXING IN THE OCEAN INTERIOR – John M. Toole, WHOI, USA

The oceans' overturning circulation involves air-sea-exchange-driven water mass modification/formation with subsequent introduction of these waters into the ocean interior by convergent wind stress and/or differential buoyancy forces. Mixing in the interior supports the mean diapycnal flow required to close the circulation. I will review present understanding of mixing processes and rates in the ocean interior based on diagnoses of circulation schemes, heat budget analyses, interpretation of ocean microstructure and fine structure, and tracer dispersion studies. By far the most intense turbulent mixing occurs in and about the highly-time-dependent surface mixed layer. In the main thermocline below the surface layer, a (small) turbulent diapycnal diffusivity of order $0.1 \times 10^{-4} m^2/s$ is sustained by internal wave breaking within the background wave field, a level confirmed by the North Atlantic Tracer Release Experiment (Ledwell et al., 1993, 1998). Apart from the equatorial currents and dense overflows from marginal seas, ocean currents do not by themselves support much diapycnal mixing either. The internal wave field intensity, and associated turbulent dissipation, is however much enhanced in localised regions such as the anticyclonic shear zones of ocean currents and mesoscale eddies and near sloping and/or rough bathymetry where diapycnal diffusivities of order $1 \times 10^{-4} m^{2/}s$ have been deduced. Salt fingering may also cause enhanced diapycnal fluxes in regions characterised by low density ratio, with the added complication of different heat and solute transports. Being localised however, these mixing "hot spots" do not appear able to boost the area-averaged diapycnal diffusivity on thermocline-depth isopycnals much above $0.1 \times 10^{-4} m^2/s$. This suggests a near-ideal-fluid model for the main thermocline waters below the surface mixed layer. Conversely in the abyss, isolated from intense surface forcing, diapycnal mixing is significant in terms of water mass budgets and circulation dynamics. The deep mixing appears to be sustained by the breaking of bottom-generated internal waves, themselves driven by near-bottom flows over rough bathymetry. Results from the ongoing Brazil Basin Tracer Release Experiment will be presented.

## THE ROLE OF TRACERS FOR OCEAN BIOGEOCHEMISTRY – Douglas W.R. Wallace, IfM Kiel, Germany

Since the era of GEOSECS, tracers have made enormous contributions to the overall field of ocean biogeochemical studies. These contributions have been so basic and fundamental that they tend to be overlooked. They range from the initial use of natural radiocarbon to estimate the overall turnover time of the World Ocean (Stuiver, Ostlund). This led directly to the determination of overall rates of cycling of biogeochemically-reactive materials in the ocean (see Broecker and Peng book). The rate of air-sea gas exchange similarly has largely been determined through tracer studies (see Wanninkhof, 1992). Particulate transport in the oceans, including scavenging rates, are generally inferred from tracers (key reference). Similarly, tracer-based interpretations of nutrients and oxygen have led to basin-wide estimates of biological productivity, respiration (see Jenkins and Wallace) and nitrogen-fixation (see Gruber) and denitrification (see Doney). Another major area of the application of tracers has been to the estimation of the uptake rate of anthropogenic $CO_2$ by the ocean. Initially, this was determined almost exclusively by modelling studies where the models were calibrated or validated by tracers such as $^3H$ and bomb-$^{14}C$ (Oeschger et al., 1975; see also Sarmiento and Siegenthaler, 1993). Increasingly, model-independent methods of assessing anthropogenic carbon uptake using tracers have been introduced (see review by Wallace, 1995). Some of these methods follow directly from the pioneering work on so-called “preformed $CO_2$” calculations (e.g. Brewer, 1989; Chen and Millero, 1986; Gruber et al., 1996). Others employ new tracers such as $^{13}C$ (Quay et al., 1992). As a result of the large data set collected during WOCE and the Global Survey of $CO_2$ in the Oceans (Sabine, Wallace and Millero, 1999) it is now becoming possible to directly compare modeled distributions and inventories of anthropogenic $CO_2$ with data-derived estimates. Most recently, a set of deliberately introduced tracers has been applied to the issue of air-sea gas exchange (reference) and the question of whether iron limits biological production in the ocean (references). These purposeful releases of tracers have been highly successful, and are likely to continue in the future. In this presentation, I present a brief, subjective review of the state of tracer applications to ocean biogeochemistry. The presentation concentrates on the following examples of the application of tracers to ocean biogeochemical questions:

- **Uptake of anthropogenic $CO_2$.** Observation-based estimates of anthropogenic $CO_2$ have recently been developed on a basin-scale by Sabine et al. (1999). These follow similar basin-scale estimates using pre-WOCE data for the North and South Atlantic Oceans (Gruber et al., 1996; Gruber, 1998). The storage patterns are being compared directly compared with output from GCM simulations. Such comparisons are already leading to identification of potential problems with the model simulations, however the comparisons must also be viewed as having the potential to highlight areas where some of the many assumptions involved in the data-based estimates may be violated. Alternative methods of evaluating the data-based estimates are discussed. Particularly, the multi-tracer relationship between estimated anthropogenic $CO_2$ and CFCs in the northern North Atlantic and the South Atlantic is examined (Koertzinger et al., submitted, Holfort and Wallace, unpubl., Figure 1). In addition, the relationship between anthropogenic $CO_2$ and the $^{13}C$ content of DIC is presented for the northern North Atlantic. The former relationship appears to vary significantly between the North Atlantic Ocean subpolar gyre, where the data imply mixing between recently formed water and very old water with little or no anthropogenic CO2, and the South Atlantic where the data appear to follow more closely to the CFC-11 vs. Anthropogenic $CO_2$ input history. The different relationships may reflect different advection-mixing relationships in the two regions. Alternatively, the relationships may reflect uncertainties or errors in the anthropogenic $CO_2$ calculations. Theoretical, modelling analyses are required to further evaluate these multi-parameter relationships. The $^{13}C$ analysis suggests that for the North Atlantic, most of the variability of the $^{13}DIC$ concentrations can be explained by a simple multivariate regression of $^{13}C$ on phosphate and anthropogenic $CO_2$. The distribution of the residuals and the magnitude of the regression coefficients suggests that the anthropogenic $CO_2$ estimates correspond well to the estimated magnitude of the oceanic Suess-effect in this region. Further testing of anthropogenic $CO_2$ estimates against $^{13}C$ distributions should be encouraged.

- **Rates of degradation of anthropogenic gases in the ocean.** Transient tracers can be applied to estimating the rates of slow transformation and degradation reactions affecting dissolved gases in the ocean. Applications to oxygen utilisation rates were discussed above. Similarly, it is possible to estimate the degradation rate of $CCl_4$ in-situ through models involving the less-reactive halocarbon compounds to constrain the rate of disappearance of the expected concentration of $CCl_4$ (see for example, Wallace et al., 1994; Bullister references). A slightly different approach was used by Butler et al. (1991) to estimate the net air-sea flux of $CHCCl_3$. In this case, the measured supersaturation of CFC-11 was assumed to represent the cumulative effect of physical effects (e.g. upwelling, seasonal temperature changes, finite-gas exchange rates) on anthropogenic halocarbon supersaturations. The difference between this "physically-derived" saturation for a non-reactive gas and the observed saturation of $CHCCl_3$ was assumed to reflect the effect of in-situ degradation of $CHCCl_3$. While this specific approach can be questioned in detail, the overall use of a stable transient tracer to place constraints on the reaction rates of other species is generally applicable. The most recent example of this is a study by Rehder et al. (1999) in which simultaneously-measured CFCs and $CH_4$ are used to infer an average oxidation rate for $CH_4$.

In summary, tracers have proven of great value for ocean biogeochemistry, especially in the area of determining large-scale, average rates of key processes. The application of tracers to the problem of anthropogenic $CO_2$ uptake has already made a significant contribution. There is a need to expand this work, through improved data synthesis involving models, data and particularly the application of multi-tracer consistency checks. However tracers are also relevant to a wide range of other biogeochemical questions, and this will be a fruitful scientific area for the future. Tracer oceanographers should therefore build strong links to their colleagues in chemical and biological oceanography. To a significant extent, tracer oceanographers and techniques can act as a "bridge" between physical oceanography and biogeochemistry. Tracer oceanographers should also work hard to develop new tracers, including purposeful tracers, for tackling new questions. Applications of existing tracers to new questions should be sought out and encouraged.

