International WOCE Newsletter

IN THIS ISSUE

News from the WOCE IPO

W. John Gould, Director, WOCE IPO and ICPO, Southampton Oceanography Centre, UK. john.gould@soc.soton.ac.uk

Once again the WOCE Newsletter has undergone a slight facelift (reflecting some of the input to our reader survey) and in many ways these changes mirror the constant readjustment that WOCE itself has undergone since it was first conceived as a Global Ocean Circulation Experiment (GOCE) in 1980.

As this Newsletter goes to press I am writing my part of the chapter in the WOCE Conference book that will say how WOCE came about and how we did the experiment. I am struck by the foresight that the originators of the GOCE/WOCE concept had and how much progress we have made towards achieving WOCE's goals. The book will be published later this year by Academic Press. An announcement will be placed in the next Newsletter. It promises to be an important summary of where WOCE-related science stands at the end of the millennium.

Two important meetings are coming up. The WOCE North Atlantic Workshop in Kiel (23-27 August) (See NL 34) already has around 100 registered attendees and promises to be an important step towards producing a synthesis in this much-observed and much-modelled basin. In August this year the papers originating from the South Atlantic Workshop will be appearing in JGR(Oceans).

In October, the Oceanobs'99 meeting in St Raphael, France, (http://www.BoM.GOV.AU/OCEANOBS99) will take an important step beyond WOCE in seeking to define the various sustained ocean observations that will be needed for climate research in GOOS and CLIVAR. This Conference is forward-looking but its conclusions will owe much to the firm foundation set by WOCE in stimulating a global view of the oceans.

About WOCE

The World Ocean Circulation Experiment (WOCE) is a component of the World Climate Research Programme (WCRP), which was established by WMO and ICSU, and is carried out in association with IOC and SCOR.

WOCE is an unprecedented effort by scientists from more than 30 nations to study the large-scale circulation of the ocean. In addition to global observations furnished by satellites, conventional in-situ physical and chemical observations have been made in order to obtain a basic description of the physical properties and circulation of the global ocean during a limited period.

The field phase of the project lasted from 1990–1997 and is now being followed by Analysis, Interpretation, Modelling and Synthesis activities. This, the AIMS phase of WOCE, will continue to the year 2002.

The information gathered during WOCE will provide the data necessary to make major improvements in the accuracy of numerical models of ocean circulation. As these models improve, they will enhance coupled models of the ocean/atmosphere circulation to better simulate – and perhaps ultimately predict – how the ocean and the atmosphere together cause global climate change over long periods.

WOCE is supporting regional experiments, the knowledge from which should improve circulation models, and it is exploring design criteria for long-term ocean observing system.

The scientific planning and development of WOCE is under the guidance of the Scientific Steering Group for WOCE, assisted by the WOCE International Project Office (WOCE IPO):
* W. John Gould, *Director*
* Peter M. Saunders, *Staff Scientist*
* N. Penny Holliday, *Project Scientist*
* Roberta Boscolo, *Project Scientist*
* Sheelagh Collyer, *Publication Assistant*
* Jean C. Haynes, *Administrative Assistant*

For more information please visit: http://www.soc.soton.ac.uk/OTHERS/woceipo/ipo.html

Newsletter New Look

Roberta Boscolo, Editor, International WOCE Newsletter, Southampton Oceanography Centre.
roberta.boscolo@soc.soton.ac.uk

Thanks to all of you who spared the time to answer questions in our reader survey and returned the card.

Almost unanimously the feedback was encouraging: the Newsletter is very useful for your work and the kind of information that it contains also interests researchers not directly involved in WOCE. However particularly welcomed were your suggestions for improvements.

Many of you requested more information on technical issues, and methods of data analysis. In addition you expressed interest in including meeting reports and more links to other relevant international programmes. We will try to meet those requests for future Newsletter issues. Meanwhile some changes have already taken place.

From this issue the Newsletter presents a new layout: this gives the opportunity to place some general information about WOCE and the IPO which can be useful for new readers and a reminder for habitual ones. In addition new web pages have been created for the Newsletter:

www.soc.soton.ac.uk/OTHERS/woceipo/acrobat.html
which are easily accessed from the main page of WOCEIPO.

Improvements include the availability in pdf format of the recent past issues – from No. 19 to No. 34 – the list of contents of all the issues and a link through the WOCE Bibliography to the list of references of all the articles appeared in the Newsletter. In addition you can find the guidelines for submission (recently revised and more flexible) and the possibility of subscribing on-line in order to receive the hardcopy by surface mail regularly.

We are currently working on making available the rest of Newsletter issues as pdf files. This involves the scanning of those copies that were produced with "scissors and glue". We are also hoping to put the complete collection on version 2 of the WOCE Data set CD-ROMs which we anticipate will be published in May 2000.

NOTA BENE: telephone number changes

The Southampton national telephone number 01703 has changed to 023 and six digit local number are prefixed with 80. For example the WOCE IPO secretary number becomes:
++44 (0)23 8059 6789.

Both new and old numbers can be used to dial Southampton till April 2000 when the use of 01703 ceases.

Ventilation of CFC-11 in a Global Ocean Circulation Model Constrained by WOCE Data
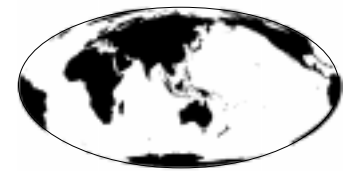
Mick Follows, Detlef Stammer, and Carl Wunsch, Program in Atmospheres, Oceans and Climate, Massachusetts Institute of Technology, USA.
mick@plume.mit.edu

One of the major reasons for observing the global ocean is to infer the transport properties of quantities important to climate, including heat, freshwater, carbon, oxygen, etc. Given the disparate observational techniques which formed the World Ocean Circulation Experiment, the only feasible approach is to combine the data with general circulation models (GCMs) to produce the required estimates. We demonstrate here preliminary global ocean circulation estimates based on an OGCM constrained by a variety of global data sets. The resulting model state is employed in an offline mode to simulate the ventilation of chloro-fluorocarbon 11 (CFC-11) into the ocean. Through a series of experiments, we demonstrate that including the tracer data itself in the state estimation procedure can provide additional constraints.

Ocean circulation state estimation

Our estimate of the ocean state is based on the ocean circulation model (MIT OGCM) and its adjoint, which have been developed recently at the Massachusetts Institute of Technology. The "forward" model is derived from the incompressible Navier-Stokes equations on a sphere under the Boussinesq approximation (Marshall et al., 1997a,b). Alone, the OGCM predicts the ocean state, permitting determination of the misfits between model and observations. The adjoint of the original model produces the misfit gradient relative to uncertain model parameters, and is then used to bring the forward component into accord with the data. Careful coding of the MIT OGCM renders it possible to obtain the adjoint model from the forward code in a semi-automatic way using the Tangent Linear and Adjoint Model Compiler (TAMC) of Giering and Kaminski (1999).

Our present focus is the estimation of the time-evolving global circulation as it emerges primarily from altimetric measurements and the OGCM. Computations, which are ongoing, constrain the MIT OGCM over the six year period 1992 through 1997. Data constraints (Fig. 1) include the absolute and time-varying TOPEX/ POSEIDON (T/P) data relative to the EGM-96 geoid model; see Lemoine et al., (1997) from October 1992 through December 1997; surface height anomalies from the ERS-1 and ERS-2 satellites; monthly mean SST data (Reynolds and Smith, 1994); and the time-varying NCEP re-analysis fluxes of momentum (tau), heat (Hq) and freshwater (Hs). Monthly means of the model state are required to remain within assigned bounds of the monthly mean Levitus et al. (1994) climatology, and NSCAT estimates of wind stress errors (D. Chelton, pers. communication, 1997) are employed.

Changes in control parameters are used to bring the model into consistency with the observations. In the present computation, the controls (adjustable model parameters) are the initial condition potential temperature (θ) and salinity (S) fields and, the surface forcing fields over the entire six year period. The control vector contains 8 million elements. The model is currently run on a 2° grid. Because the optimisation is not yet complete results presented here, after 30 optimising iterations, are highly preliminary and may be considered as constrained but not yet optimal (Fig. 2, page 19).

Offline CFC-11 simulations: first results

We use the six year "climatological" annual cycle of the circulation model to simulate the ventilation of CFC-11 into the ocean in an "offline" mode. CFCs are of entirely anthropogenic origin, with well documented production

Figure 1. Schematic of the ongoing optimisation. While the upper part of the figures shows the data constraints and their distribution in time, the lower part shows the control parameters.

rates. Their atmospheric concentrations, which increased rapidly from the 1950s to 1990s, have been closely observed since the 1970s and are well constrained prior to that. CFCs are soluble, and inert in the oceans (see e.g. Weiss et al., 1985).

The governing equation for CFC-11 is

$$\frac{\partial C}{\partial t} = \mathbf{u} \cdot \nabla C + \nabla \cdot (K \nabla C) - \frac{V_p}{\Delta z}(C - K_0 pC^{at}) + S_c \quad (1)$$

where C is the CFC-11 concentration in water and $\mathbf{u}$ is the model flow field. The parameterisation of subgridscale mixing processes is as used for tracers (T, S) in the OGCM. Vertical convective mixing of tracers, S_c, is achieved in a manner which reproduces the monthly statistics of convective mixing in the GCM using a diagnostic "convective index". Surface exchanges of CFC-11 are parameterised with a wind-speed dependent piston velocity, V_p, following Wanninkhof (1992). Δz is the depth of the surface layer and K_0 is the temperature and salinity dependent solubility of CFC-11 (Warner and Weiss, 1992). The effects of ice cover are parameterised. The offline CFC-11 model is initialised with $C = 0$ and integrated from 1950 to 1997, during which time pC^{at}, the atmospheric partial pressure of CFC-11, is specified according to the observed atmospheric history.

Comparison of unconstrained and constrained flow fields

We compare three CFC-11 simulations based on three different circulation state estimates: experiment [i] unconstrained model, [ii] constrained using initial condition and surface fluxes as control variables, and [iii] constrained using only surface fluxes as control variables. As a result, experiment [ii] exhibits strong surface heat fluxes but a somewhat weaker overturning circulation, relative to [i]. In contrast, [iii] shows the opposite tendencies.

All three CFC-11 simulations capture the broad features of the observed global, CFC-11 distribution with surface concentrations close to saturation, and higher concentrations in cool waters at high latitudes. We focus on the modelled CFC-11 distributions in the North Atlantic ocean in 1983, and compare them to the observations of Weiss et al. (1985). The models display elevated CFC-11 concentrations at depth in the Labrador Sea in 1983 (Fig. 3a), with some indication of a tongue of elevated CFC-11 concentrations associated with the deep western boundary current. Compared to the observations, however, the tongue of CFC-11 is diffuse and does not penetrate far enough equatorwards. Figs. 3b and 3c show difference maps of the CFC-11 distributions derived from the two constrained models referenced to the unconstrained model (Fig. 3a). The difference maps indicate that each of the optimised models results in an improved simulation, with enhanced CFC-11 ventilation in the western boundary current relative to the unconstrained model.

The improvement of CFC-11 simulation in experiment [ii] is due to enhanced deep convection (associated with enhanced surface heat fluxes) in the Labrador Sea (Fig. 4), but due to enhanced thermohaline circulation in experiment [iii], where convective activity (and surface fluxes) are weakened relative to the unconstrained experiment (Fig. 4).

Summary and outlook

These preliminary results demonstrate the application of optimised flow fields for computing the movement of tracers through the ocean: CFC-11 simulations with optimised ocean currents do show improved results over that with the unconstrained model. The improvement can be brought about by adjustments to convective mixing, deep ocean currents, or both, depending upon the control variables of the optimisation. The results show that the inclusion of transient tracers in such an optimisation can provide added constraints to the circulation state estimate. As we learn to use the tracer data, we expect, among many
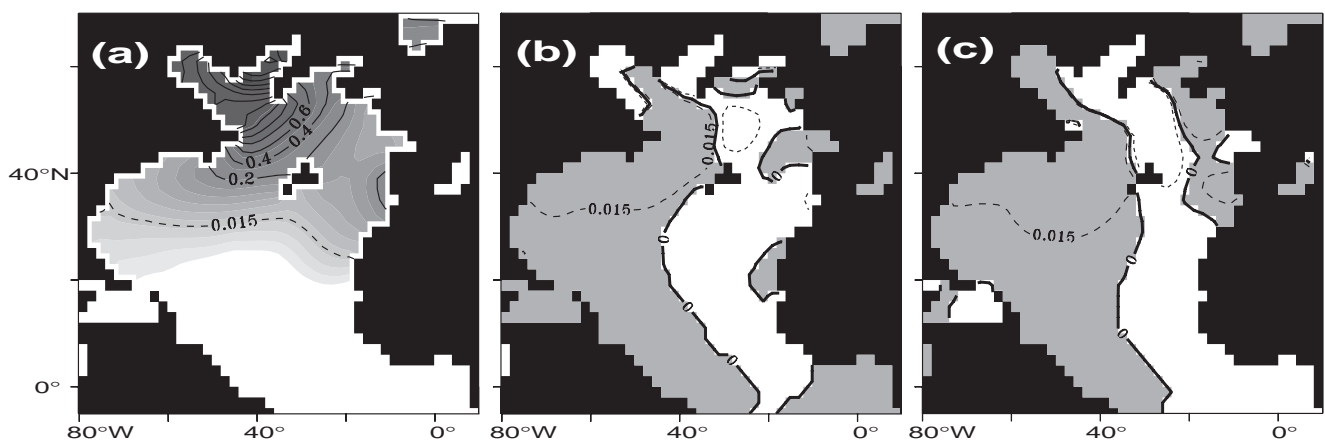

Figure 3. (a) Modelled CFC-11 concentration (pmol/kg) at 1975 m depth, end of 1983, using [i] (the unconstrained model). Solid contours, 0.2 pmol/kg; dashed contour 0.015 pmol/kg (b) Difference of modelled CFC-11 concentration (pmol/kg) between [ii] and [i], at 1975 m in 1983 ([ii]-[i]). Shaded areas represent a positive difference. ±0.015 pmol/kg contours are overlain. (c) As (b), but difference of modelled CFC-11 concentration between experiments [iii] and [i].
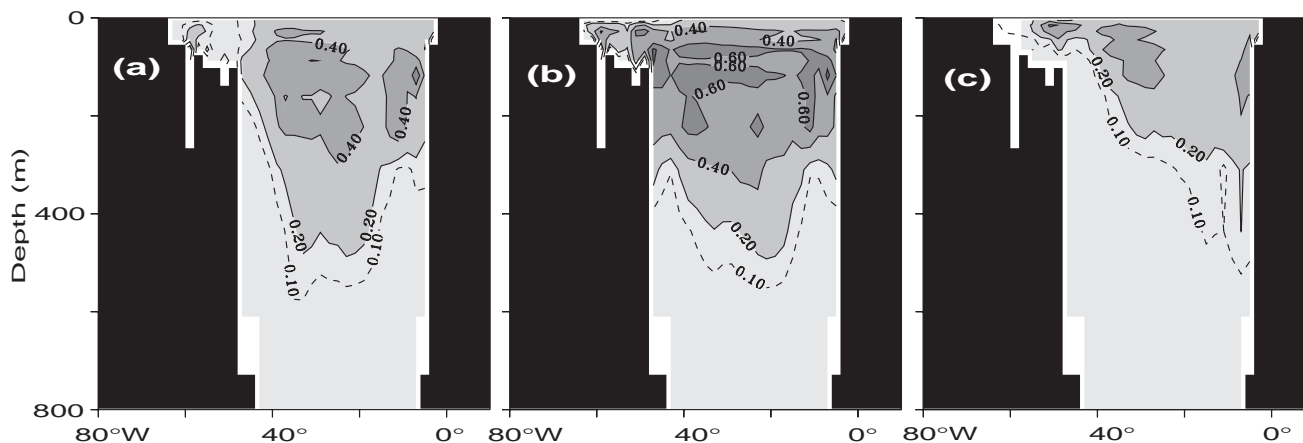
Figure 4. Six year average of convective index at 48°N in the model; (a) unoptimized model, [i], (b) with surface fluxes and initial condition as control variables, [ii], and (c), with surface fluxes only as control variables [iii]. Convective index varies between 0 and 1, with higher values indicating more active mixing.

possible applications, to compute property flux divergences, and diagnose oceanic biogeochemical fluxes.