## ROLE OF TRACERS TO ASSESS/IMPROVE OCEAN MODELS – Claus Böning, IfM Kiel, Germany

(Note that this talk was not delivered, abstract is reproduced for completeness)

The first goal of WOCE is "to develop models useful for predicting climate change and to collect the data necessary to test them". In which ways can chemical tracers contribute to this goal? In order to address this question, we should first reflect upon the main problems and needs in the current state of ocean model development. The prime difficulty of ocean modelling lies in the significance and complex interaction of physical mechanisms on a vast range of space and time scales. Experience from a host of model sensitivity studies and intercomparison exercises suggests that it is useful to rationalise the solution behaviour in terms of two different classes of dynamics which govern the ocean's response at different time scales. Circulation models are found to be robust concerning the simulation of variability at seasonal to interannual time scales where wind forcing is the prime generation mechanism, even for deep current fields (DWBC). This in sharp contrast to the simulation of "mean" flows and their response to thermohaline forcing on (inter-)decadal time scales which is extremely dependent on the representation of interior, often very small-scale processes and their, sometimes hidden, manifestation in different numerical model concepts, or choices of horizontal and vertical resolution. Improving ocean models for climate studies hence critically depends on a better understanding of the key processes and the various numerical factors that affect their representation in the models. A principal means for obtaining this are sensitivity studies into alternative parameterisations and model concepts, and the question at hand hence is: how relevant are tracers in this? The examples to be discussed will primarily (but not exclusively) concern aspects of the thermohaline (overturning) circulation in the Atlantic Ocean. Comparison with chemical tracer patterns cannot be a substitute for testing the meridional transports of mass and heat, usually on the basis of hydrographic section inversions. However, the integral view of the pathways of deep water masses with different origin does provide critical, complementary pieces of information. Because of the strong dependence on parameterisations, models with very different sources of deep water can be tuned to look “realistic” on canonical numbers, e.g., of mass and heat fluxes through 24°N. However, a realistic representation of the different sources could be very important, especially when it comes to simulations of climate change: e.g., recent studies suggest that the response of the large-scale meridional fluxes of mass and heat to atmospheric forcing (e.g., freshwater) anomalies at high latitudes critically depends on the representation of the effect of the overflows from the Nordic Seas. The clear signature of different source water masses in the tracer concentrations of deep western boundary current(s) far away from the source obviously make these a prime target for model testing. Examples from recent model studies using both idealised (“age”) and realistic tracers (especially, CFCs) demonstrate the value of diagnostics focusing on the DWBC for testing alternative parameterisations for the outflow physics. Using tracers to assess and rationalise interior, recirculating flow regimes (e.g., subpolar gyres) appears much more demanding; its potential for aiding in the identification of causes for model deficits has yet to be determined.

## ASSIMILATION OF TRACERS INTO MODELS – Reiner Schlitzer, AWI, Germany

The simulation of ocean tracers with models of varying complexity and resolution has become a standard tool for model verification, calibration and comparison. However, there are only few examples for the use of tracer data in inverse or data assimilation studies, in which observations are directly used (inverted) to determine oceanographic rate parameters like mass and property fluxes, mixing coefficients, biogeochemical production and degradation rates and air-sea exchange fluxes. Two main reasons are seen for this lack of “data-driven” investigations: (1) sparseness of tracer data and (2) methodological difficulties. Traditional inverse methods require data along oceanographic sections that define the control volumes (boxes) of the model. Property budget equations are formulated and used as constraints for the calculation of the unknown rate parameters. For steady-state tracers, single, possibly non-synoptic realizations of the sections are sufficient to define the data needed by the model. The availability of high-resolution WOCE hydrographic, nutrient and carbon data has stimulated inverse models of the biogeochemical nutrient and carbon cycles in the ocean already. For transient tracers like tritium, bomb-$^{14}$C or chlorofluorocarbons (CFC) the available WOCE measurements are not sufficient to construct “strong” property budget constraints for section inverse calculations because of the non-synopticity of the data and the unknown time-rate of change of the tracer concentrations. Considering other data assimilation methods, one of the popular techniques (nudging) seems not to be adequate for tracer modelling because of the artificial property sources and sinks introduced by the nudging term. A model strategy that applies the adjoint method and combines tracer simulations with automatic parameter adjustment based on the misfits of the simulations is proposed as an alternative method for transient tracer data assimilation. Usage of the adjoint method requires considerable methodological development and model extensions and imposes a heavy computational burden. Given the limitations of manual model tuning, these efforts still seem worthwhile, and the adjoint technique might prove to be the only method to fit even complicated global dynamical models to tracer observations. The adjoint method allows the exact formulation of tracer budgets, multiple tracers can be combined and assimilated, situations with very few data can be handled and considerable flexibility in model design and formulation of additional constraints is provided. Use of original, measured concentration data instead of derived quantities, like tracer ages, is seen as an additional advantage. Recently, an automatic adjoint code generator has become available that greatly reduces the model development effort. Improvements in computer technology will allow more complex, higher-resolution applications in the future. For the purpose of determining large-scale water mass transports and air-sea fluxes, tracers with simple geochemistry and known input history are prime candidates for assimilation studies. CFCs seem to satisfy these requirements best. Global tracer datasets are needed, and monitoring the temporal evolution of transient tracer fields appears to be as important as obtaining a good spatial coverage. An issue that has to be addressed more closely in the future is the development of efficient error-estimation techniques for large-scale assimilation problems. This is necessary in order to evaluate the significance and information content of tracers versus other types of oceanographic data sources.

## CONCEPTUAL MODELS VERSUS GENERAL CIRCULATION MODELS IN TRACER OCEANOGRAPHY: A FALSE DICHOTOMY – Scott C. Doney, NCAR, USA

As soon as one moves beyond simple descriptive oceanography, the interpretation of tracer field data inherently is framed, either implicitly or explicitly, in terms of a model. The choice of the "model" is crucial, however, shaping the scientific questions we ask about the data. A model can be as simple as the statement "advection and mixing occur preferentially along isopycnal surfaces" to as complex as a full numerical ocean general circulation model. Some of the more memorable and lasting advances in tracer oceanography are directly linked to very simple conceptual models; examples come to mind such as Munk estimating the abyssal vertical diffusivity as O(1 $cm^2/s$) using $^{14}C$ in the 1-D advection-diffusion equation or Jenkins' demonstrating the dominance of lateral over vertical ventilation processes at Bermuda Hydrostation S with tritium-$^3He$ data in a two box model. The last two decades have also seen significant, though perhaps not so dramatic, results from ocean general circulation model (OGCM) tracer simulations such as the work of Toggweiler et al. on bomb-radiocarbon or GCM predictions of anthropogenic carbon uptake. The question posed for this talk is simply put: has the era of the simple, often kinematic conceptual models come to an end? and if so, how does the community exploit GCMs to achieve the same goals? The key role for conceptual models, by which I mean things like box models, 1-D pipe models, 2-D gyre models, etc. has been two fold—they allow one to cleanly pose specific hypotheses about the ocean, hopefully helping to reject one on occasion, and they provide a method to quantitatively constrain rates of ocean dynamics. Schematic models have a number of strengths relative to full OGCMs since they are straightforward to construct, focus on only the question at hand, and are computationally inexpensive, all of which together are conducive to an extensive exploration of parameter space. By contrast, OGCMs incorporate more realistic spatial and temporal geometry and a much fuller suite of physics, but at the cost of complexity, a more limited number of simulations, and often crucial regional errors in the base solutions, which may compromise direct, quantitative model-data comparisons. The general circulation simulated by an OGCM results from complicated, non-local interactions of the surface forcing, grid resolution, and sub-gridscale physical parameterisations, and it is often difficult to isolate the cause of the presence or absence and character of any particular features of interest such as southern ocean intermediate water formation. In fact, the growing complexity of GCM solutions points to a hierarchy of modelling where conceptual models are used as a supplement to and analysis tool for the full OGCM simulation. Turning the original question around, I also could argue that the continued need for good conceptual models is driven by the poor skill of the present generation of OGCMs and a persistent under-utilisation and limited, in-depth analysis of existing solutions. Typically, the underlying rationale or justification for tracer simulations is model assessment and verification. As is often the case, the modeller declares success, or more commonly failure, after examining only a handful of tracer sections or different chemical tracers, which argues strongly for greater availability of synthetic tracer data sets and standard, objective criteria for judging model-data mismatch. If time permits a limited series of sensitivity runs may be run for a small set of parameters or parameterisations, a good example being England's work on the effect of the Gent-McWilliams mesoscale eddy mixing scheme on CFCs in the southern hemisphere, before the next round of model development and testing is begun. Ocean GCM solutions should be exploited to address exactly those problems which are intractable for simpler conceptual models. A certainly incomplete list would include: how does the three dimensional term balance for tracer ventilation vary in space and time for the thermocline (e.g. Jenkins work at Bermuda and in the eastern subtropical N. Atlantic) and deep water formation and transport regimes? where and how do the assumptions behind common conceptual models breakdown (e.g. compare Doney and Jenkins DWBC pipe model to observed flow patterns of Lozier)? what is the relationship between passive and dynamical tracers (e.g. potential vorticity and salinity) on the mesoscale and how does that impact large-scale distributions? How important are the second order (or perhaps first order) temporal evolution terms (e.g. Robbins work on tritium-$^3He$ age); what are the signatures of interannual to decadal variability in the ocean tracer fields? At a minimum, a much richer set of model diagnostics will be needed to address such questions.