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Ocean and Atmospheric Data Management becomes a Journal

Elsevier Publisher in collaboration with the co-editors Ben Searle (Australian Oceanographic Data Centre, Sydney) and Bill Emery (University of Colorado) is launching a new journal: Ocean and Atmospheric Data Management.

The OADM aims to facilitate accessibility of data, improve its availability and assist in the generation of information relative to this rapidly evolving discipline. It is intended to provide discussion on the broad spectrum of multi-disciplinary marine and atmospheric data management issues, as they are experienced through data collection, manipulation, storage and dissemination. In addition to papers on traditional data management and archiving issues, the journal will include examples of the innovative use of data for operations, data assimilation and product creation.

OADM will be available on paper and on WWW. The paper version will be published quarterly, the web version will be updated more regularly and will include pre-prints thus sharing results and discussions at an early opportunity.

The complete description of this new journal can be found at:

http://www.elsevier.nl/locate/oadm

Authors interested in submitting a paper and accompanying data, software or information should register their interest with the editors:

Ben Searle (Founder)
Head, AODC
Sydney
Australia
oadm@ozemail.com.au

Bill Emery
University of Colorado
Boulder, CO
USA
emery@frodo.colorado.edu

Colleagues involved in ocean and atmosphere data management are encouraged to take advantage of this new journal and submit manuscripts.

WOCE Chemical Tracer Measurements Aid the Assessment of Ocean Climate Models

Matthew H. England, Centre for Environmental Modelling and Prediction (CEMAP), Australia, M.England@unsw.EDU.AU

The first goal of WOCE is to develop models useful for predicting climate change and to collect the data necessary to test them. To this end, WOCE chemical tracer data provide a unique set of constraints on ocean circulation models that are incorporated into climate prediction systems. In contrast to pre-WOCE ocean modelling, geochemical tracers are now widely used to assess the simulated circulation in 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 along with their various applications and properties in ocean model assessment (taken from England and Maier-Reimer, 1999).

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-

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

Tracer:	Chemical formula:	Main source(s):	Properties:	Measurability:	Applications:	Key references:
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	12.43 year half-life	2.5 litres	Transient (favours NH)	*Sarmiento [1983]*
Chlorofluoro-carbon	CCl_NF_M	Refrigerants, foams, solvents	Stable, inert	0.030 litres	Transient	*England et al. [1994]*
Argon-39	^{39}Ar	Natural radioactive isotope of ^{40}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 [1998]*
Cesium-137	^{137}Cs	Bomb-produced, Chernobyl	30 year half-life	0.030 litres	Regional models	*Staneva et al. [1998]*
Sulphur Hexafluride	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	Air-sea flux of gaseous oxygen	Biogeochemical	0.150 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 tracer.
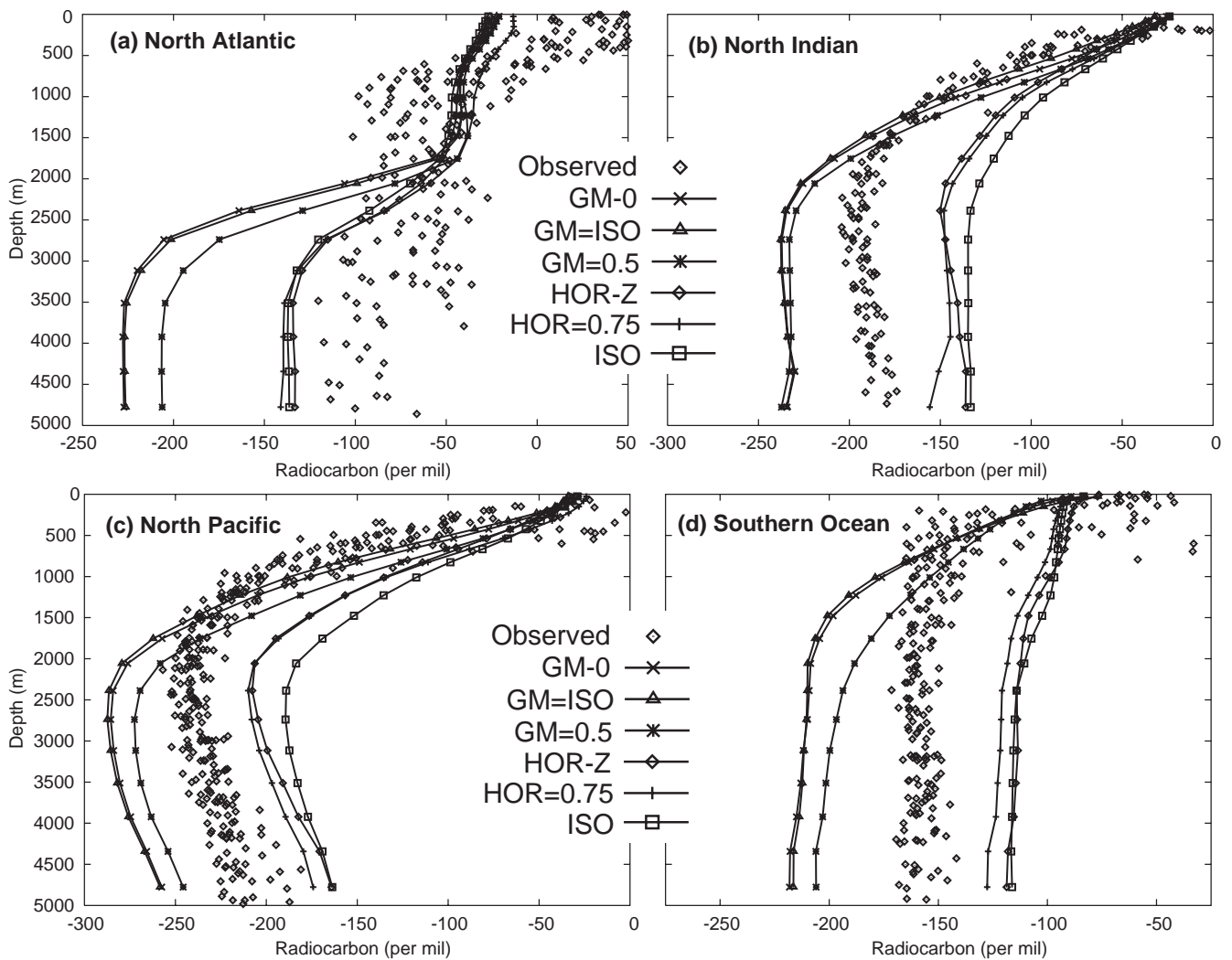
Figure 1. Mean model profiles of radiocarbon in (a) the North Atlantic Ocean (0°–70°N), (b) the Indian Ocean north of the Equator, (c) the North Pacific Ocean (0°–70°N), and (d) the Southern Ocean at the latitude band 55°S–70°S in the experiments of England and Rahmstorf (1999). The model cases include runs with either Cartesian (HOR), isopycnal (ISO), or Gent and McWilliams (1990, GM) mixing parameterisations (see Table 2). Scatter plots of basinwide GEOSECS observations are overlaid for comparison.

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. A comprehensive review of the use of chemical tracers in assessing ocean models can be found in England and Maier-Reimer (1999).

The purpose of this note is to highlight the use of chemical tracers in assessing the circulation and flow patterns in global and regional ocean models. Crucial information can be derived from chemical tracers that cannot be obtained from traditional hydrographic properties alone. For example, temperature-salinity (T-S) can provide only limited information on model water-mass formation time-scales, such as indicating the depth of rapid ventilation associated with surface layer mixing. In addition, T-S together determine density which in part controls model flow patterns, so they do not provide an independent measure of model skill. T-S are also themselves controlled

by air-sea heat and freshwater fluxes, which are both poorly known and in the case of temperature, partly determined by the model circulation and convection patterns. This makes T-S less than ideal as validation tracers. Geochemical tracers, in contrast, can provide detailed information on the pathways and rates of water-mass renewal beneath the surface mixed layer, and as they do not affect density or circulation, provide an independent measure of model performance. This provides ocean modellers with a powerful tool for assessing simulated ocean circulation patterns.

Long time-scale ventilation processes

The distribution of natural radiocarbon provides the best measure of deep ocean ventilation rates over long time-scales; say, century time-scales and beyond. Other radionuclides have either too rapid a decay rate or are too sparsely observed to be useful in this context. Also, anthropogenic compounds such as chlorofluorocarbons (CFCs)

are yet to penetrate the ocean in measurable quantities beyond a 50-year time-scale. With biological processes affecting chemical tracers such as phosphate, oxygen, nitrate and so on, natural radiocarbon is the most obvious choice for validating model behaviour in regions such as the deep Indian and Pacific Oceans. Another candidate is mantle helium, which enters the deep ocean in hydrothermal fluids in seafloor volcanoes. However, uncertainty in the input distribution of helium in hydrothermal fluid remains rather large (Farley et al., 1995).

To date a number of researchers have exploited radiocarbon as a tracer for assessing circulation and water-mass formation in ocean models. Normally radiocarbon is simulated as the deviation of the $^{14}C/^{12}C$ ratio from a standard atmospheric value (denoted $\Delta^{14}C$), thereby minimising uncertainties associated with isotopic fractionation effects and biological conversion processes. Further details of radiocarbon modelling techniques can be found in Toggweiler et al. (1989a,b).

An example of a study employing natural radiocarbon to assess model circulation and water-mass formation is that of England and Rahmstorf (1999; hereafter ER99), who analyse idealised age and $\Delta^{14}C$ in a series of experiments with different tracer mixing parameterisations. Fig. 1 shows the mean model profiles of radiocarbon in (a) the North Atlantic Ocean (0°–70°N), (b) the Indian Ocean north of the Equator, (c) the North Pacific Ocean (0°–70°N), and (d) the Southern Ocean at the latitude band 55°S–70°S in ER99. Scatter plots of basinwide GEOSECS ^{14}C observations are included for comparison. Their model experiments are run with either Cartesian (HOR), isopycnal (ISO), or Gent and McWilliams (1990, GM) mixing parameterisation (see also Table 2). The goal of their study was to assess which, if any, mixing scheme results in a realistic simulation of deep ocean ventilation.

Observations of $\Delta^{14}C$ show that the North Atlantic Ocean is relatively well-ventilated to great depth (Fig. 1a). In contrast, all model experiments of ER99 underestimate the depth of NADW penetration, with a clear delineation between upper well-ventilated NADW and lower $\Delta^{14}C$-depleted waters (particularly under GM). Additional GM experiments with an exaggerated wintertime surface T-S and/or inclusion of the topographic stress parameterisation of Holloway (1992) did not rectify this problem. In the Pacific and Indian Oceans the simulated ventilation time-scales vary greatly between the GM and non-GM runs: typical mid-depth water is far too depleted in radiocarbon in the GM runs and too rich

in $\Delta^{14}C$ in the HOR/ISO experiments. This turns out to be due to errors in the simulated circulation patterns in the Southern Ocean. There, the model equivalent of CDW is too young in the HOR and ISO cases and too old under GM. GEOSECS $\Delta^{14}C$ data indicate a near-uniform Southern Ocean value of -160‰, whereas the HOR and ISO cases simulate radiocarbon to be about -120‰. This is due to rapid overturn of $\Delta^{14}C$-rich surface waters at this latitude (see also England and Hirst (1997)). In contrast, all GM cases overestimate the $\Delta^{14}C$ depletion of CDW. Under GM, the model simulates slow downslope flows and weak interior currents around Antarctica, even with enhanced surface salinities. This explains the spuriously depleted levels of interior $\Delta^{14}C$. Overall, no model case considered by ER99 captures global ocean renewal rates to acceptable levels of accuracy.

Short time-scale ventilation processes

Shorter time-scale ocean ventilation, say decadal to centennial, is best assessed using tracers whose atmospheric or input history has a distinct transient signal during the last few decades, such as CFCs and bomb-produced radionuclides (e.g., tritium/helium, ^{14}C). Tritium (^{3}H) and ^{14}C were produced by atmospheric nuclear bomb testing in the 1950s and 1960s in an amount greatly exceeding their natural abundance. The tritium input function into the World Oceans is rather complex; depending on rainfall, air moisture, geographic location and river input (Weiss and Roether, 1980; Doney et al., 1992). Whilst an entry function for tritium into the global oceans has been calculated, there remains some uncertainty as to the various source terms (see also Heinze et al., 1998). Bomb-produced ^{14}C enters the ocean via air-sea gas exchange, and atmospheric histories are estimated in general as a function of latitude and time (see, e.g., Broecker et al., 1980). Bomb-produced radionuclides favour a Northern Hemisphere oceanic uptake. Tritium in particular has a strong Northern Hemisphere input due to slow mixing of ^{3}H in the troposphere.