## TRACER DATA PRODUCTS: NEEDS AND ISSUES – Mark Warner, University of Washington, USA

The production of data products is an integral part of the WOCE analysis, interpretation, modelling, and synthesis (AIMS) phase. The tracer community has begun this process, but it needs to further determine what products should be produced, where they should be archived, and what steps need to be performed to ensure that this process is completed. The WOCE Data Products Committee envisions, as a final WOCE product, a completely integrated data set. The set of CD-ROMs containing all of the available WOCE data sorted by data type is an initial step in this direction. The DPC has taken the view that each community of those who make the measurements or archive them should generate these products at first. This community will know which products they find most useful. Feedback from the users of these data products will guide the development of future data products. The data products can be categorised into three levels loosely determined by the amount of scientific effort required to generate them. The classification scheme is:

- **Zeroth Order:**
  - Quality-controlled data
  - Metadata
- **First Order:**
  - Basin-wide quality-control of the data
  - Gridded sections
- **Second Order:**
  - Derived quantities
  - Tools

The zeroth order products in most cases are PI-generated on a section by section basis. Metadata describes aspects of the data collection and post-cruise processing which are essential to the production of the basin-wide data set. Examples of metadata for the CFCs would be analytical technique, PI and shipboard analysts, tables of replicate CFC measurements, blank corrections, air measurements, estimates of precision/accuracy with any variations during the cruise, and standard cylinder with its calibration scale. These metadata should be added to the .doc file at WHPO as an appendix. Basin-wide quality control will result in an internally-consistent data set. The exact method for performing the quality control will depend upon the basin and the tracer. Sections will be gridded using a standard technique. The raw data will be available for those who prefer to grid the data themselves. Derived quantities provide information on the oceanic uptake and transport of the various transient tracers. Examples of derived quantities include tracer ages, water column inventories, water mass inventories, and maps of properties on neutral surfaces (or isopycnal surfaces). Several of these products will require the correction of the data to a common date. The technique(s) for performing these corrections need to be determined for each tracer. The tools used to perform the age corrections should also be made available for those who wish to correct the data to a different date. The US tracer community has been guided by the US WOCE SSC to submit proposals for the global integration and interpretation of the individual tracer data sets. Currently, the proposals to carry out the basin-wide QC and produce basin-wide and global tracer data products have been funded for the CFC, tritium/$^3$He, $^{14}$C, $^{13}$C, carbon dioxide system, and nutrients. The South Atlantic CFC and tritium/$^3$He integration and interpretation will be carried out by W. Roether, and the North Atlantic CFC atlas will be produced by M. Rhein. Web-sites for the various products will be maintained and linked to the WHPO web site. The archival of the various products will be accomplished in a variety of ways. Printed data reports will be issued by the CFC PIs. The zeroth and first order data products will be archived by the WHPO. The archival of the second order data products by WHPO needs to be discussed. The tracer community should suggest which products should be archived, and the DPC should respond to this request. The current requirements for the success of the basin-wide QC process are that the PIs should confirm that their data and metadata are at the WHPO. The groups of PIs for individual tracers should co-ordinate the generation of derived data products. The integration of the tracer data sets should also be co-ordinated with the ongoing production of atlases of the standard hydrographic properties. Preliminary input from potential users of these products will also be helpful in the decision of which data products should be generated. The tracer should also attempt to have the pre-WOCE data sets archived at WHPO. Future efforts may involve the production of multi-tracer products. Other future developments will also be guided by feedback from the various users in the community.

## ABSTRACTS OF POSTERS

The abstracts are listed in alphabetical order of the first author.

### CFC TIME SERIES IN THE DEEP WATER MASSES OF THE WESTERN TROPICAL ATLANTIC, 1990–1996 – C. Andrie and S. Freudenthal, LODYC, CNRS/ORSTOM/Université, Paris, France; and M. Rhein and O. Plähn, Institut für Ostseeforschung Warnemünde, Germany

CFC measurements performed along the 35°W meridian during seven WOCE sections between 4°S and 7°N have been studied in order to investigate the variability of the circulation of the North Atlantic Deep Water (NADW). Transient tracer data are compared with salinity and oxygen measurements respectively at the lower NADW and upper NADW levels. Within the LNADW, the oxygen distribution and its associated CFC core is mainly topographically constrained in the middle of the equatorial channel. Heterogeneous tracer cores are observed within the UNADW layer, highly variable in space and time, totally linked to the salinity cores. This variability presumably results from the seasonal or semi-annual variability of the regional deep circulation. At a longer time scale, a surprisingly similar temporal variability of the CFC mean concentrations of the upper and lower components of the NADW over the 90–96 time series is discussed. There is no CFC content increase within the Antarctic Bottom Water ABBW during this time.

### RADIOCARBON MEASUREMENTS ALONG WOCE WHP P9, P24 AND JAPAN SEA – M. Aoyama, M. Ishii, T. Miyao and K. Hirose, Geochemical Research Department, MRI, Japan

Vertical profiles of radiocarbon in dissolved inorganic carbonate are carried out along WOCE WHP P9, P24 and Japan Sea together with the DIC and Silicate. At the mid-depth around 1500–3500 dbar along P9 and P24, relatively old water ($\Delta^{14}$C<-220 per mil) was observed at all of the stations. Among the stations along P9 and P24, relatively older water ($\Delta^{14}$C<-230 per mil) between 25°N (P9–31) and 10°N (P9–61) is a one prominent feature. In the waters deeper than 3500 dbar, near-bottom relative maximum ($\Delta^{14}$C>-220 per mil) was observed. Among the profiles, one prominent feature is the relatively young water ($\Delta^{14}$C ca. -55–65 per mil) in the Japan Sea, not the WOCE station, deeper than 1500 dbar to the just above the sea bottom.

### RADIOCARBON MEASUREMENTS IN SOUTHERN PHILIPPINE BASIN WATER ALONG WOCE WHP PR1S, PR23 AND PR24 – M. Aoyama, Geochemical Research Department, MRI, Japan); T. Kawano and C. Saito, Ocean Research Department, JAMSTEC, Japan; J. Van der Plicht, Centrum voor Isotopen Onderzoek, Groningen, the Netherlands; and M. Katagiri, KANSO, Japan

Vertical profiles of radiocarbon in dissolved inorganic carbonate are carried out in the southern Philippine sea waters. The $\Delta^{14}$C in the waters deeper than 2000 dbar is almost constant between -210 and -220 per mil down to just above sea bottom. This is unlike the mid-depth minimum observed in the Pacific Ocean around 2000–3000 dbar. South Pacific Tropical Water (SPTW) south of latitude 5°N, which has salinity maximum of 35.4 PSS at $\sigma_\theta$=25.0, showed subsurface maximum of $\Delta^{14}$C of up to 107–118 per mil at salinity maximum layer. Relatively ‘young” waters around -200 per mil were found deeper than 6000 dbar in the south of Philippine trench.

### DECADAL VARIABILITY OF THE ATLANTIC OCEAN CIRCULATION: USING CFCS TO ASSESS AN OCEAN MODEL – J.-O. Beismann and B. Barnier, LEGI, Grenoble, France; and L. Mémery, LODYC, Paris, France

Observational evidence for decadal variations of the Atlantic thermohaline circulation has increased in recent years. These variations seem to be linked to atmospheric phenomena like the North Atlantic Oscillation. In the framework of the CLIPPER project, a medium-resolution (1°) ocean model in both level- and $\sigma$-coordinate configurations is being used to investigate the inter-annual and decadal variability of the thermohaline circulation. The models are forced with the 40-year climatology of ocean-atmosphere fluxes from NCEP/NCAR. Simulating the spreading of CFCs in these models enables us to trace water masses in different model configurations, thereby helping to understand the mechanisms of variability and their representation in ocean models.

### TRACING THE WATER MASSES OF THE NORTH ATLANTIC AND THE MEDITERRANEAN WITH OGCM EXPERIMENTS: FIRST RESULTS OBTAINED WITHIN TRACMASS, A MAST III, EEC-FUNDED, RESEARCH PROJECT – B. Blanke, K. Pailler, S. Speich, and M. Valdivieso da Costa, LPO, Brest, France; V. Rupolo, ENEA, Casaccia, Italy; and G. Madec, LODYC, Paris, France

In the framework of TRACMASS, a MAST III research project supported by the European Community and gathering scientists of ENEA, IFA-CNR, KNMI, LPO, MISU and SOC, we use Lagrangian calculations to evaluate the mass transfers between given sections of a selected OGCM simulation. Some first results, obtained jointly at ENEA and LPO, deal with some theoretical developments related to the study of the minimal sampling period of the OGCM output that is required for the achievement of robust Lagrangian diagnostics, in off-line, time-varying, velocity fields. The diagnostics include the computation of typical space and time scales (as deduced from the computation of a large number of individual trajectories) over selected sub-domains of the Mediterranean Sea (for the GFDL MOM model run at ENEA) and the North Atlantic (for the LODYC OPA model analysed at LPO). Other studies carried out at LPO already provide some qualitative and quantitative estimates related to the global three-dimensional ocean circulation: Lagrangian trajectories calculated from a reference OPA simulation allow us to describe the preferential paths followed by the NADEW in the North Atlantic, including its possible recirculation, along with the associated characteristic time scales and mass transports. Moreover, this particular approach permits to study in a convenient way the NADW transformations as it flows equatorward, in terms of the evolution of the mass transport, and modification by mixing with surrounding water masses. On a more global scale, the transports for the so called warm water path (i.e., waters coming to the North Atlantic from the Pacific, through the Indonesian Throughflow) and the cold water path (i.e., waters entering the South Atlantic at the Drake Passage) are diagnosed. The three-dimensional structure of these paths are presented together with some associated characteristic time scales (in terms of average transfer and recirculation times).

### TRACER SIGNALS OF AABW IN THE SOUTH WEST INDIAN OCEAN – S.M. Boswell and D. Smythe-Wright, Southampton Oceanography Centre, Southampton, UK

Using a simple T-S based mixing model we have assessed the dilution of AABW as it moves away from the Weddell Gyre and into the South West Indian Ocean. By combining these results with CFC tracer measurements from the two SWINDEX cruises (South West Indian Ocean Experiment, 23 March–3 May 1993 and 6 January–26 February 1995), we have been able to make estimates of the large-scale translation rates of AABW in this region. Two major flows, northward across the Agulhas into the Mozambique Basin, and eastward between the Conrad Rise and the South West Indian Ridge, have speeds of around 0.9 cm $s^{-1}$, with several weaker flows having also been identified. We subsequently extended the mixing model to look at the development of AABW’s characteristic dissolved silicate signal: previous studies of the spread of AABW have been based on a combination of classical hydrography and dissolved silicate content. This signal is the result of a combination of dissolution of sinking diatomaceous particles and diagenetic release. By looking at the deviations of both dissolved silicate and oxygen from that predicted from simple mixing, we have been able to distinguish between the two sources of silicate to the water column. The CFC-derived timescales have enabled us to calculate silicate fluxes at various points across our study area. The diagenetic release of dissolved silicate to the overlying water is generally between 300 and 760 $\mu$mol $m^{-2}$ $y^{-1}$, in agreement with results from sediment core studies in the Southern Ocean. Values for the remineralisation flux are lower, <415 $\mu$mol $m^{-2}$ $y^{-1}$, but are consistent with budget calculations which have hitherto been the only means of estimating this flux. The variability of both these fluxes across our study area indicates that care must be taken when using dissolved silicate as a quantitative tracer.

### ESTIMATING TURNOVER TIMES AND SUBDUCTION RATES OF SACW FROM CFC-11 AND TRITIUM DATA – M. Butzin and W. Roether, Universität Bremen, Germany.

CFC-11 and tritium data are used for an analysis of the upper level circulation in the South Atlantic ($\sigma_0$=26, 0–27, 1 kg/m$^3$). Tritium data were obtained during WOCE cruises. CFC-11 data originate from the programmes WOCE and SAVE. Water mass dating in the subtropical gyre yields average CFC-11 concentration ages between 5–18 years and average CFC-11/tritium ratio ages of 2–12 years. Turnover times are also estimated from the tritium budget of the mixed layer only. This method gives comparable results in the range 7–12 years. Tracer ages and the tritium budget of the mixed layer lead to estimates of flow velocities and volume transports. In the subtropical gyre the tracer based integrated meridional volume transport agree with the Sverdrup transport. Tracer based subduction rates exceed Ekman pumping rates indicating lateral recirculation within the subtropical gyre. The integrated subduction rate (~16 Sv) is smaller than the integrated meridional volume transport (~19 Sv). This difference may be due to uncertainties in climatological sea surface data or may hint additional import of water into the thermocline of the South Atlantic.

### SENSITIVITY OF THE OCEANIC VENTILATION TO THE SUBSURFACE-MIXING PARAMETERISATION IN THE OPA MODEL: SIMULATION OF CFCS AND TRITIUM-HELIUM3 UPTAKE – J.-C. Dutay, LSCE, Laboratoire des Sciences du Climat et de l'Environnement, France; and G. Madec, LODYC, Laboratoire d'Océanographie et de Dynamique du Climat, France

The uptake and redistribution of passive tracers in the ocean is a real opportunity to test the circulation and mixing process of OGCMs. The sensitivity of the OPA model (LODYC/IPSL, France) to different subgrid-scale mixing parameterisation is analysed with results from CFC and tritium-$^3$He uptake simulation. Four simulations are presented which differs by their vertical or lateral mixing parameterisation. The first two experiments are with horizontal diffusion, one has an analytical profile and a convective adjustment for vertical mixing, while it's derived from a turbulent kinetic energy closure (TKE) for the second experiment. The two other experiments are realised with the TKE closure for vertical mixing parameterisation, but their lateral mixing is changed. In Experiment 3, lateral diffusion is isopycnal (with no horizontal background diffusion), and in the fourth one the Gent and McWilliams parameterisation for mesoscale baroclinic eddies is added. We compare model's results to measurement collected during major ocean observation programmes, with a particular focus on the northern hemisphere thermocline ventilation, where "tracer age" is used to study how these different parameterisations affects the model's ability to realistically simulate the subduction and propagation of tracers in the thermocline.

### SUBTROPICAL/TROPICAL EXCHANGE IN THE PACIFIC OCEAN – R.A. Fine, B. O'Connor, and D.B. Olson

Data are presented that give compelling evidence about long-term subtropical-equatorial exchange as part of the shallow meridional circulation cell inferred from earlier tracer work and models. This exchange is important because of the potential role of extra tropical subduction of upper ocean temperature anomalies and their subsequent equatorward advection in modulation of ENSO on decadal time scales. Data used are hydrographic, tracers, drifters, satellite and climatology. We quantify time scales, effective spreading rates, large scale subtropical/tropical flux, and subduction rates for individual water masses. In addition, both mean subduction rates and effects of interannual variability are presented.

### GLOBAL FLUXES OF NUTRIENTS AND OXYGEN FROM THE WOCE TRANSOCEANIC SECTIONS – A. Ganachaud and C. Wunsch, MIT, Boston, USA

The large-scale oceanic circulation and its property fluxes are determined globally from the zonal transoceanic WOCE sections. A linear inverse "box" model combines the sections to produce a geostrophic circulation (with Ekman layers) that is consistent with near-conservation of mass, salt, heat and other tracers such as silica, PO138 and NO. The global fluxes of nutrients and oxygen will be the focus of the poster. Estimates of their divergences are, where statistically significant, estimates of primary productivity. We explore the limits of such a linear, integral-steady-state model for estimating the ocean circulation. Although the deep circulation appears relatively stable in time, variation in the baroclinic shear at intermediate depths occasionally leads to large mass residuals, rendering difficult the interpretation of property divergences.