Since chlorofluorocarbons are relatively stable and

Table 2. Model runs of England and Rahmstorf [1999]. The seven cases listed include Cartesian-mixing experiments (HOR-Z and HOR=0.75), an isopycnal mixing experiment (ISO) and four Gent and McWilliams (1990; GM) experiments. A_{HH} refers to the horizontal diffusivity, $A_{\rho}(z)$ to a depth-dependent profile for isopycnal diffusion, and κ to the GM isopycnal thickness diffusivity.

| Experiment:	Subgrid-Scale Eddy Parameterisation:
HOR-Z	Horizontal mixing profile, A_{HH} = 1.0 [surface] to 0.5 [bottom] x 10^3 m²/sec.
HOR=0.75	Horizontal mixing (constant A_{HH} = 0.75 x 10^3 m²/sec).
ISO	Isopycnal mixing profile $A_{\rho}(z)$, background A_{HH} = 0.75 x 10^3 m²/sec.
GM-0	GM, κ = 1 x 10^3 m²/sec, isopycnal mixing profile $A_{\rho}(z)$. Zero A_{HH}.
GM-H	As in GM-0, only A_{HH} is non-zero (0.75 x 10^3 m²/sec).
GM=ISO	As in GM-0, only $A_{\rho} = \kappa$ = 1 x 10^3 m²/sec.
GM=0.5	As in GM-0, only κ = 0.5 x 10^3 m²/sec.
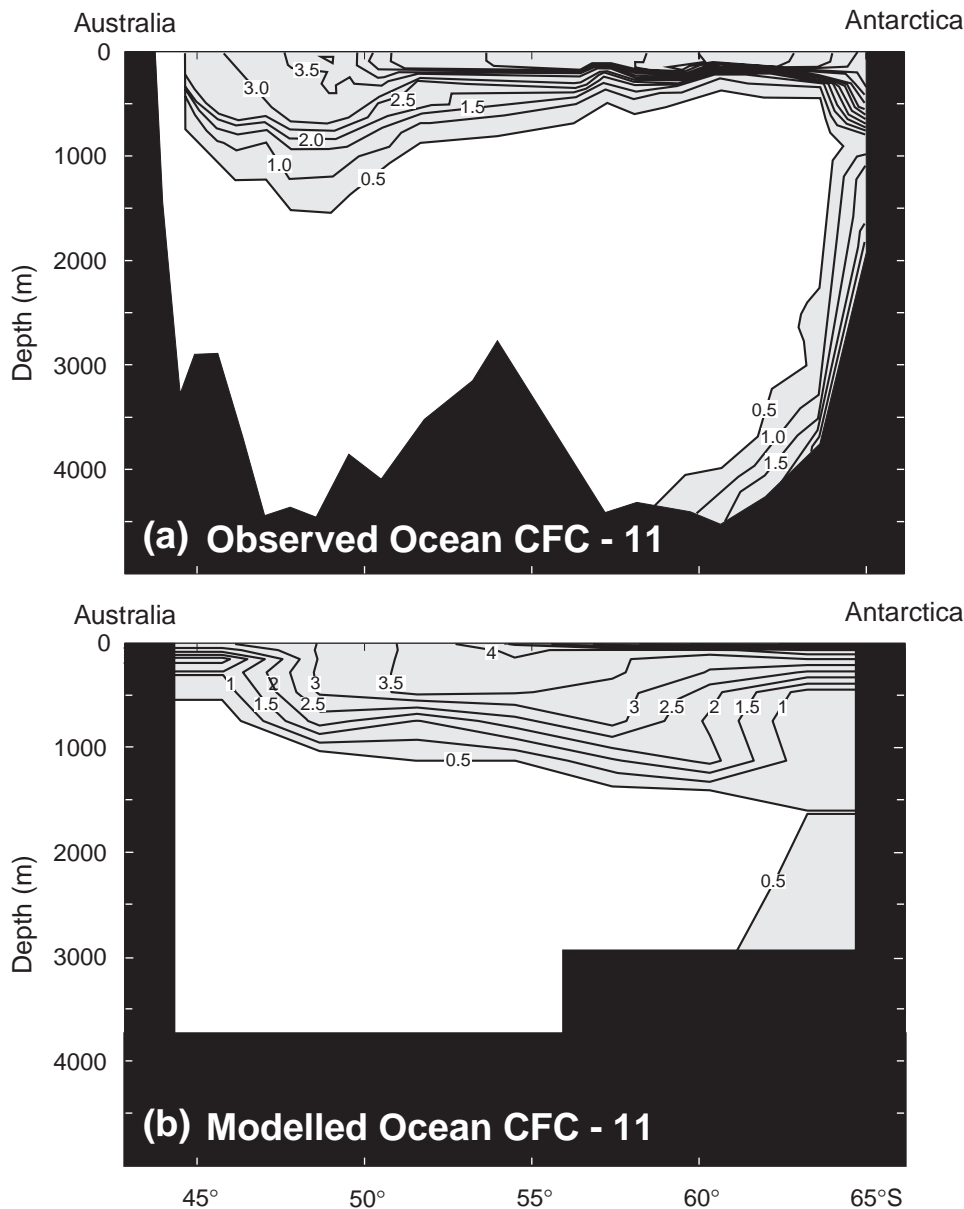
Figure 2. Latitude-depth sections of dissolved CFC-11 along WOCE section SR3 across the Southern Ocean at approximately 150°E during 1991 (a) observed (data provided courtesy of Dr J. L. Bullister), (b) in the model of England (1995). Contour levels are drawn at intervals of 0.5 pmol/kg.

have included CFC uptake for validation purposes (see review by England and Maier-Reimer, 1999). Fig. 2 shows CFC concentrations for the WOCE SR3 section across the Southern Ocean at approximately 150°E in 1991 compared with the model of England (1995). The model uses traditional horizontal/isopycnal mixing and is similar to ocean models used in climate studies prior to the emergence of recent tracer mixing schemes such as GM. The SR3 CFC section runs south from Australia to the Antarctic continent. The measured CFC shows intermediate/mode water penetration at about 45°S, sharp vertical gradients of CFC near 300-m from about 55°S to 65°S, and a very thin band of recently formed AABW adjacent to the Antarctic continental slope. The vertical gradients of CFC in the subpolar waters indicate regions of upwelling of CDW and little surface mixing below the seasonal thermocline. The model fails to reproduce much of the observed structure: mode water formation is too shallow at 45°S, erroneously deep surface layer convection appears at 55°S to 65°S, and only a broad weak signal of AABW is simulated adjacent to Antarctica. These model problems turn out to be due to low horizontal resolution and excessive diapycnal mixing, as well as poor treatment of the bottom boundary layer in z-level models (England and Hirst, 1997, ER99).

Uncertainties, limitations and future work

There are some remaining limitations and uncertainties in using chemical tracers to assess ocean models, and models to interpret observed tracer distributions. Many of these issues were discussed at the recent WOCE-AIMS Tracer Workshop in Bremen. Future work in a number of areas is required to ensure that the utility of the WOCE tracer data sets is maximised in the context of ocean climate model assessment and development. These issues are briefly summarised here and will be discussed in the final

quite rapidly mixed in the troposphere, their oceanic input function is reasonably similar for all latitudes. Southern Hemisphere atmospheric concentrations lag Northern Hemisphere values by about 1 year. Air-sea fluxes of CFCs are estimated using an appropriate parameterisation of the gas piston speed, estimates of the atmospheric CFC history, and knowledge of their solubility properties (see, e.g., England et al., 1994). Sea-ice coverage must also be considered as it can shield the upper ocean from air-sea gas exchange. Technical details of simulating CFCs in ocean GCMs can be obtained from the WWW site http://www.maths.unsw.edu.au/metweb/matthew/cfc.html.

There are numerous ocean modelling studies that

workshop report.

Firstly, input functions and boundary conditions must be well known for chemical tracers to be used meaningfully in ocean models. For example, parameterisation of the air-sea gas piston velocity remains a source of uncertainty. Atmospheric histories of gases are generally well known, however, unknown error distributions in global climatologies of wind speed and sea-ice coverage can limit our ability to force realistic gas uptake in ocean models. Coupled models might not simulate these properties realistically, confounding the issue of validating climate models using internally generated fields for air-sea gas forcing. The input function of tritium is complex to estimate and remains a source of possible error in bomb-tritium simulations. Mantle helium sources are very difficult to quantify directly; present estimates have quite large error bars associated with them. Overall, modellers need error estimates of these source terms to be able to assess model skill in a statistically meaningful way.

In a related manner, 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.

Other limitations in chemical tracer modelling include the following:

- *Measurement density and data products*
  Transient tracers have ever-evolving interior distributions that must be measured for modellers to develop the most stringent benchmarks of model skill. Modellers often seek derived data products, such as integral quantities, column inventories, tracer fields objectively mapped onto isopycnal surfaces, and so on. Yet the temporal/spatial gaps in WOCE tracer data (exacerbated for transient tracers) render many derived products difficult to estimate and subject to unknown error. Some other tracers, for example ^{39}Ar, have ideal properties for ocean model assessment, yet remain poorly sampled due to measurement complexity. Unforeseeable developments in measuring technologies could see such tracers emerge as vital tools for ocean model validation.
- *High resolution models*
  Tracer integration techniques are sometimes used to minimise the cost of running computationally expensive models with additional tracers beyond T-S. Examples include simple off-line models, wherein velocity and T-S fields from a prognostic model are used to advect and mix a chemical tracer without having to rerun the whole model. Uncertainties exist,

however, in the degree to which this technique can alias internal model variability; for example, in surface layer convection and in eddy behaviour.

- *Regional models and data extrapolation/interpolation*
  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. Adjoint methods combined with appropriate ocean models could be useful for extrapolating/interpolating the spatial/temporal gaps in the WOCE tracer data set.

Summary and conclusions

WOCE chemical tracer measurements are greatly assisting in the assessment of ocean models used today in climate prediction systems. Different chemical tracers have different source functions and uptake/decay properties, giving modellers a suite of possible benchmarks to assess model skill. Future tracer measurement programmes are required to realise the full benefits of the WOCE tracer survey, both in terms of capturing the ever-changing transient tracer signal in the ocean and for determining the representativeness of the WOCE period for the long-term behaviour of the ocean.

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. Because property-property analyses provide a more powerful assessment of ocean model skill than single property assessment, particularly when using properties that give relatively distinct information, multiple tracer modelling is recommended. A cost-effective approach is to simulate natural radiocarbon to assess long time-scale processes, and CFCs for decadal to interdecadal ocean ventilation.

Acknowledgements

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German WOCE: Final Scientific Seminar, Bremerhaven, 28 April 1999

Prof. Dr Ernst Augstein, Alfred-Wegener-Institut, Bremerhaven, Germany. eaugstein@awi-bremerhaven.de

Twenty-one research groups from five Universities and four Research Institutes have participated in the German WOCE Programme. The funding from the Deutsche Forschungsgemeinschaft and the Bundesministerium für Bildung und Wissenschaft lasted from October 1989 to March 1999. This Programme was formally completed in the framework of a scientific seminar on 28 April 1999 in Bremerhaven.

The meeting was opened by the Parliamentary State Secretary Mr W.-M. Catenhusen, representing the Ministry of Education and Research. Mr Catenhusen acknowledged the German scientific contributions to WOCE and highlighted the importance of the results in the perspective of the better understanding of global climate changes. He also accentuated the need for a continuation of oceanic research and held out the prospect of a future financial support of ocean and climate research by his Ministry particularly with respect to CLIVAR.

In a brief review of the German WOCE activities E. Augstein, former chairman of the German WOCE Committee, portrayed the field work in the northern, southern and equatorial Atlantic as well as the equatorial Indian Ocean and he stressed achievements in ocean and climate modelling. He also emphasised the improved insight into the role of the polar and subpolar oceans in the renewal of North Atlantic Deep Water and Antarctic Bottom Water. Furthermore, he pointed out that the evidence of oceanic variations in the decadal periodic range – which seem to be primarily forced by the atmosphere – give rise to future oceanic studies under the CLIVAR programme.

G. Siedler discussed the reservoir and transport effects of the oceans within the climate system. He addressed in particular new aspects of the large scale oceanic fluxes of mass and heat which have been revealed from hydrographic, float and tracer measurements.

J. Meincke concentrated on air-sea interactions in subpolar regions with emphasis on the North Atlantic. He drew attention to the rather fast response time of the oceanic circulation and heat transports to variations of atmospheric forcing. He also showed that tracer analyses illustrate a significant acceleration of the eastward spreading of Labrador Sea Water in the northern part of the Atlantic during the last 10 years.

C. Böning demonstrated the high sensitivity of improved ocean models to small-scale influences. He referred to effects of the bottom topography in the Denmark Strait and the Faroe Islands Ridge as well as deep convection in the Labrador Sea on the large-scale oceanic circulation.

Finally, D. Olbers discussed mechanisms causing instabilities in coupled ocean atmosphere models, which may be critical to predicting climate changes. He stressed this point by the fact that present model experiments already suggest remarkable changes of the large-scale thermohaline circulation in response to weak perturbations of the North Atlantic surface conditions.

Besides these review papers the results of the 21 subprojects were displayed on posters. The German WOCE Review Board took these posters into detailed consideration. On the basis of the oral and poster presentations as well as a written final report the Board expressed their full satisfaction with the national WOCE activities.

The analysis and the scientific interpretation of the data are not yet finalised. Therefore, part of WOCE investigation will continue under the umbrella of CLIVAR until 2002. The funding of this work which started in March 1999 is fully assured.

Spreading of CFCs in Numerical Models of Differing Resolution

René Redler, GMD SCAI, Sankt Augustin, Germany; and Joachim Dengg,
Institut für Meereskunde, Kiel, Germany. rene.redler@gmd.de

Tracing the uptake and redistribution of chlorofluoro-carbons (CFC) provides a powerful tool to study ocean circulation and the mechanisms of water mass formation, both in the real ocean and in numerical simulations (e.g. Rhein, 1994; England, 1995). The intercomparison of field measurements and modelled CFC distributions may thus serve as an additional means of assessing the models' capability of describing processes in key regions, such as the Deep Western Boundary Current (DWBC) regime.

CFCs have been frequently used for this purpose in the recent literature (e.g. England, 1995; Dixon et al., 1996; Döscher, 1994), mostly with models of rather coarse horizontal resolutions of about 1° to 2° in latitude and longitude. In comparing the results of these models with observations, the question arises: which aspects of the model solutions can be assumed to be fairly independent of model resolution and/or configuration, and which features are likely to change with future generations of models of higher resolution? This brief report will attempt to provide one example of what can be expected.

The models used in this paper are part of the FLAME (Family of Linked Atlantic Model Experiments) configuration (see also Redler et al., 1998, or FLAME Group, 1998 (draft available from the authors)). The numerical code is based on the GFDL MOM (Pacanowski et al., 1995). The model domain covers the North and South Atlantic, extending from 70°N to 70°S with open boundaries across the Antarctic Circumpolar Current in the Drake Passage and south of Africa at 30°E and restoring zones at the artificially closed boundaries.