### CONSTRAINING A NORTH ATLANTIC OCEAN GENERAL CIRCULATION MODEL USING CFC OBSERVATIONS – T.W.N. Haine and S.L. Gray

We have developed and tested a novel, general theory for comparing passive tracer observations with ocean general circulation models using a Green's function method. We have estimated the optimal CFC air/sea flux, est error, and the mid-latitude tracer wavenumber spectrum. These quantities are required for any model/data comparison of this kind. Using a substantial CFC dataset we have applied the new method to a 4/3 degree resolution isopycnic model of the North Atlantic ocean. We find the model tracer fields are inconsistent with the measurements on scales of order a few 100 km. There are systematic differences between the model-predicted CFC field and the observations in the subpolar gyre. We use the Green's function itself to perform a comprehensive water-mass/fluid age diagnosis of the model flow to understand the nature of the erroneous circulation.

### HELIUM ISOTOPES IN THE SOUTHERN OCEAN: AN OVERVIEW OF ONGOING PROJECTS – R. Hohmann, P. Schlosser, A. Ludin, R. Weppernig, G. Bönisch, B. Turrin, R. Bayer, M. Mensch

Helium isotopes have found a variety of applications in the Southern Ocean including estimates of average heat fluxes and addition of glacial meltwater. During the last decade, we collected more than 3000 water samples on numerous cruises to all tree sectors of the Southern Ocean. Most of the samples were measured at the Lamont-Doherty Earth Observatory and the Institute for Environmental Physics at the University of Heidelberg. In this contribution we discuss concepts for the evaluation of the data and present preliminary results.

### MULTIPLE LINEAR REGRESSION AS A INTER- AND EXTRAPOLATION TOOL – J. Holfort and D.W.R. Wallace

Compared to CTD measurements the spatial resolution of bottle measurements is poor. Furthermore not all parameters can be measured from all bottles and sometimes even cannot be measured at all on a particular cruise. We present a interpolation method using multiple linear regression to get data values for all bottles and even interpolate parameters that were not measured using data from other cruises and also to extrapolate bottle data onto the CTD measurements. The advantages compared to simple linear interpolation are generally smaller interpolation errors and the ability to fill data gaps.

### SUBDUCTION RATES AND VOLUMES FOR THE SOUTHERN INDIAN OCEAN THERMOCLINE – J. Karstensen, Institut für Meereskunde, Universität Hamburg, Germany; and D. Quadfasel, now at NBI/AFG, University of Copenhagen, Denmark

Using a kinematic as well as a transient tracer/oxygen approach, the subduction rates for water into the southern Indian Ocean thermocline were calculated and compared. For both techniques, the rates were found to be of the same magnitude with respect to the error margins. Comparing Ekman and Ekman+lateral induced rates in density increments of the winter mixed layer, the side-by-side existence of Indian Central Water and Mode Water is evident. The total volume of subducted water into the permanent thermocline was found to be 32 Sv for the density range $\sigma$=25.3 to 26.9 kg/m$^3$. This is comparable to recent estimates for the North Atlantic (27 Sv) and North Pacific (35 Sv) Ocean. However, the proportion of the lateral volume transport in the Indian Ocean (20 Sv) is twice as large compared to the Northern Hemisphere oceans (NA 10 Sv; NP 10 Sv). This is in agreement with the large volume of Mode Water, which can be found in the Indian Ocean. The formation of the Mode Water through mid-latitude convection is located south of the subtropical front, whereas its subduction in the thermocline is lateral, as a combination of the eastward flow field along the front combined with the southern tilting of the front.

Relating the rates to tracer distribution in the winter mixed layer depth, enabled us to determine source tracer characteristics of the Mode and Central Water, respectively. The characteristics may be used for further mater mass mixing analysis.

### EXTENDED OMP ANALYSIS AS A TOOL IN TRACER OCEANOGRAPHY AND BIOGEOCHEMISTRY – J. Karstensen, Institut für Meereskunde, Universität Hamburg, Germany; and A. Hupe, Institut für Biogeochemie und Meereschemie der Universität Hamburg, Germany

A linear inverse mixing model, the extended OMP analysis, is uses with hydrographic and biogeochemical tracers (T, S, $O_2$, $PO_4$, $NO_3$, $Si(OH)_4$, DIC, $T_{ALK}$) to separate mixing and biogeochemical cycling part of observational data. It results in water mass fractions, the amount remineralised organic matter, the amount of denitrified nitrate, and the amount of inorganic carbon. The method is applied to WOCE/JGOFS data in the Arabian Sea intermediate and deep waters, a region where all resolvable processes occur. Even if not included explicitly as a variable in the model, an iterative technique can be applied to calculate the anthropogenic $CO_2$ inventory. For the Arabian Sea we found:

1. Obtained water mass fractions indicate the enhanced vertical exchange of properties

2. Remineralisation ratios (Redfield ratios) are found to be depth dependent and in agreement

3. The difference from a linear N:P ratio (dN in the model) is comparable to N*

4. Anthropogenic $CO_2$ can be deduced, making use of the DIC residuals

We used GESOCES data, with all the uncertainties in the carbon components, to define the source water types of the model. Thus, we assume improvement of the results using high quality WOCE and JGOFS data.

### TRANSPORT PROPERTIES OF MESOSCALE EDDIES – G.K. Korotaev, Marine Hydrophysical Institute, Sevastopol, Crimea, Ukraine

A prominent feature of a mesoscale eddy on a rotated sphere is self-propagation with respect to the ambient fluid. A self-propagation manifesting is a shaping of a volume of fluid travelling together with an eddy. The conservation of an angular momentum rules a form of the volume of fluid captured by an eddy. Tracers being captured by an eddy should be transported along an eddy trajectory up to hundreds kilometre from the original position. An eddy trajectory is determined by the distribution of background potential vorticity. An eddy propagation differs from simple transport by a local flow and does not follow gradient of a local current. Influence of Rossby waves may cause stochastic form of an eddy trajectory. A moving eddy decreases in size and provides slow exchange of the captured volume with an ambient fluid. Additionally small scale oscillations of an eddy centre induce diffusion of any substances from the interior of eddy to an ambient fluid.

### WATER MASS MODIFICATION AND TRANSPORT TIMES IN THE NORTH ATLANTIC – C.R. Harris, H. Leach, Oceanography Laboratories, The University of Liverpool, Liverpool, UK; D. Smythe-Wright, S.M. Boswell and R.T. Pollard, Southampton Oceanography Centre, Southampton, UK

The North Atlantic Conveyor begins at the Faeroe Bank Channel with the overflow of Iceland-Scotland Overflow Water (ISOW). This water flows anticlockwise around the northern rim of the Iceland Basin changing its properties as it goes, losing salt and gaining silica. On reaching the Charlie Gibbs Fracture Zone (CGFZ) at the south-west end of the Reykjanes Ridge the ISOW splits with part flowing through the gap into the Western Basin and part continuing southwards in the Eastern Basin of the North Atlantic. West of the Ridge the ISOW flows anticlockwise round the rim of the Irminger Basin still losing salt but now also losing silica too. By the time it reaches Cape Farewell at the southern tip of Greenland it can be seen as a silica-rich and CFC-poor layer deep down on the slope sandwiched between the

Labrador Sea Water (LSW) above and the Denmark Strait Overflow Water (DSOW) below. In the Eastern Basin the ISOW flows on southwards from the CGFZ providing a source of saline water between the LSW above and the Lower Deep Water (LDW) below.