There are two model versions, both using an isotropic, Mercator grid in the horizontal, but differing in resolution. One uses an eddy-permitting grid of 1/3°, the other a grid of 4/3°. There are 45 non-equidistant levels in the vertical in both cases. Atmospheric forcing is based on a 3-year monthly mean climatology of ECMWF analyses (Barnier
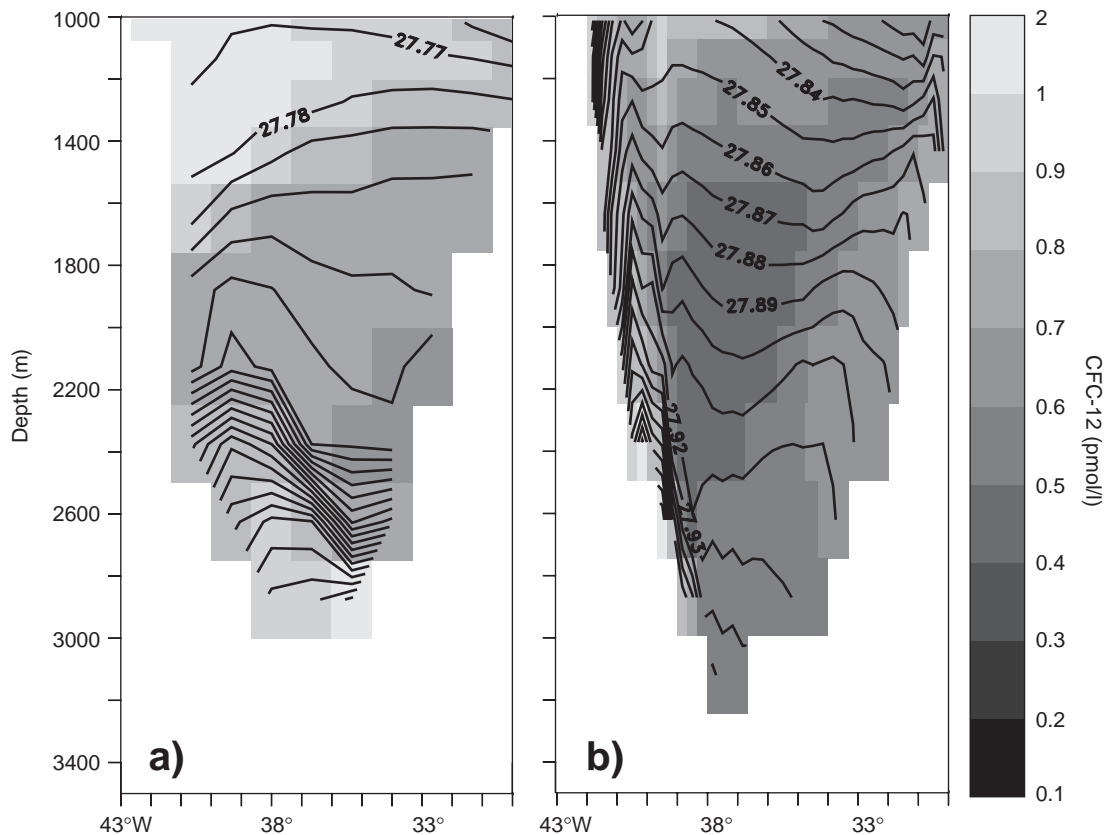

Figure 1. Section along 60°N for the lower water column through the Labrador Sea and Irminger Basin, CFC-12 concentrations in pmol/l are shaded, contour lines indicate the density for the 4/3° model (a) and the 1/3° model (b).
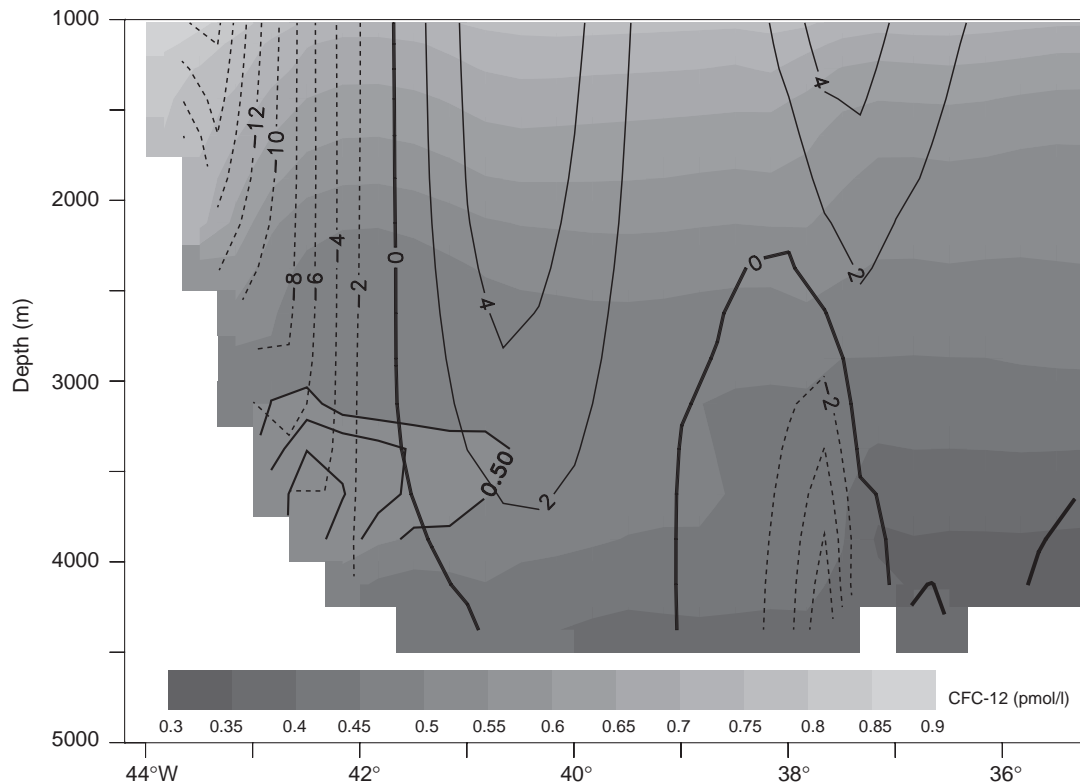
Figure 2. Section of CFC-12 in pmol/l along 48°N in the western basin in a 1/3° North Atlantic model, the meridional velocity is contoured with an interval of 2 cm/s. Note the CFC-signal in the Deep Western Boundary Current located at depths around 3500 m.

et al., 1995), and relaxation to surface salinity given by Boyer and Levitus (1997). Air-sea fluxes of CFC-11 and CFC-12 are implemented by a relaxation of surface concentrations to saturation. The relaxation time scale chosen correspond to a constant piston velocity of 5.6 cm/h. The CFC simulation starts with atmospheric CFCs in 1950 and continues to 1988. Both model configurations use the bottom boundary layer scheme proposed by Beckmann and Döscher (1997) in combination with isopycnal mixing of tracers to maintain the signal of dense water overflowing the Greenland-Iceland-Scotland Ridge. This leads to overflow signals that follow the deep western boundary currents in the overflow regions, rather than getting mixed with the surroundings when they cross the ridges.

To demonstrate the impact of horizontal resolution on the tracer distributions in 1988, a section along 60°N through the Irminger Sea (Fig. 1) shows the pronounced CFC-12 signal of the Denmark Strait Overflow Water (DSOW) in the Irminger Basin, located at depths below 2000 m at the continental slope of Greenland at about 40°W. At the coarser (4/3°) resolution the CFC signal (and the western boundary current) is much broader (Fig. 1a) than in the 1/3° realisation (Fig. 1b). While the maximum CFC concentration (between 1.0 and 1.5 pmol/l) and density ($\sigma_\theta = 28.0$) indicating the core of DSOW have nearly the same values in both models, the location of DSOW differs substantially in this section. Note that the absolute CFC

values may be underestimated in the present model realisations due to insufficient CFC surface flux in the northern restoring zone. The 1/3° model produces a core of DSOW at a depth of around 2500 m with clear slope current characteristics, but in the 4/3° simulation this water is found at the bottom of the Irminger Basin. The reasons for this striking difference are presently being investigated.

A second major difference between the two models (possibly closely related to the feature just described) is manifest further south at 48°N in a cross-section between the Grand Banks of Newfoundland and the Mid-Atlantic Ridge (Fig. 2). In the 1/3° model the core of DSOW within the DWBC is maintained on its way from the overflow regions to the subtropics. CFC-12 concentrations of more than 0.5 pmol/l at depths between 3000 and 4000 m agree reasonably well with observations recently published by Bulsiewicz et al. (1998). In previous simulations with level models of comparable horizontal resolution (e.g., Döscher, 1994), the deep core of high tracer values was absent due to overly strong mixing in the outflow regime (see also, DYNAMO Group, 1997). The effect of the new parameterisation scheme for near-bottom transport appears much weaker in the 4/3° model, where most of the southward flowing, CFC-rich overflow water stalls at the bottom in the subpolar gyre north of 52°N.

To give an impression of the resulting horizontal distributions and the propagation of the CFC-signal with the NADW, we show CFC-12 on isopycnal surfaces for

both models (Fig. 3, page 20). The density level has been chosen separately for each model as the surface on which the CFC-12 maximum is found at the equator ($27.86\sigma_\theta$ units for the 1/3° model and $27.80\,\sigma_\theta$ units for the 4/3° model). The path of NADW is roughly similar in both models. However, the NADW signal is much more diffusive in the coarse resolution run than a smoothing of the high-resolution results to the coarse grid would suggest: at 1/3°, the CFC appears to be concentrated in a DWBC while at 4/3° it is spread fairly evenly across the whole subtropical gyre. Note however, that even in the 1/3° model there is only a weakly concentrated DWBC between Flemish Cap and the Bahama Bank. In this area the CFC-pattern produced at high resolution is in reasonably close agreement with measured CFC concentrations published by Smethie (1993).

In addition to the spatial patterns, spreading rates seem to differ in the two models: the downstream transport of newly formed NADW occurs somewhat faster in the high resolution integration. After 38 years of integration, the trailing signature of NADW (defined as a threshold CFC concentration of 0.01 pmol/l) has propagated well beyond the equator in the 1/3° integration. This is contrasted by the 4/3° model, where the trailing edge is found at 5°N.

In conclusion, these preliminary results indicate that coarse resolution models are able to produce tracer distributions that are not inconsistent with the results at higher resolution, but they appear to overestimate the large-scale spatial spreading while underestimating the rates of propagation of tracer signals. Even at a "medium" resolution of about 1° the successful numerical representation of spreading of tracers in the ocean may be hampered by their overly strong lateral mixing in these models. The quantitative effect for, e.g., the uptake and redistribution of anthropogenic CO_2, in long-term climate studies still needs to be examined. For climate studies interested in stationary states, this may not be relevant, but it will be a concern for studies interested in the variability on timescales of several decades.

Acknowledgement

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MEETING TIMETABLE 1999/2000

19–30 July 1999	IUGG XXII General Assembly	Birmingham, UK
23–27 August 1999	WOCE North Atlantic Workshop	Kiel, Germany
23–27 August 1999	2nd Conference on Reanalyses	Reading, UK
13–17 September 1999	Modelling of Global Climate and Variability Conference	Hamburg, Germany
5–7 October 1999	WOCE-26 (SSG) Meeting	La Jolla, CA, USA
18–22 October 1999	The Ocean Observing System for Climate	S. Raphael, France
25–27 October 1999	Topex/Poseidon/Jason-1 SWT	S. Raphael, France
27–29 October 1999	US WOCE SSC Meeting	Irvine, CA, USA
13–17 December 1999	AGU Fall Meeting	S. Francisco, CA, USA
24–28 January 2000	AGU Ocean Sciences Meeting	S. Antonio, TX, USA
13–17 March 2000	WCRP-JSC XII	Tokyo, Japan

North Atlantic Ventilation Constrained by CFC Observations

Thomas Haine, University of Oxford, UK; and Suzanne Gray, Department of Meteorology, University of Reading, UK. T.Haine1@physics.ox.ac.uk

Man-made transient tracers such as chlorofluorocarbons (CFCs) and tritium play an important role in estimating the ocean circulation. These passive, inert substances have reasonably well-known atmospheric distributions and very long lifetimes in seawater. Their tropospheric origin and decadal time-scale make them ideal tracers of the circulation that ventilates the basin-scale ocean. Substantial efforts have been made to develop reliable measurement techniques and obtain high-quality datasets from the global ocean. In contrast, there have been relatively few attempts to combine these observations with general circulation models (GCMs) in order to improve understanding of the ocean circulation (notable exceptions include: Robitaille and Weaver (1995), England (1995), England and Holloway (1998), Heinze et al. (1998). Here we report first results from a systematic investigation of this issue.

The general interpretation of passive tracer distributions in terms of ocean circulation is a problem with many close relatives in geophysics. We cannot directly measure the quantity of interest (the large-scale, low-frequency flow) but have observations of a related variable (tracer). Using a prognostic theory (tracer predictions from a GCM) we indirectly derive information about the quantity of interest from the data with an inverse method. In practice there are two distinct stages: first, we test the hypothesis that the GCM tracer predictions (and hence the circulation itself) are statistically consistent with the observations. If they are, then the data provide no useful additional information about the circulation. One may conclude that more measurements are required at this stage. Alternatively, if the data are inconsistent with the GCM, then the modelled circulation requires improvement. Once this has been achieved, we return to the consistency hypothesis and repeat the procedure. In a certain formal sense, we only learn something new about the circulation when this hypothesis is rejected. We cannot claim that the model (and hence the circulation) has been "validated" or "verified", only that it is demonstrably wrong (Wunsch, 1996; Oreskes et al., 1994; Randall and Wielicki, 1997).

A section of CFC-11 concentration nominally along 20°W in the North Atlantic Ocean (Fig. 1, page 20) illustrates these ideas. Fig. 1a shows the observations made in 1993 (Castle et al., 1998) while Fig. 1b is a GCM CFC-11 field from a 4/3° version of the Miami isopycnal model (MICOM, see below). Given the inevitable errors in the data and the air-sea CFC flux a key question is whether these two fields are statistically different. This is the issue we have addressed using a large database of CFC-11 and CFC-12 measurements and a state-of-the-art (non-eddy-resolving) GCM.

Methods and data

The advection-diffusion equation for the passive transient tracer concentration C is

$$\frac{\partial C}{\partial t} + \mathbf{u} \cdot \nabla C - \nabla \cdot (\kappa \nabla C) = 0 \qquad (1)$$

where C is a function of position $\mathbf{x}$ and time t, $\mathbf{u}$ is the (non-divergent) three-dimensional flow and κ is the (variable) diffusion coefficient. We solve this problem, without loss of generality, using the Green's function G associated with the linear advection-diffusion operator (see Morse and Feshbach, 1953). The solution is

$$C(\mathbf{x},t) = \kappa(\mathbf{x}_s t_0) G(\mathbf{x},t;\mathbf{x}_s t_0) \circ B(\mathbf{x}_s,t_0)$$

where B is the (uncertain) flux of tracer through the sea surface $\mathbf{x}_s$ and $\circ$ means integration over all time and over the surface of the ocean. (This formalism is easily extended to cover other tracer sources and sinks.)

This Green's function solution allows us to determine if the tracer data contain information that constrains our best-guess North Atlantic circulation (from the GCM). We allow errors in the tracer measurements and the air/sea exchange and find the optimal tracer boundary flux that gives the best least-squares-fit of the GCM-predicted tracer to the observations. This optimal tracer flux $\hat{B}$ is given by

$$\left(\kappa G_d^T \mathbf{P}_d \kappa G_d + P_b\right) \circ \hat{B} = \kappa G_d^T \mathbf{P}_d \mathbf{d} + P_b \circ B_1 \quad (2)$$

where G_d is the Green's function at the places and times of the observations and $\mathbf{P}_d$ and P_b are data and boundary-flux weights, respectively (that is, inverse error covariances). The tracer observations are $\mathbf{d}$ and the prior tracer flux into the ocean is B_1. In practice, the optimal tracer flux $\hat{B}$ is estimated using a discretized version of eq. (2).

A substantial quantity of pre-WOCE and WOCE CFC-11 and CFC-12 data in the North Atlantic has been collated. The cruises span the years 1982–1994 and cover most regions in the North Atlantic during that period. Most cruises contained full depth measurements of both CFC-11 and CFC-12 concentrations (> 5000 samples of each species in total). We gratefully acknowledge the assistance and advice given by the investigators who provided these measurements for our analyses.

We have used the MICOM primitive equation GCM to predict the North Atlantic CFC transient (Bleck and Smith, 1990). The resolution is 4/3° in longitude and 4/3° × cos(latitude) in latitude yielding an isotropic grid (this configuration is described by the DYNAMO (1997). There are sponge layers at the open boundaries (including the Straits of Gibraltar) with 20 density layers in the vertical

and a thermodynamically active mixed layer. The model is forced with monthly climatological fluxes derived from the ECMWF analysis (1986-1988) with the sea surface salinity relaxing to the Levitus 1982 climatology. Sub-grid-scale processes are parameterised using Laplacian diffusion along density surfaces with a small diapycnal mixing. Our simulations begin from an adjusted flow which is nearly in steady state on annual time-scales. A tracer model to solve eq. (1) and hence derive the Green's function, is included in the dynamical code.

To decide if the modelled CFC field is consistent with the tracer data we require a measure of the expected misfit (that is, the P_d and P_b in eq. (2)) and the prior-guess flux (B_1). The data uncertainty arises from instrumental error and navigational error (uncertainty in geographic position). However, misfits caused by oceanic variability that is missing from the GCM are substantially greater. Such variability is caused by meso-scale eddies, inertia-gravity waves and three-dimensional turbulence at scales that are unresolved by the GCM. We call this uncertainty a "model-variability error." While instrumental and navigational errors are relatively straightforward to estimate, the model-variability error is a complex, scale-dependent quantity. It is directly related to the variance spectrum of the tracer in question.

Calculations of tracer spectra from eddy-resolving numerical experiments suggest that the spectral shape depends only weakly on the details of the (large-scale) tracer source and sink (Haine and Gray, 1999). Therefore, we have estimated the tracer variance spectrum of potential temperature on isopycnals in the North Atlantic ocean using high resolution hydrographic data. We have then used this spectrum as a proxy for the CFC spectrum in the North Atlantic and hence estimated the data weight P_d in eq. (2). The magnitude of this model-variability error may reach 50% in regions of strong eddy activity.

In comparison, the CFC flux error is smaller (O(20%)). Although the details of the air/sea exchange are poorly known, the net flux B_1 in eq. (2) is primarily limited by the ventilation of the mixed layer. The prior boundary flux estimate itself is determined by comparing realistic MICOM CFC simulations that use different air/sea exchange parameterisations (Asher and Wanninkhof, 1998).

Results

The results from our inverse calculations are that on intermediate and large scales (O(500) km and larger) the MICOM CFC fields are in reasonable agreement with the observations when we properly include the effects of unresolved variability. However, at shorter scales there are significant discrepancies, especially in the subpolar gyre. It appears that the subpolar ventilation mechanisms in the GCM do not penetrate deeply enough and are not in the correct locations (as Fig. 1 suggests). Heinze et al. (1998) have also recently concluded that CFCs, anthropogenic tritium and tritiugenic helium-3 are inconsistent with a 3.5° resolution global GCM. Although our North Atlantic data
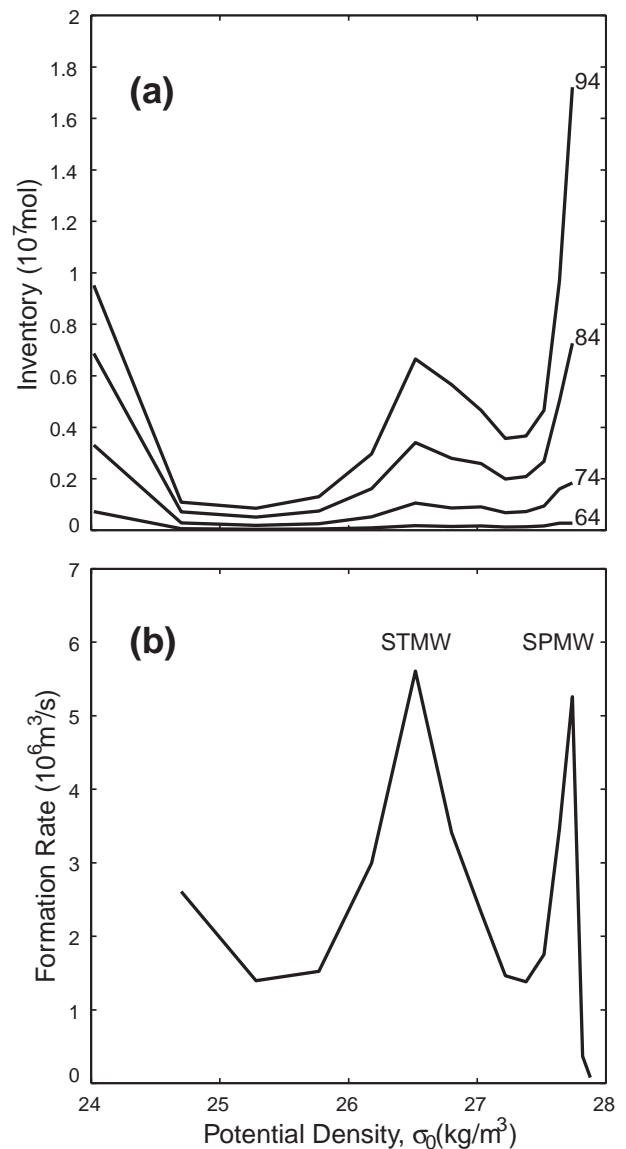

Figure 2. (a) North Atlantic CFC-11 inventory (10^7 Moles) for densities less than $\sigma_0 = 27.92\,kg\,m^{-3}$ based on the 4/3° MICOM model using CFC-11 fluxes fitted to observations. Years 1964, 1974, 1984 and 1994 are shown. (b) Formation rate ($10^6\,m^3/s$) calculated from the CFC inventory and a simple box mixing model. STMW is Sub-tropical Mode Water and SPMW is Sub-polar Mode Water; see text for details.

seem to be inconsistent with the 4/3° MICOM model the normalised misfit is not particularly large. There are also several sources of error in our analysis. In particular, our estimate of the North Atlantic tracer variance spectrum is uncertain. In this light we take the view that, on balance, the data are only marginally inconsistent with the GCM. In other words, we believe that relatively minor changes in the model circulation would bring the GCM in to statistical agreement with the data.

To investigate the implications of our results, we have estimated some ventilation diagnostics based on our best-fit CFC fields. Fig. 2a shows the total inventory of CFC-11

in density classes directly ventilated south of the Greenland-Scotland ridge. The tracer is being absorbed in the seasonally mixed surface layers and in the two principal mode waters formed in the North Atlantic: Subtropical Mode Water (STMW, $\sigma_0 \approx 26.5\,\mathrm{kg\,m^{-3}}$) and Subpolar Mode Water (SPMW, $\sigma_0 \approx 27.75\,\mathrm{kg\,m^{-3}}$) (Speer and Tziperman, 1992). Taking all the waters lighter than $\sigma_0 \approx 27.82\,\mathrm{kg\,m^{-3}}$ (pressures less than about 2000 db) together, the North Atlantic ocean was near 20% saturated with CFC in the mid-1990s.

Using a simple box mixing model we can calculate the corresponding residence time and hence estimate typical ventilation rates. These fluxes, averaged over the last 20–30 years and based on our synthesis of CFC data and the MICOM circulation, are shown in Fig. 2b. The formation of STMW and SPMW with peak rates around 5 Sv is clear. It is also remarkably consistent with the estimates of (Speer and Tziperman, 1992) based on an independent surface buoyancy analysis. Interestingly, their analysis suggests no formation between the two mode waters. Our estimate is about 1.4 Sv at $\sigma_0 = 27.3\,\mathrm{kg\,m^{-3}}$ and may be due to processes (such as interior diabatic mixing and lateral transfers in the mixed layer) which are very hard to estimate using other methods (see also Sarmiento, 1983).

In conclusion, we have established a foundation for the systematic interpretation of transient tracer data using GCMs. Our results are that the CFC measurements are marginally inconsistent with a good North Atlantic circulation model when we include the effects of unresolved variability. Using the best-fit CFC fields we have estimated the net North Atlantic ventilation rate. We find good agreement with independent prior results for mode water formation and interesting disagreement that may be caused by interior water mass transformation mechanisms. We are now expanding our tracer database, modifying the model circulation and investigating the critical processes controlling the North Atlantic CFC budget.

Acknowledgements

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Assessing the Importance of Subtropical Waters in Ventilating the Equatorial Pacific Thermocline: a Combined Transient-Tracer Approach
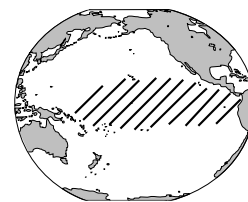
S. Peacock, Lamont-Doherty Earth Observatory of Columbia University, USA;
W. Jenkins, Southampton Oceanography Centre, UK; R. Key, Princeton University,
USA; and W. Broecker, Lamont-Doherty Earth Observatory. synte@ldeo.columbia.edu

The fundamental circulation pathways in the Equatorial Pacific thermocline can be described by a complex system of predominantly zonal currents, which exhibit significant spatial and temporal variability (Wyrtki, 1967; Wyrtki and Kilonsky, 1982). Present within this current system are waters subducted into the thermocline in the northern and southern subtropics and subsequently upwelled at the equator. There is also a possible contribution from sub-thermocline waters, which may be incorporated by processes of diapycnal mixing or upwelling. However, there is still some uncertainty as to both the degree of communication between sub-thermocline and thermocline waters in the Pacific, and to the relative importance of the northern and southern hemispheres in ventilating the equatorial thermocline. The task of accurately quantifying the source of waters in the equatorial current system is exacerbated by the strongly time-varying circulation. It is because of this high temporal variability that tracer budgets (which integrate over long time periods) offer great potential for elucidating the time-mean contributions of waters subducted in the subtropics of the northern and southern hemispheres to the equatorial thermocline.

There have been previous tracer-based approaches to the problem of quantifying the relative contributions of waters subducted in the subtropics to the Equatorial Pacific thermocline, most commonly via salinity budgets (e.g. Toole et al., 1988; Tsuchiya et al., 1989; Wijffels, 1993), but also using tritium (Fine et al., 1993). Salinity mass budgets imply that the southern subtropical gyre provides the main source water to the Equatorial Undercurrent (EUC). This conclusion is supported by various modelling studies: A study of GCM velocity fields by Blank and Raynaud (1997) implies that the EUC is composed of almost 60% water entering through its southern edge, and in a 3.5 layer model study, Lu et al., 1998, show that 63% of southern hemisphere extratropical water is present within the EUC.

While the salinity distribution is certainly an excellent tool with which to attack the problem, the definition of source waters in light of a strongly time-varying circulation remains problematic. Further, if there is any exchange between thermocline and sub-thermocline waters in the equatorial or subtropical regions, this will be an additional source of error. The use of a single transient tracer such as tritium is problematic because either the dilution of newly ventilated northern hemisphere waters by less well ventilated thermocline waters, or any mixing with sub-thermocline waters, would have a similar imprint on the tritium signature as advection of southern source waters into the northern hemisphere.

The approach

We here outline a new method for assessing the relative contributions of waters subducted in high latitudes of the northern and southern Pacific to the equatorial thermocline over the last few decades. We propose that the ratio of two transient tracers with similar input histories can be used as to formulate a 'new' tracer complementary to, and with certain advantages over steady-state tracers, and over any transient tracer considered in isolation. The concept is very simple: this new tracer can be regarded as a pair of 'dyes' injected into high-latitude northern- and southern-hemisphere surface waters at some time t_0. Some amount of time later (at time t_1), the dyes will have reached the equator. If this 'ventilation time' ($t_v = t_1 - t_0$) can be constrained, and if the dye (tracer) concentrations are known both at time t_0 and time t_1, then the degree of mixing between waters originating in the northern and southern hemispheres can be deduced. It is suggested that the bomb tritium-bomb radiocarbon tracer pair is ideally suited for answering questions regarding ventilation sources in the equatorial Pacific thermocline.

The bomb tests injected both tritium and radiocarbon into the atmosphere, with a peak in the mid-1960s. Bomb-derived tritium has a strongly asymmetric latitudinal input function, and was delivered predominantly to the northern hemisphere oceans via precipitation, water vapour exchange and river runoff as HTO (tritiated water; Weiss and Roether, 1980). Bomb-derived radiocarbon was delivered to the surface ocean via CO_2 exchange, but because it became well mixed in the atmosphere before entering the surface ocean, its input is nearly symmetric about the equator. Due to the presence of a significant natural background, in order to estimate the amount of radiocarbon contributed to any given water sample as a result of nuclear testing, it is necessary to 'separate' the natural and bomb-produced components of radiocarbon. To do this we used the silicate-based method described by Broecker et al., 1995.

Radiocarbon decays with a half-life of 5730 years, and hence on decadal timescales, the loss due to decay is negligible. Tritium, however, decays with a much shorter half-life of 12.43 years. By converting measured tritium to 'TU81' units (i.e. by decay-correcting measured tritium concentrations to 1 January 1981), the tritium lost to decay is explicitly accounted for, and the tracer 'TU81' can be thought of as a passive dye-like tracer with a pulse-like input in the high latitudes of the northern hemisphere.