## THE DEEP HELIUM FIELD IN THE PACIFIC OCEAN – J. Lupton, R. Well, L. Evans, and R. Greene

We present deep helium isotope data from the WOCE lines P13, P16, P17, P19 and the pre-WOCE cruises P1 and P3 in the Pacific. By showing vertical sections and surface plots at different depths, the pattern of the deep Pacific circulation in certain regions can be deduced. At 2500 m, the westward spreading of waters north (8°N) and south (14°S) of the Equator is marked by helium maxima originating at the East Pacific Rise (EPR). An eastward current at the Equator, indicated by a slight helium minimum, is likely – as is an eastward circulation at about 28°S. At 2000 m in the Northeast Pacific, water movement in a south-westerly direction is apparent, because of helium sources located on the Juan de Fuca Ridge (JdFR, 45°N, 130°W). At 1100 m, hydrothermal helium input from Loihi, an active volcano on the flank of Hawaii, marks a helium plume spreading eastward at 20°N. In a manner similar to variations in potential temperature, variable helium contents can indicate the flowpath of bottom water masses. Finally, in contrast to the hydrothermal helium plumes, we have also identified the presence of radiogenic helium (from a-decay of U and Th in sediments and in oceanic crust) in deep Pacific waters, especially in the north-eastern Pacific.

## SUBDUCTION IN THE SUBTROPICAL NORTH PACIFIC: OBSERVATIONS AND MODEL SIMULATIONS OF THE SUBSURFACE CFC MAXIMA – S. Mecking, M.J. Warner, and K.E. Greene, School of Oceanography, University of Washington, Seattle, USA; and J.L. Bullister, Pacific Marine Environmental Laboratory, NOAA, Seattle, USA

Pre-WOCE measurements made in the period 1985–1989 first showed that subsurface CFC maxima persist as permanently subducted features throughout the thermocline of the subtropical North Pacific. In the western and central subtropical gyre, the densities of the maxima were found to be close to the densities of, respectively, Subtropical Mode Water (STMW) and Central Mode Water (CMW) which are identified as both thermostads and minima in potential vorticity. Comparison of potential vorticity and CFC sections that were collected in 1993 during WOCE P10 (along 150°E) confirms that STMW and the CFC maximum in the western subtropical gyre coexist in the same density range. In the central subtropical gyre in 1991 during WOCE P16N (along 152°W), however, the core of the CFC maximum lies above the potential vorticity minimum of CMW. To develop a physical reasoning why the presence of the subsurface CFC maxima and of the mode waters are possibly related, it is important to understand how the CFC maxima are formed. The inferred pCFC-ages increase monotonically with depth which suggests that the CFC concentration maxima are not due to advection maxima at the respective densities. To determine the role of isopycnal processes in combination with the spatially varying surface boundary conditions of CFCs, we simulate the oceanic CFC uptake by applying a simple isopycnal advection-diffusion scheme on the density surfaces that outcrop in the subtropical and subarctic North Pacific. The locations and the hydrographic properties of the wintertime outcrops of the isopycnals as well as the geostrophic flow fields used in this model are derived from climatological data. The first model results with varying horizontal diffusivities will be presented.

## THE DISTRIBUTION OF $\delta^{18}$O IN THE WATER MASSES BETWEEN THE SOUTHERN INDIAN OCEAN AND ANTARCTICA – M.P. Meredith, K.J. Heywood and P.F. Dennis, School of Environmental Sciences, University of East Anglia, Norwich, UK; and R.D. Frew, Department of Chemistry, University of Otago, Dunedin, New Zealand

We present measurements of the stable isotopes of oxygen from samples collected on the Antarctic Deep Outflow Experiment (ADOX) cruises in the Southern Ocean and southern Indian Ocean, February to March 1993 and 1994. The data are used in conjunction with hydrographic data to infer characteristics of the formation and mixing of water masses found in the region. The isotopically heaviest waters ($\delta^{18}$O around 0.65ä) of the survey were found at the surface of the Madagascar Basin, a consequence of evaporation-induced enrichment of the heavier molecule. The isotopically lightest waters ($\delta^{18}O$ around -0.57ä) were found on the continental shelf of Antarctica, adjacent to the Princess Elizabeth Trough (PET); these waters are made isotopically light by the injection of around 1% of glacial ice melt, and are probably advected to the region from further east by the current associated with the Antarctic Slope Front. They appear to be locally disassociated from the Antarctic Surface Water and Winter Water (WW) further north in the PET. The WW of the Enderby Basin is isotopically lighter than the PET WW (-0.45ä, compared to -0.4ä) and also fresher, indicating the presence of an additional component of glacial ice melt or high-latitude precipitation. North of the Antarctic Circumpolar Current (ACC), the $\delta^{18}O$ of the surface waters show a strong correlation with salinity, but extrapolate to an apparent freshwater end-member which is too isotopically light to be reasonable; advection and mixing of the water masses dominate over the local water balance at this location. The Subantarctic Mode Water of the southern Indian Ocean lies on the line of the surface waters in salinity-$\delta^{18}O$ space, a consequence of its formation at the surface of the region by deep convection. The Antarctic Intermediate Water also lies on the same line, but this is somewhat coincidental since it does not originate in the region. Consequently, the observation does not, in fact, necessarily imply formation by local deep convection. Unlike previous findings in the Drake Passage and north-western Weddell Sea, there is no firm evidence in the data from the two repeated surveys of the Crozet-Kerguelen Gap to suggest interannual variability in the amount of glacial ice melt contributing to Antarctic Bottom Water (AABW) formation in the Weddell Sea. This is perhaps due to the greater distance of the waters from their source, and the comparatively small time elapsed between sampling (one year). Further repeats would be interesting to more fully examine the possibility. A previous hypothesis based on a subset of the data used here (the first year of data from the PET) suggested that the PET AABW is not formed in either the Weddell or Ross Seas, and instead described local formation of AABW by deep convection of surface waters and mixing with the Warm Deep Water layer. Based on the potential temperature-salinity characteristics of the AABW observed on ADOX, we find that whilst the source of the PET AABW does indeed appear to be outside the Weddell and Ross Seas, we can also exclude the PET itself from being the formation location of a significant amount of AABW. Instead, the potential temperature-salinity characteristics suggest that its major component is advected to the region from the Australian-Antarctic basin further east.

### TRITIUGENIC $^3$HE AND TRITIUM-$^3$HE AGES ON SOUTH ATLANTIC WOCE LINES – M. Müller and W. Roether, Institut für Umweltphysik, Universität Bremen, Germany

Prominent terrigenic $^3$He in combination with low tritium renders the separation of tritiugenic $^3$He in southern hemisphere waters a problematic task. We have used the approach described elsewhere (Roether et al., Component separation of oceanic helium, JGR, 103, 27931–27946, 1998), in which the ocean-derived $^3$He is separated into its terrigenic and tritiugenic components using a correlation of the former component with silica. Results for section WHP A9 (19°S; METEOR M15/3, 1991; left figure) and A14 (appr. 9°W; CITHER 3, 1993; right figure) are presented. Meaningful tritium-$^3$He ages are obtained. The ages have considerable uncertainty margins (standard errors typically 20‹30 %), however, i.e., larger than typical of tracer ages obtained in other ways. The tritium-$^3$He ages should still be useful, considering that the cause of the age signal is very different from that for the other ages. We plan a comparative assessment of the various ages for the entire South Atlantic WOCE data set.

### THE USE OF TRACERS IN MODELLING THE MEDITERRANEAN – P.G. Myers, K. Haines, K. Stratford and P. Wu, Department of Meteorology, University of Edinburgh, UK; and R. Williams, Oceanography Laboratories, University of Liverpool, UK

Due to its relatively small size and its well defined boundaries the Mediterranean provides a natural laboratory for studying the different ocean thermohaline circulation regimes which may be possible under given surface climatic conditions. Recently, modelling studies have been able to correctly reproduce the thermohaline circulation of the basin, with respect to both the circulation and the hydrography. Measurements of CFC-12 (e.g. Roether et al., 1996) however place useful additional constraints on several water masses within the eastern Mediterranean, forcing a re-evaluation of the GCM results. Work is also ongoing, attempting to understand the recent changes that have been observed between 1987 and 1995 in the water masses of the Eastern Mediterranean. Offline calculations of oxygen and nutrients are also helping us improve our understanding of the circulation modes associated with sapropel formation (layers of enhanced carbon deposition in the sediments) during paleo-climatic times.

### AGE DISTRIBUTIONS, A CONCEPT TO INTERPRET TRANSIENT TRACER MEASUREMENTS – A. Putzka, O. Huhn, G. Martinic and C. Rodehacke, Institut für Umweltphysik, Universität Bremen, Germany

Transient tracer concentrations in the ocean deliver information about the ventilation ages of the water. Conventional dating concepts using tracer concentrations or ratios to determine ages lead to different results for tracers with distinct input history. The reason for this is mixing in the ocean which causes the superposition of various vintages of the water mass in question. Age distributions represent a concept which explicitly takes into account different ages of different components within a water parcel. With this concept it should be possible to interpret simultaneously different transient tracer measurements and if stationarity is assumed also non synoptical data. From a one-dimensional advection mixing differential equation one gets an analytical expression for age distributions depending on only two parameters. For a two-dimensional box model with different advection geometries more realistic age distributions could be derived. These more complex age distributions could be approximated by a linear combination of two analytical age distributions derived form the one-dimensional case. The age distribution concept will be explained and principal properties, advantages and problems will be shown. Some applications will be discussed for different sets of tracer data including the CFCs F-11, F-12 and $CCl_4$, and tritium/helium and $^{14}C$. Results for renewal times of water in certain regions in the Atlantic (NADW in the South Atlantic and deep waters in the Weddell Sea) will be shown. For a PDF-version of the poster see www-page: http://pacific.physik.uni-bremen.de/poster/alfpost/

### FREON-VENTILATION AND SOUTHWARD TRANSPORT OF NADW IN HIGH RESOLUTION ATLANTIC MODELS – R. Redler, Alfred-Wegener Institut für Polar- und Meeresforschung, Universität Kiel, Germany; and Joachim Dengg, Institut für Meereskunde an der Universität Kiel, Germany

The numerical simulation of the uptake and redistribution of anthropogenic chlorofluorocarbons (CFC) provides a powerful tool for studying the mechanisms of water mass formation and spreading in ocean circulation models. In the present study we use dissolved CFC-11 and CFC-12 as tracers to analyse the renewal of North Atlantic Deep Water in different prognostic 3-D models of the Atlantic. Results of several long-term model integrations are presented to discuss the physical processes determining the temporal evolution of the 3-D CFC distribution in the deep ocean. Effects of different sub-grid scale parameterisations and of different horizontal resolution are shown. In particular, we address the respective roles of deep winter convection and of the overflow across the Greenland-Iceland-Scotland Ridge for the CFC-uptake in the subpolar North Atlantic, as well as the southward transport of CFC-enriched water with the Deep Western Boundary Current.

### METHANE IN THE NORTHERN ATLANTIC CONTROLLED BY MICROBIAL OXIDATION AND ATMOSPHERIC HISTORY – G. Rehder, R.S. Keir, and E. Suess; GEOMAR Forschungszentrum für Marine Geowissenschaften der Universität Kiel, Germany; M. Rhein; Institut für Meereskunde an der Universität Kiel, Germany

During May–August 1997 the distributions of dissolved methane and $CCl_3F$ (CFC-11) were measured in the Atlantic between 50° and 60°N. In surface waters throughout the region, methane was observed to be close to equilibrium with the atmospheric mixing ratio, implying that surface ocean methane is tracking its atmospheric history in regions of North Atlantic Deep Water formation. Despite the different atmospheric history and ocean chemistry of $CH_4$ and CFC-11, their spatial distribution patterns in the water column are remarkably similar. One-dimensional distributions have been simulated with an advection-diffusion model forced by the atmospheric histories. The results suggest that the similar patterns result from the increasing input of $CH_4$ and CFC-11 to newly formed deep waters over time, combined with the effect of horizontal mixing and the oxidation of methane on a 50 year time scale.

### ATLANTIC AND INDIAN OCEAN – M. Rhein, Institut für Ostseeforschung Warnemünde, Rostock, Germany; and O. Plähn, Institut für Meereskunde, Kiel, Germany

The WOCE Kiel CFC activities from 1990–1998 was mainly focused in three regions, the North Indian Ocean and the tropical and subpolar North Atlantic. The tracer distributions, combined with hydrographic data, direct velocity profiles and other tracers as tritium and helium gave new insight into the times scales and spreading paths of newly formed Labrador Sea Water in the subpolar North Atlantic (Sy et al., 1997) and the circulation, age and variability of deep water masses in the western tropical Atlantic (Rhein, 1994; Rhein et al., 1995; 1998a; 1998b; Fischer et al., 1996). The tracer data from the Arabian Sea were used to estimate the mean transport of intermediate water masses into the Arabian Sea (Rhein et al., 1997). The CFC-12 pollution in the outflow of the Persian Gulf, which was presumably caused by the release of fire extinguisher and solvents during the Gulf War in 1991 was a suitable means to estimate spreading rates and paths as well as dilution factors of this water mass in the Arabian Sea.

### ON THE USE OF SALINITY NORMALISATION FOR THE CALCULATION OF OCEANIC PROPERTY TRANSPORTS – P.E. Robbins, Scripps Institution of Oceanography, La Jolla, USA

The transport of chemical properties by ocean currents, and thus the divergence/convergence of properties within ocean regions, can be strongly influenced by the global hydrological cycle. Specifically, a significant flux of properties such as inorganic carbon and total alkalinity may accompany the oceanic transport and redistribution of freshwater. Accurately estimating the transport of these properties within the ocean requires accurate knowledge of the oceanic branch of the global hydrological cycle. Previous investigators have proposed the use of “salinity normalisation” to eliminate the impact of the poorly known freshwater flux on the calculation of the meridional transport of inorganic carbon and dissolved oxygen. The validity of these normalisations is examined. Three different forms of “salinity normalisation” are found in the literature. Analysis presented here shows that none of these methods results in a normalised property whose transport and flux divergence is independent of the freshwater cycle. Using these previous attempts as guidance, a new form of salinity normalisation is found which does satisfy the goals of yielding an accurate estimate of the net oceanic flux of property without specific consideration of the global hydrological cycle. It is proposed that this new form of salinity normalisation be employed in future calculations of oceanic transport of inorganic carbon.

### ON THE IMPORTANCE OF LATERAL DIFFUSION FOR THE VENTILATION OF THE LOWER THERMOCLINE IN THE SUBTROPICAL NORTH ATLANTIC – P.E. Robbins, Scripps Institution of Oceanography, La Jolla, USA; W.J. Jenkins, Southampton Oceanography Centre, Southampton, UK; J.F. Price and W.B. Owens, Woods Hole Oceanographic Institution, USA

An analysis of the physical mechanisms contributing to the ventilation of the lower subtropical thermocline ($26.5<\sigma_\theta<27.3$) of the North Atlantic is presented. Examination of the surface forcing suggests that this density range in the Atlantic should be strongly ventilated by flow from the surface winter mixed layer. In contrast to this expectation, the isopycnic distribution of tracers within the shielded thermocline fails to show evidence of net advective penetration of recently ventilated waters into the eastern North Atlantic. Instead, the presence of the Azores Current appears to block the net southward invasion of mass from the region of the isopycnal surface outcrops. Tracer properties of recently ventilated waters enter the gyre by diffusive exchange across the Azores Front. Evidence of this diffusive ventilation based on both steady-state and transient tracers is presented. Mean basin-scale property distributions on $\sigma_\theta$= 27.0 are diagnosed from an expanded high-quality hydrographic database. The Montgomery streamfunction reveals no evidence of pathways for direct geostrophic ventilation on this density horizon; low values of potential vorticity are confined to the region of formation north of the Azores Current. To complement the examination of the steady-state tracer distribution, an interpretation of the temporal evolution of the tritium-helium age in the eastern Atlantic is considered. The penetration of the coupled tritium and $^3$He tracers provide a sensitive diagnostic of the effects of mixing. Lateral mixing creates robust and predictable changes in measured Eulerian tritium-helium age in response to the oceanic input of anthropogenic tritium. Simple kinematic models of the ventilation of tritium and $^3$He are compared with the observed temporal character of the tracer age field. Circulation scenarios characterised by direct geostrophic ventilation of the lower thermocline require excessively large magnitudes of lateral diffusivity (>4000 $m^2/s$) to accurately simulate the transient tracer observations. On the other hand, the observations can be reconciled with canonical magnitudes of lateral diffusion (1000–1500 $m^2/s$) if the ventilation is mediated by diffusive transmission across the Azores Current.