We define the ratio of tritium to bomb radiocarbon as $R = 25(TU81/bomb^{14}C)$. The multiplicative factor is simply present in order to make the range of the new tracer fall
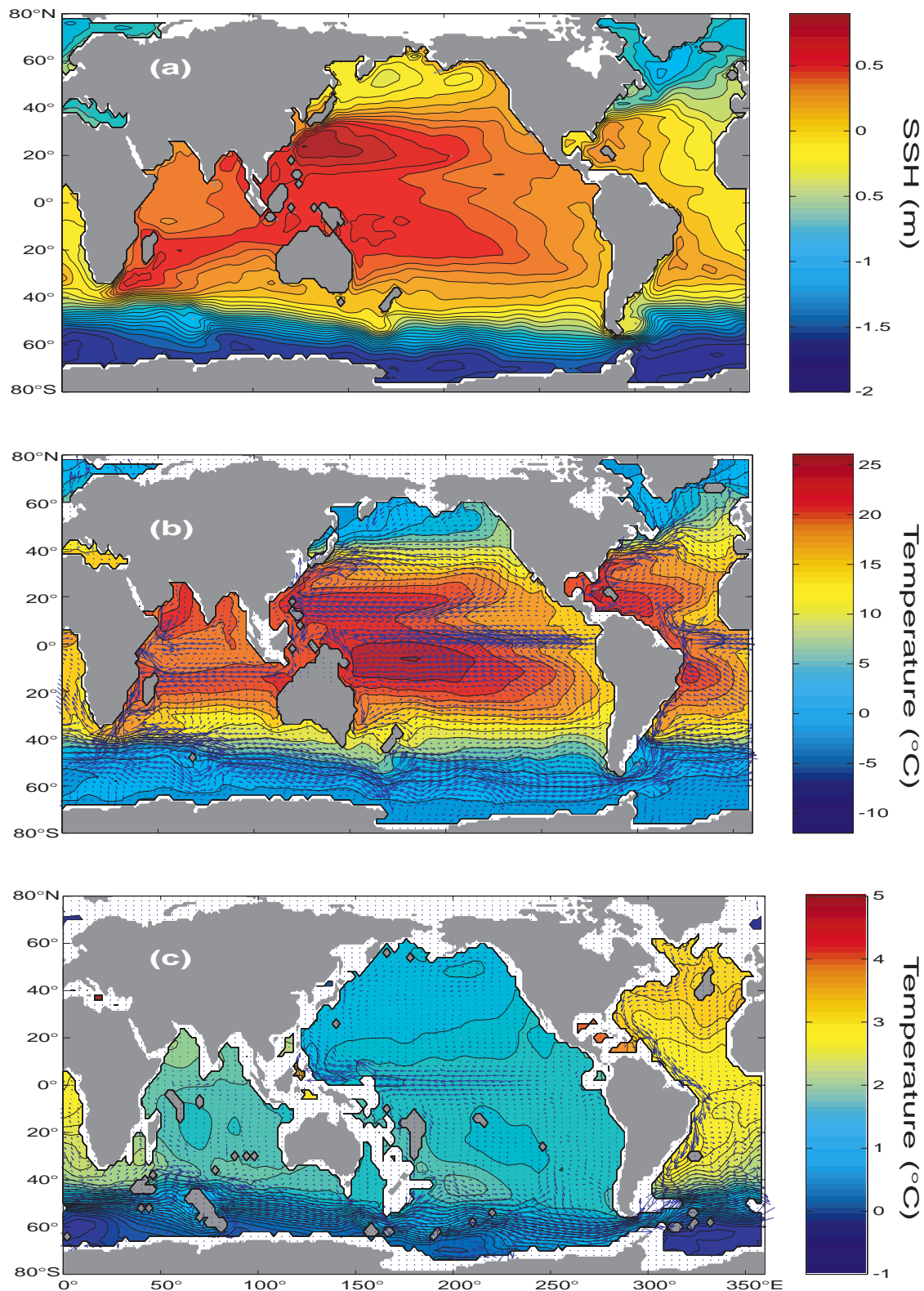
Follows et al., page 3, *Figure 2. (a) The mean sea surface height field relative to the geoid, as it results from the entire six year optimisation period. This field displays all major known elements of the general circulation but with sharp frontal structures smoothed owing to the limited spatial resolution. The optimisation has removed erroneous initial features known previously to have resulted from errors in the geoid estimate. These are particularly pronounced in the absolute circulation of the tropical Atlantic and Pacific Oceans. (b) The optimised mean (over six years) temperature and velocity field at 112 m depth (cm/s). As in the surface height field, the flow field also contains all major elements of the general circulation but with the expected spatial smoothing. (c) Same as (b), but from 2500 m depth.*
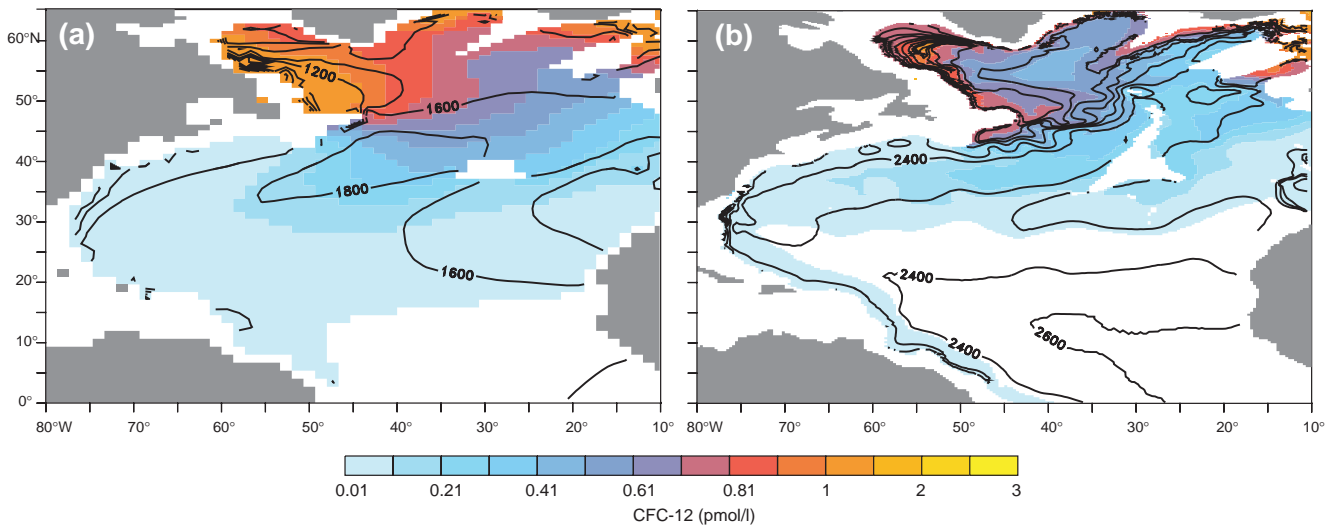
Redler and Dengg, page 12, *Figure 3. Horizontal distribution of CFC-12 on isopycnal surfaces corresponding to the NADW in each model. The colour bar indicates CFC-concentrations in pmol/l, contoured is the depth of the isopycnal surfaces. (a) shows results for year 1988 in the 4/3° model, in (b) the corresponding distribution is plotted for the 1/3° model.*
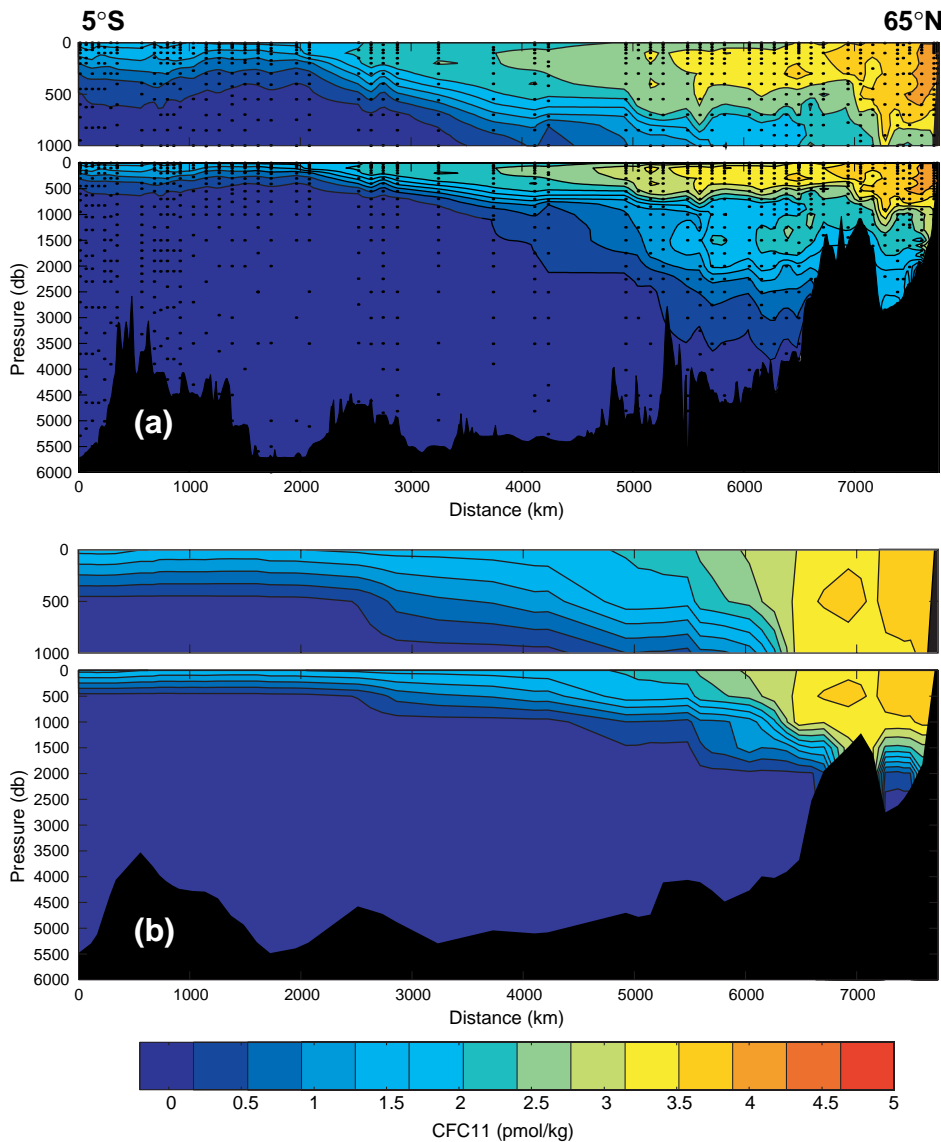
Haine and Gray, page 15, *Figure 1. Sections of CFC-11 concentration (pmol/kg) nominally along 20°W in 1993. (a) Field observations (Castle et al., 1998) (dots show the bottle locations), and, (b) MICOM prediction. The upper panel in each case shows the top 1000 db expanded. See text for details of the MICOM configuration.*
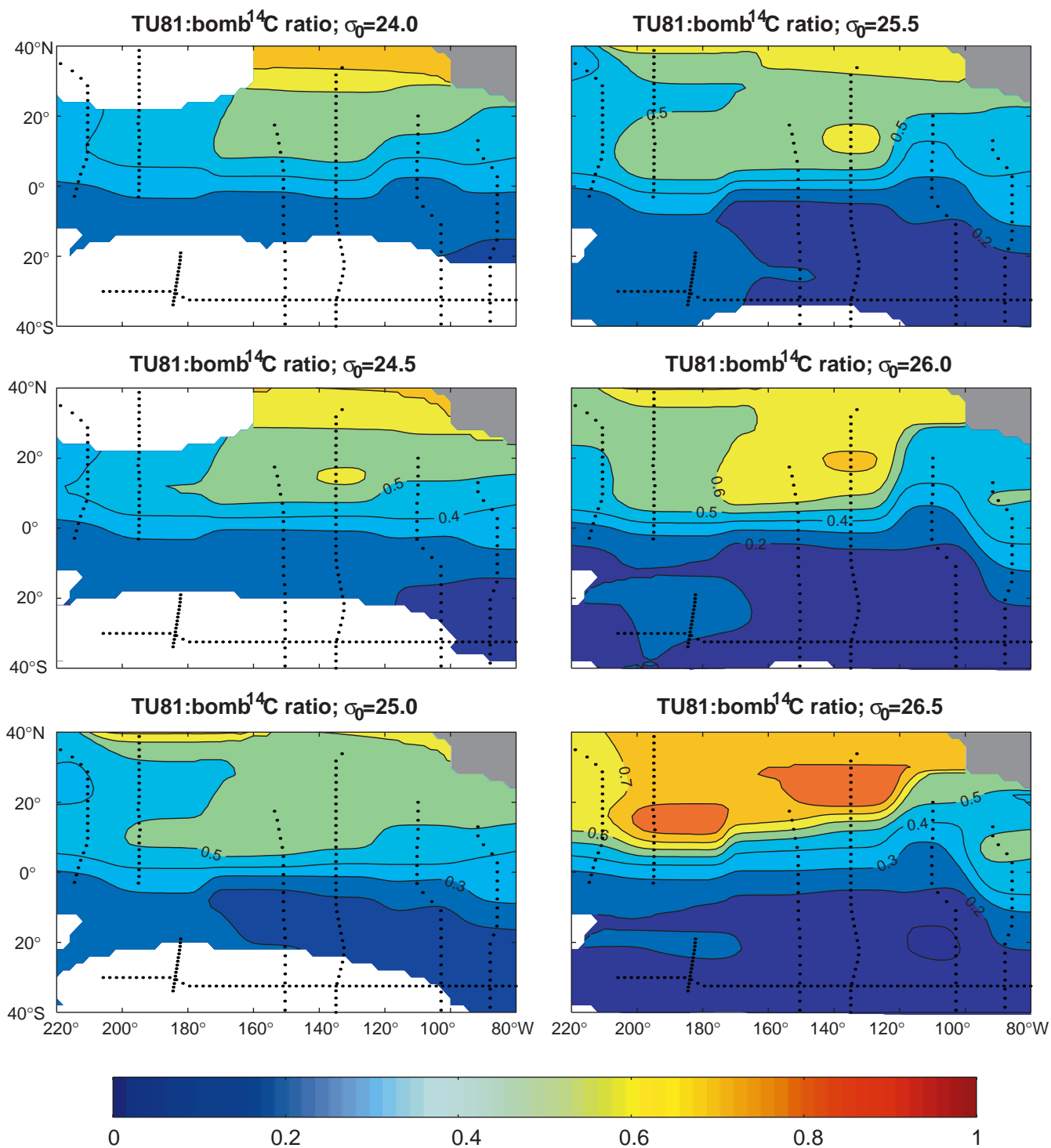
Peacock et al., page 18, *Figure 1. R(25(TU81/bomb^{14}C)) at the time of WOCE on selected isopycnal surfaces in the Pacific. The station locations for WOCE P6, P10, P13, P14, P16, P17, P18 and P19 are shown by the black dots. Maps were constructed using an objective mapping technique. The grey area in the upper right-hand corner is a region in which there is no data. White areas are regions in which the isopycnal surfaces outcrop.*
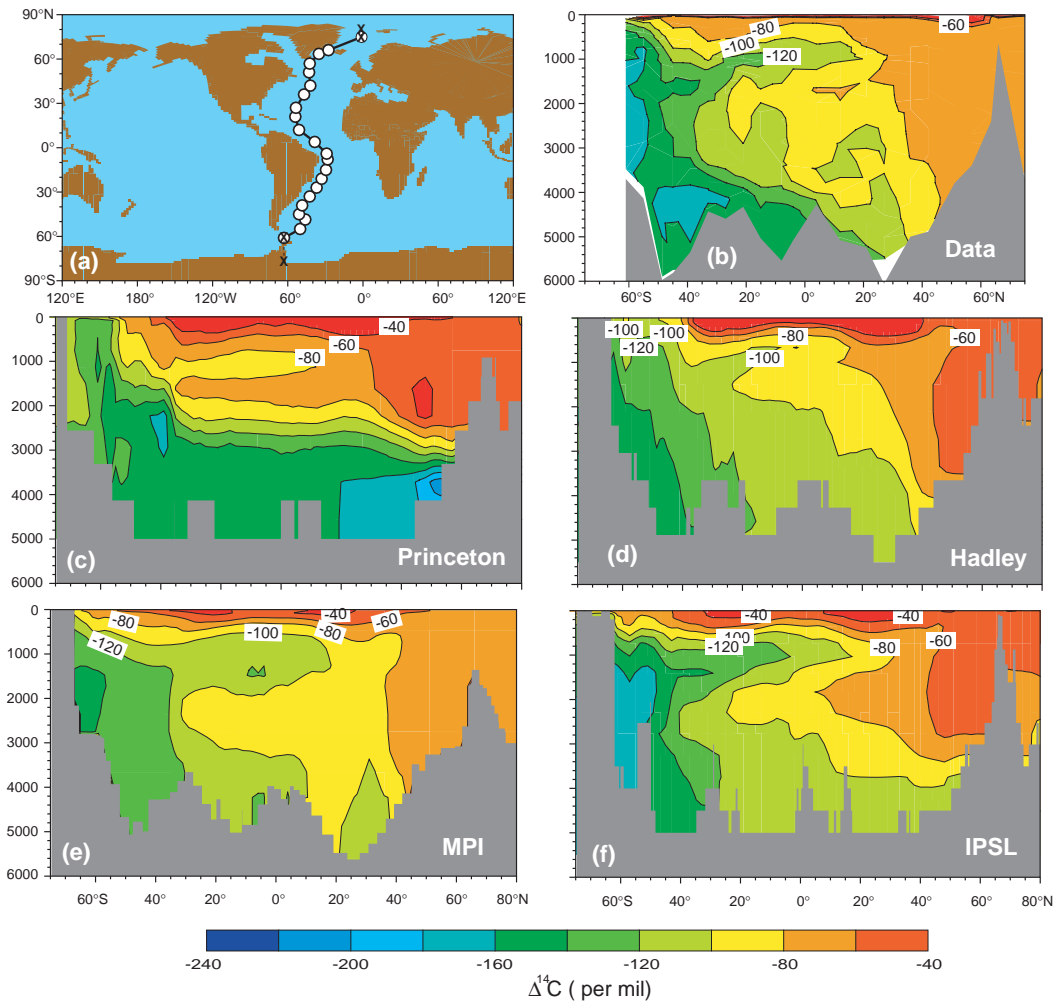
Orr, page 24, *Figure 1. Section of natural $\Delta^{14}C$, the fractionation-corrected $^{14}C/^{12}C$ ratio (in per mil) along (a) the Western Atlantic GEOSECS cruise track (b) as estimated from observations by (Broecker et al., 1995), and in the (c) Princeton-GFDL, (d) Hadley, (e) MPI, and (f) IPSL models.*
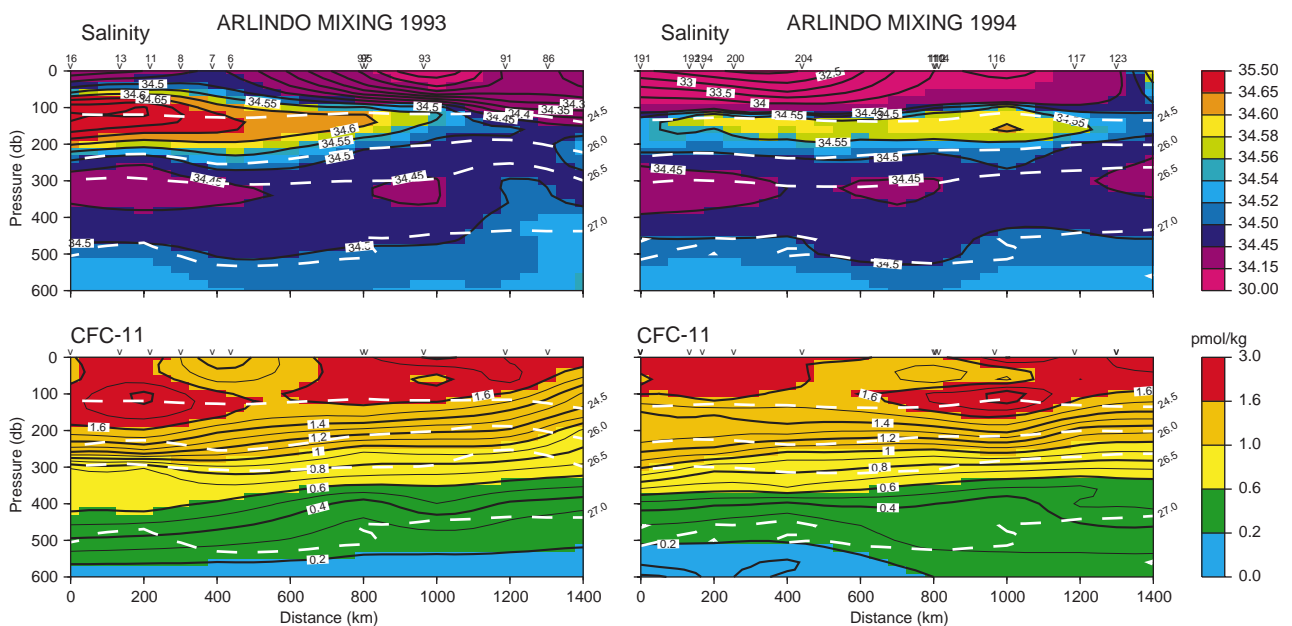
Wawaruntu et al., page 26, *Figure 1. Salinity and CFC-11 sections from Makassar Strait to Flores Sea to Banda Sea (same section as top Fig. 2) during AM93 and AM94.*
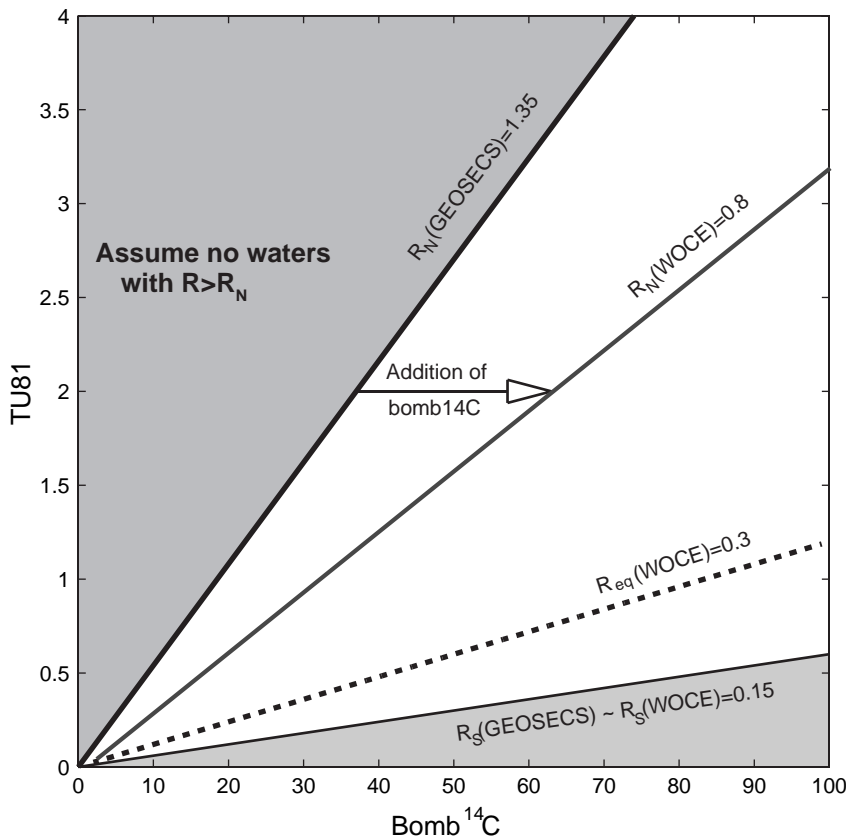
Figure 2. Schematic figure to illustrate how R is expected to change with time in the northern and southern subtropics. The uppermost line shows R in the northern subtropics at the time of GEOSECS. Continued addition of bomb¹⁴C to the system, but a much smaller input of tritium would cause the ratio to evolve in the manner shown by the horizontal arrows. R in southern tropical waters (Rₛ) would be expected to change by only a small amount between the GEOSECS and WOCE surveys, and hence we have made the assumption that Rₛ remained roughly constant at 0.15. The dotted line shows R measured on the equator at the time of WOCE.

roughly in the range zero to one. In computing R, all data points with TU81<0.1 or bomb^{14}C < 20 per mil were eliminated, due to the sensitivity of R to small errors at these low values.

One advantage of the tritium- bomb^{14}C tracer pair is that the time evolution of the end-member concentrations in surface waters is known fairly well. Further, water added to the thermocline by isopycnal or diapycnal mixing or by upwelling of older waters will carry zero-concentrations of bomb-tritium and bomb-radiocarbon. Hence admixture of thermocline waters with older waters will not change the ratio of bomb-tritium to bomb-radiocarbon.

In order to accurately assess the relative importance of waters originating in the northern and southern subtropics in ventilating the equatorial Pacific thermocline, one would ideally need to know the TU81 : bomb^{14}C ratio in water which is now at the equator at the time when it was subducted. Therefore, some measure of the time taken to transport waters from the high latitude surface to the subsurface equatorial thermocline is required. One such measure can be obtained by computing the 'tritium-helium

age' (Schlosser, 1992; Jenkins, 1996). The tritium-helium age section constructed by Jenkins (see Jenkins, 1996, for details) along P17 (~135°W) shows that, at the equator between roughly σ_θ 25.5 and 26.5, the tritium-helium age lies between 15 and 20 years.

Preliminary results

The distribution of R on selected isopycnal surfaces at the time (t_1) of WOCE (early 1990s) is shown in Fig. 1 (page 21).

We obtain an estimate of the 'ventilation time', t_v, from the WOCE tritium-helium data. Finally, R is estimated at subduction latitudes at time $t_0 = t_1 - t_v$. While there has been a significant change in the TU81 : bomb^{14}C ratio in northern hemisphere waters over the last 30 years (due primarily to the continued addition of bomb^{14}C), the change in R in high-latitude southern hemisphere waters over the same time period is barely detectable. As illustrated in Fig. 2. this is due to the very low initial TU81 : bomb^{14}C ratio in the southern subtropics.

A ventilation age of 15 to 20 years for equatorial waters in the lower thermocline would require that these waters be at the surface in the early to mid 1970s (which was the period of the GEOSECS surveys). Based on the GEOSECS data, we assign to these waters an initial R_n (the TU81 : bomb^{14}C ratio in high latitudes of the northern hemisphere) of 1.35, and an initial R_s (the TU81 : bomb^{14}C ratio in high latitudes of the southern hemisphere) of 0.15. The TU81 : bomb^{14}C ratio in equatorial waters at the time of the WOCE surveys is close to 0.3 on all density surfaces, and shows little variation with longitude (see Fig. 1).

By writing a simple budget equation to estimate the relative contributions of northern and southern source waters to the equatorial thermocline, $X_n R_n + X_s R_s = R_{eq}$, and using the values in table 1, the required contributions from the northern and southern subtropics to the equator are as follows: $X_s = 88\%$, $X_n = 12\%$ (where X_n = amount of water originating in the northern subtropics; X_s = amount

Table 1. Values assigned to variables in the budget equation for the estimation of contributions of northern and southern source waters to the equatorial thermocline.

$R_n(t_0)$	$R_n(t_1)$	$R_s(t_0)$	$R_s(t_1)$	$R_{eq}(t_1)$
1.35	0.8	0.15	0.15	0.3

of water originating in the southern subtropics, and $X_n + X_s = 1$). This implies that equatorial waters in the lower thermocline are made up almost exclusively of water of southern hemispheric origin. This result is somewhat higher than that from calculations based on salinity budgets and GCM transports (e.g. Blanke and Raynaud, 1997; Lu et al., 1998; Tsuchiya et al., 1989); but it supports the view that the southern subtropical gyre is the dominant source of water to the Equatorial Undercurrent.

Discussion

Our findings are best interpreted as upper bounds on the importance of waters subducted in the southern extra-tropics in ventilating the Equatorial Pacific thermocline. If the tritium-helium based ventilation age or the TU81 : bomb^{14}C ratio at the time of subduction is spuriously high, or if there is significant downward mixing of overlying waters, our estimate of the importance of the southern component will need to be reduced.

The ventilation age obtained from the tritium-helium pair may be biased high as a result of addition of primordial helium due to upwelling or upward diapycnal mixing. As an extreme lower bound on the southern-component, a ventilation age of zero can be assumed by using $R_n(t_0) = R_n(t_1) = 0.8$ as the northern end-member. Such a scenario would require $X_s = 77\%$, $X_n = 23\%$.

Another possible source of error may arise from the different time-history of tritium and bomb-radiocarbon input to the ocean. Because the input of tritium was more pulse-like than that of radiocarbon, there has been continued addition of bomb radiocarbon to the surface ocean over the last 30 years, but a much smaller input of tritium. Therefore the effect of downward mixing would be to preferentially mix down bomb^{14}C, leading to a spuriously low TU81 : bomb^{14}C ratio. Thus this would, again, lead to an over-estimate of the importance of the southern component. We therefore suggest that the result that equatorial waters consist of roughly 90% southern-derived waters be taken as an uppermost limit.

We have presented preliminary conclusions regarding the relative importance of waters subducted in the northern and southern subtropics in ventilating the equatorial Pacific thermocline. These conclusions are based on the tritium-bomb^{14}C pair and on tritium-helium age estimates. It is likely that estimates could be further improved by the simultaneous consideration of CFC and salinity budgets.

Acknowledgements

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Ocean Circulation and the Ocean Carbon-Cycle Model Intercomparison Project

James C. Orr, LSCE, Unite Mixte CEA-CNRS, CEA Saclay, France.
orr@cea.fr

Ocean general circulation models provide the foundation upon which ocean carbon-cycle models are built. The success of the latter in simulating the distribution of oceanic carbon and related biogeochemical tracers is closely tied to the skill of the former in predicting patterns of ocean circulation. For this reason, recent efforts in the ocean carbon-cycle community to compare global-scale models have included substantial emphasis toward validating model-predicted patterns of ocean circulation.

The Ocean Carbon-Cycle Model Intercomparison Project (OCMIP) began in 1995 as an effort to identify the principal differences between existing ocean carbon-cycle models. This effort was initiated via the Global, Analysis, Interpretation, and Modelling Task Force (GAIM) of the International Geosphere Biosphere Programme (IGBP). The first phase of this project (OCMIP-1), included four groups (Max Planck Institute of Meteorology, Hamburg; Princeton University/GFDL, Princeton; Hadley Centre,

UK Met. Office, Bracknell; and Institute Pierre Simon Laplace, Paris). Emphasis during OCMIP-1 focused both on the natural and anthropogenic components of oceanic carbon and radiocarbon (^{14}C).

The natural component of ^{14}C is particularly interesting as a tracer of deep-ocean circulation because horizontal and vertical gradients are produced in the ocean due largely to its radioactive decay (half-life of 5730 years). Thus natural ^{14}C provides invaluable time-dependent information, unlike other more classical tracers such as temperature and salinity (e.g., see Toggweiler et al., 1989). During OCMIP-1, modellers compared simulated natural ^{14}C with the observed natural component of C-14 as estimated by Broecker et al. (1995) from measurements taken during GEOSECS.

An example of the utility of ^{14}C, is shown by the OCMIP-1 comparison along the GEOSECS section in the Western Atlantic (Fig. 1, page 22). To properly simulate natural C-14 in the Western Atlantic, a model must obtain the proper balance between filling of its deep North Atlantic with NADW from the north, and infiltration of AABW from the south. Observations along the Western Atlantic GEOSECS section reveal that the basin north of the equator is filled with young waters (all less than 500 years old) penetrating from the north. The youngest deep water penetrating south is a tongue at mid-depth, centred at 2500 m. Antarctic waters have an older signature, despite their recent contact with the atmosphere, due to mixing with the ocean's oldest waters from the Pacific. Antarctic Waters penetrate northward both along the bottom (AABW) and at intermediate depths (AAIW).

In the GFDL/Princeton model, younger waters from the north penetrate southward but they extend no deeper than 2500 m. The ^{14}C signature of this problem was first identified by Toggweiler et al. (1989). The GFDL model's oldest Atlantic deep waters are found at depth in the north, unlike the observed distribution, which has the oldest deep waters in the south. In a more realistic fashion, the MPI, Hadley, and IPSL models simulate younger waters which fill the entire North Atlantic basin. All three of these models simulate a tongue of younger water penetrating from the north (NADW) confined by "older" water both above (AAIW) and below (AABW). However the skill varies between these three models in their ability to reproduce the observed distribution. For example, the general distribution in the MPI model appears somewhat too smooth, the age minima in the tongue of NADW in the Hadley model appear too shallow, and the along-bottom gradient north of 40°N in the IPSL model has a vertical instead of a horizontal structure.

Further analysis of the time information from natural ^{14}C in the Western Atlantic reveals that the MPI, Hadley, and IPSL models all exhibit inadequate northward penetration of AABW. In contrast are ^{14}C results from the GFDL model which shows excessive northward penetration of AABW due to lack of a deep component of NADW. A similar pattern of inadequate northward penetration of AABW was found along the Western Pacific GEOSECS section, in all four models.

These and other large differences between models, particularly in the Southern Ocean, have prompted modellers to launch a second phase of OCMIP. That effort involves 13 different models and new simulations for additional tracers of ocean circulation and biogeochemistry. A key component of OCMIP-2 involves the recent capability to exploit essential new data sets for CFC-11, CFC-12, ^{14}C, and CO_2, thanks to the collaborative efforts of associated observationalists who are leading related WOCE and JGOFS data synthesis efforts. During the first two phases, OCMIP has compared simulations run under present climatological conditions, where circulation patterns vary only seasonally. A third phase of OCMIP is currently being planned during which model comparison will focus on the impact of climate change on air-sea fluxes of CO_2 and marine productivity. Those coupled carbon-climate models will be evaluated by diagnosing their ability to reproduce observed interannual to decadal variability.