### A PRELIMINARY MODEL/DATA COMPARISON FOR BOMB-$^{14}$C IN THE PACIFIC THERMOCLINE – K. Rodgers, MPI, Hamburg, Germany; S. Peacock, LDEO, Columbia University, USA; M. Latif, MPI, Hamburg, Germany; and B. Key, Princeton University, Princeton, USA

A comparison is made between the simulated bomb-$^{14}$C distribution using a high resolution ocean model and the measurements obtained during the WOCE survey of the Pacific Ocean. The fundamental scientific objectives are to better understand the intergyre exchange pathways for the upper Pacific Ocean, and to further our understanding of the physical processes which control the stratification of the upper Pacific Ocean, since these same processes could also play an important role in climate variability. The ocean model used for the study is the HOPE (Hamburg Ocean Primitive Equation) model, which has also been used for the coupled climate variability studies of Latif and Barnet.

### SPACE AND TIME DEPENDENT TRACER DIFFUSIVITY FIELD IN A OGCM – V. Rupolo, ENEA, Roma, Italy; A. Babiano, LMD-ENS; V. Artale, ENEA, Roma, Italy; and D. Iudicone, IFA-CNR, Roma, Italy

A new time and space dependent parameterisation of tracer eddy diffusivity field is implemented in a Bryan Cox derived OGCM applied to the Mediterranean Sea. The aim of this work is to define a tracer diffusivity parameterisation suitable for velocity field characterised by non-local dynamics and by the presence of quasi 2-D turbulent macrostructure. In this work we emphasise the two dimensional character of geostrophic turbulence imposing a dependence of the eddy diffusivity on horizontal shear of velocity and kinematic variables averaged horizontally. This kind of strategy can be considered as complementary to the more usual approach of mimic baroclinic instabilities in OGCM establishing relation between eddy diffusivity and some baroclinic index. The well-known Taylor relation

$$K \sim E * TL \tag{1}$$

(where K is the eddy diffusivity, E is the eddy kinetic energy and TL is the Lagrangian correlation time), is exploited to estimate diffusivity by the relation

$$TL \sim Z\text{-}1/2 \tag{2}$$

(where Z is the enstrophy). Validity of (2) is discussed in different dynamical flow regimes and the impact of the presented parameterisation is studied comparing results from three long integration experiments performed using definition (1), Smagorinsky parameterisation and constant eddy diffusivity.

### FITTING A GLOBAL OCEAN CIRCULATION MODEL TO CFC OBSERVATIONS – R. Schlitzer, M. de las Heras and J. Schröter, Alfred-Wegener Institut für Polar und Meeresforschung, Bremerhaven, Germany

Chlorofluorocarbons (CFC), a group of man-made substances that have been released to the atmosphere in increasing amounts during the last few decades and are invading the ocean since then, have been routinely measured on most WOCE WHP cruises and are widely considered as valuable water mass tracers. Using repeated CFC measurements, the spreading of the intermediate, deep and bottom waters can be monitored, however, in order to quantify these flows, the use of CFC-calibrated circulation models is required. A new model strategy that applies the Adjoint Method to fit a global ocean circulation model to hydrographic and CFC observations is presented, and it is shown that global ocean hydrography and the available CFC data can be reproduced by the optimal model solution realistically. Water mass transports for four isopycnal layers representing warm surface, intermediate, deep and bottom waters show that CFC observations in the South Atlantic are consistent with a meridional overturning cell consisting of northward flows of about 9.4 Sv intermediate water, 4.8 Sv warm water and 3.1 Sv bottom water ($\sigma_4$>45.9). The zonally stretched CFC intermediate water maximum at about 40°S in the South Atlantic is explained in the model by a vigorous, zonally stretched gyre with inflow of intermediate water in the Benguela region. The model does not confirm the northward flow of intermediate water along the South American coast between 45 and 25°S as indicated by Wuest. Global water mass transports as well as heat and CFC fluxes will be presented.

### REMINERALISATION OF PARTICULATE MATTER IN THE WORLD OCEAN: ESTIMATES BASED ON DISSOLVED NUTRIENT DATA – R. Schlitzer, Alfred-Wegener Institut für Polar und Meeresforschung, Bremerhaven, Germany

Remineralisation of sinking particulate material affects dissolved nutrient and oxygen distributions in the ocean which is most clearly seen in shallow nutrient maxima and oxygen minima in the Pacific, Atlantic and Indian Oceans. Here, the large global historical database of dissolved nutrients and oxygen is used in a bio-geochemical circulation model that is driven towards the observations by means of the adjoint method. Particle fluxes as functions of depth are formulated as f(Z)=a Z-b laws (Z is depth normalised by depth of euphotic zone) and the parameters "a" representing the export flux at the base of the euphotic zone and "b" determining the shape of the particle flux profile and the depth of remineralisation are calculated by the model. Optimal values for a and b are determined requiring realistic oxygen and nutrient simulations by the model. It is found that in order to achieve optimality, the remineralisation scale heights b for organic material must be significantly larger than previously published values in the Southern Ocean and in tropical regions, indicating that decomposition of organic material is fast and occurring mainly in the upper few hundred meters of the water column just below the euphotic zone. On average, only 5% of the organic material but about 50% of $CaCO_3$ and more than 60% of the opal export reach the bottom. Oxygen utilisation rates OUR in 175 m depth range from more than 100 µmol/kg/yr in coastal upwelling zones to about 30-50 µmol/kg/yr in high productivity regions in the Southern Ocean. Bottom layer OUR in productive shelf areas exceed 500 µmol/kg/yr. Results from sensitivity runs using different element ratios for organic material and including dissolved organic matter are presented.

### OBSERVATIONS IN THE NORTH EAST ATLANTIC ALONG 20°W AND IN THE ROCKALL TROUGH – Denise Smythe-Wright, Southampton Oceanography Centre, Southampton, UK

In May, 1998 a repeat occupation of the 20°W line in the North Atlantic from 20°N to Iceland was made as part of CHAOS (a Chemical and Hydrographic Atlantic Ocean Survey). This was followed by four zonal sections along the length of the Rockall Trough and a section across the Rockall Plateau and Hatton Bank. Full depth CTDO/LADCP and water bottle measurements were made at a total of 138 stations and water samples analysed for a range of chemical parameters including CFC and nutrient tracers, naturally produced halogenated gases, $CO_2$, plant pigments and biological species. In addition, underway ADCP, XBT atmospheric gas and meteorological measurements were made. Particular objectives of the survey were

1. to repeat a number of stations dating back to 1957 to examine decadal scale variability in the eastern Atlantic over the last 40 years.

2. to establish sources and sinks of halogenated biogases in subtropical and subpolar waters during Spring bloom conditions.

3. to study the spreading, mixing and ventilation rates of Labrador Sea Water, Mediterranean Water and waters of Southern Ocean origin.

4. to make a detailed study of the water masses in the Rockall Trough with particular emphasis on their circulation/recirculation patterns.

5. to quantify the magnitude of the northward flow between Iceland and the UK.

Results from the survey are still at a very early stage, but comparison with data collected during Oceanus cruise 202, 10 years previously, highlights some differences. In addition it is clear that the Rockall Trough and its surrounds, particularly to the south, are regions of complex circulation/recirculation flow patterns controlled by topography. Evidence suggests that derivatives of Antarctic Bottom Water, and Labrador Seawater enter the Trough in spite of its shallowing topography and circulate and re-circulate to at least 56°N.

### WATER MASS TRANSFORMATIONS IN THE INDONESIAN SEAS – J.M. Waworuntu, R.A. Fine and D.B. Olson, Rosenstiel School of Marine and Atmospheric Science, University of Miami, USA; and A.L. Gordon, Lamont-Doherty Earth Observatory of Columbia University, USA

Water from the western Pacific flows through the Indonesian Seas following different pathways and is modified by various processes to form the uniquely characterised isohaline Banda Sea Water. The processes contributing to the isohaline structure are studied using data from three ARLINDO cruises in 1993, 1994, and 1996. An inverse-model analysis using salinity and CFC-11 data is done for a vertical section along the main path of flow, from the Makassar Strait to the Flores Sea and Banda Sea. The model reproduces the seasonal and interannual variability of the throughflow and shows reversals of flow in the vertical structure. The model solutions suggest strong baroclinic flows during south-east monsoon of 1993 and 1996 and a small, more barotropic flow during north-west monsoon of 1994. The isohaline structure can be accounted for by isopycnal mixing of different source waters and by vertical exchanges, which are significant in this region. A downward flux equivalent to a downwelling velocity of $5\times10^{-7}$ m/s is estimated for the section. The total balance also suggests that seasonally variable backflushing of water from the Banda Sea into the Straits makes an important contribution to the isohaline structure of Banda Sea Water.

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