The OCMIP modellers and data specialists have pooled resources and defined a battery of standardised validation tests. These detailed tests are more rigorous, better documented, and thus easier to implement than those normally applied by individual groups. Furthermore, OCMIP has also produced a legacy of standard forcing fields, common analysis tools and techniques, and databases of selected model output and observations, all of which facilitate model-data and model-model comparison. The ocean carbon-cycle community now has a growing reference, accessible to both modellers and observationalists, which would not exist had it not been for OCMIP. These efforts are leading to accelerated diagnosis and improvement of ocean carbon-cycle models. More information concerning OCMIP can be found on its Web page (http://www.ipsl.jussieu.fr/OCMIP/).

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Spreading and Velocity Patterns of the Indonesian Throughflow

Jorina M. Waworuntu, Rana A. Fine, and Donald B. Olson, Rosenstiel School of Marine and Atmospheric Science, University of Miami, USA; and Arnold L. Gordon, Lamont-Doherty Earth Observatory of Columbia University, USA. jwaworuntu@rsmas.miami.edu
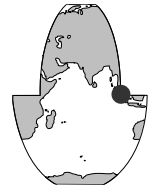
Water from the western Pacific flows through the Indonesian Seas following different pathways and is modified by processes that vary seasonally and interannually. The processes are studied using data from three cruises in 1993, 1994, and 1996. An inverse-model analysis using salinity and CFC-11 data 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 (SEM) of 1993 and 1996 and a small, more barotropic flow during north-west monsoon (NWM) of 1994. The water masses observed in the region can be accounted for by isopycnal mixing of different source waters, backflushing, and by vertical exchanges, which are significant in this region.

Introduction

The circulation and transport through the Indonesian Seas have a large annual variation due to the strong monsoonal change in the wind pattern in this area. Three Arlindo cruises were made during different monsoon periods to study the change in the circulation pattern and processes in the Indonesian Seas. The three cruises are Arlindo Mixing 1993 (AM93) from 6 August to 12 September 1993 in a SEM period, Arlindo Mixing 1994 (AM94) from 26 January to 28 February 1994 during the NWM, and Arlindo Circulation 1996 (AC96) from 18 November to 15 December 1996 during an intermonsoon between SEM and NWM.

Changes in the flow pattern and transport variability in turn produce changes in the water mass and properties. During different monsoon seasons, water from different sources flows to the Indonesian Seas, and the result can be seen in the variation of salt, temperature, and other tracers from the surface down to the lower thermocline (Fig. 1, page 22) (Gordon and Fine, 1996; Ilahude and Gordon, 1996). Local processes such as precipitation and coastal upwelling also contribute to these changes.

Transient tracer distributions are often used to determine the spreading pattern of a water mass. CFC-11 distributions during the Arlindo cruises indicate a main Throughflow pathway of North Pacific thermocline water flowing through
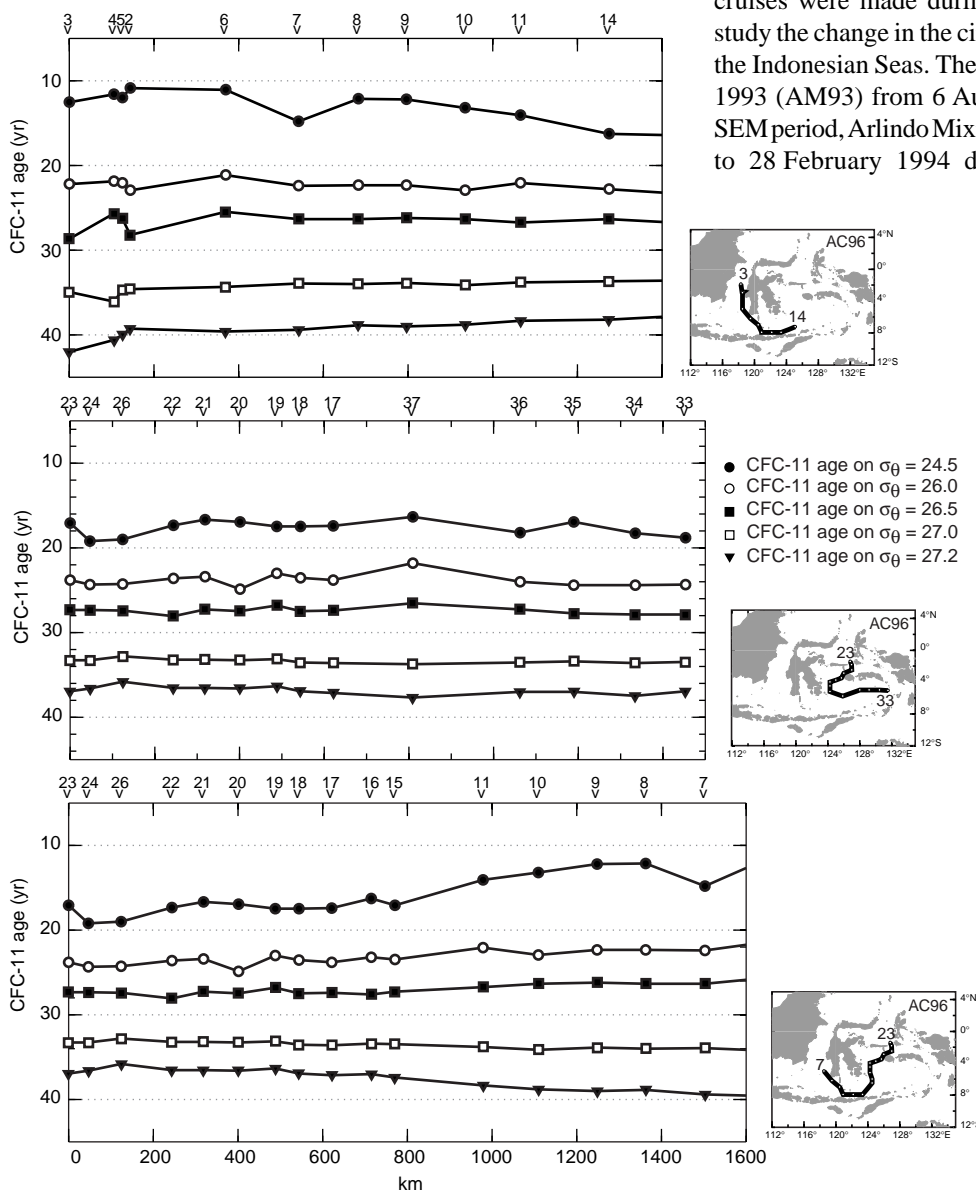

Figure 2. CFC-11 derived ages on σ_θ surfaces along different sections during AC96.

Makassar Strait. At intermediate levels, mainly South Pacific water spreads southward and westward through the channels east of Sulawesi (Fig. 2).

In many areas in Indonesia, the surface currents switch direction following the monsoon wind patterns (Wyrtki, 1961; Mariano et al., 1995). Changes in the direction of the surface current suggest that the flow is highly baroclinic. The Pacific to Indian Ocean pressure gradient across the shallow sills surrounding the area and the change in direction and strength of the wind presumably force the baroclinic flow throughout the whole region. Vertical motion could also play an important role in the water distribution and transformation in this region. Lack of direct and long term measurements make it difficult to get a complete picture of circulation and processes in the region, especially the vertical distribution of the circulation.

The inverse model

The tracer distribution at a certain location is a result of the advection and mixing history prior to the observation. The distribution is also subject to the different boundary conditions for each individual tracer. The observed tracer distribution reflects the dynamics integrated over time. If a
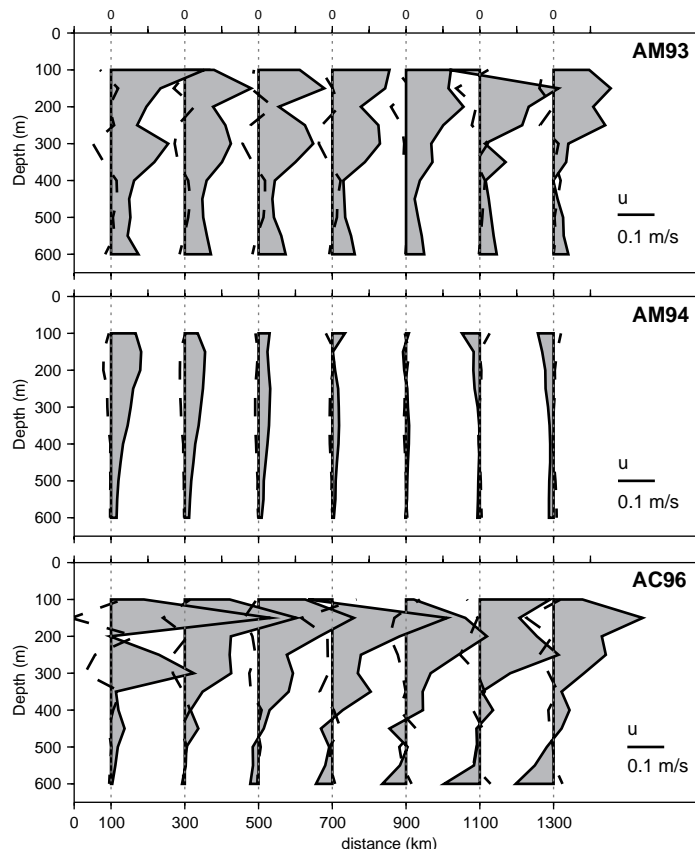

Figure 3. Horizontal velocity u for AM93, AM94, and AC96 section from Makassar Strait to Flores Sea, to Banda Sea. Output from inverse calculation with uniform vertical diffusivity coefficient $K_v = 10^{-3}$ m^2/s. The dashed lines are the corresponding residual horizontal velocity.

system is stationary and there are enough linearly independent tracers, it is possible to obtain an optimal solution of the circulation field and mixing parameters that can produce the observed tracer field.

A steady advective-diffusive equation for a conservative tracer C can be written as

$$-\mathbf{v}.\nabla C + \nabla.(K\nabla C) = 0$$

A steady advective-diffusive equation for an ideal tracer age T can be written as

$$-\mathbf{v}.\nabla T + \nabla.(K\nabla T) + 1 = 0$$

The factor one comes from the increase in age by one per unit time, if we follow a particle from the time it leaves the surface.

An inverse method similar to that of McIntosh and Veronis (1993) is used to quantify the advective and diffusive processes in the eastern Indonesian Seas. The model is applied to a two-dimensional vertical section along the flow path from Makassar Strait to Flores Sea and Banda Sea (Fig. 1), for 1993, 1994, and 1996. It is assumed that these Straits and Seas act as a channel, and the flow and tracer fields are uniform across the channel. A quasi steady state is assumed for the tracer distributions.

The model input is salinity and CFC-11 age distribution. The model solves the horizontal and vertical velocities. Vertical diffusivity K_v is assumed uniform throughout the channel. There is no horizontal diffusivity in the model. The optimal solution is obtained by minimising a penalty function and smoothing the solution field simultaneously.

Fig. 3 shows the optimal solution for horizontal velocity profiles for $K_v = 10^{-3}$ m^2/s. Other diffusivities larger than 10^{-5} m^2/s will give very similar velocity profiles, scaled with the mixing coefficient used.

Discussion

The optimal solutions of the inverse calculation suggest that strong baroclinic flows occur during AM93 and AC96. On the other hand, a small and more barotropic flow is the optimal solution obtained for the tracer distribution in AM94. The seasonal flow variability given by the solution supports the observation that the Throughflow is minimum during the NWM season. In the large diffusivity case, the horizontal velocity for the AM94 (NWM) is about 15% to 20% of the velocity in the AM93 (SEM) and AC96 (end of SEM).

While the pattern of the circulation in the Indonesian Seas strongly depends on the local forcing and the distribution of boundaries, the strength of the Throughflow seems to be more closely related to the pressure difference between the remote Pacific and the Indian Ocean. The solutions show a relatively stronger flow to the east in the upper thermocline during AC96 compared to AM93. This supports the argument that during a La Niña phase, the build-up of the warmpool in the western Pacific will strengthen

the Throughflow (Gordon and Fine, 1996; Gordon et al., 1998).

The model solutions show that the eastward flow in 1996 is also accompanied by a reversal flow to the west in the lower thermocline. The strengthening of the pressure gradient in the lower thermocline between the Pacific Ocean and the Indonesian Seas during a La Niña year could increase the flow in the deeper thermocline through the eastern passages.

This study shows marked changes in the Through-flow volume and character seasonally and interannually. The model is also able to estimate the vertical exchange processes that are important to the local weather pattern and productivity.

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WOCE-AIMS Tracer Workshop

Scott C. Doney, NCAR, USA; and Wolfgang Roether, Universität Bremen, Germany. doney@ucar.edu

The WOCE-AIMS Tracer Workshop was held at the University of Bremen, 22–26 February 1999 as one of the topical workshops arranged by international WOCE to structure the data evaluations during WOCE-AIMS and possibly beyond. More than 70 people from 8 countries attended, and with a few exceptions, all groups active in ocean tracer observations and in tracer modelling were represented. The workshop started with a series of invited overview talks on the role of tracer studies in physical, chemical and biological oceanography to structure the subsequent discussions. This was followed by working group and plenary meetings focused on various aspects of the WOCE tracer data, their evaluation, and subsequent incorporation into numerical models. Individual scientific projects were presented through an ongoing poster session over the week.

The tasks of the workshop had been defined in advance by the a planning group (W. Roether, S. Doney, W. Jenkins, Y. Watanabe, W. Smethie, C. Böning, and M. England) coordinating with WOCE SSG and WOCE IPO:

(1) Further the oceanographic interpretation of the WOCE tracer data sets

(2) Encourage the synthesis, compilation and dissemination of tracer data sets.

(3) Establish mechanisms for the production of data products (gridded and derived) for the use of a broader community.

(4) Identify strategies to facilitate assimilation and incorporation of tracer data into models.

(5) Initiate collaboration and interaction between tracer geochemists and modellers.

Discussions during the meeting were lively, with a general consensus that the workshop was timely, providing a good basis for meeting the targets of WOCE-AIMS. The compilation and initial interpretations of the WOCE tracer data set are well underway and considerable scientific progress is to be expected with the completed WOCE data set now in hand. There were four major working groups addressing

(i) physical oceanographic issues and tracers,

(ii) biogeochemical issues and tracers,

(iii) model—data interaction, and tracer data issues.

A smaller group dealt with assimilation of tracer data and other modelling issues of a more general character. Future developments of the field were covered a series of open ended plenary discussions. 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; and current questions/limitations and future directions for the work. The outcome of the working groups and plenary sessions have been synthesised into a set of general workshop recommendations:

- 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).

- 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 inter-annual variability.

- 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 re-addressed either through analysis of available non-WOCE data or specifically targeted field cruises.

- 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).

- 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.

- Enhance legacy of WOCE tracer data set as a bench-mark 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:

- 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 both ocean physics (e.g. diapycnal 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:

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

- 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.

- 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 formation of a committee to draft a white paper, to be completed in approximately one years time, addressing in detail issues of scientific objectives, implementation, sampling strategies (e.g. time series, repeat sections), and technological developments (e.g. sensors, platforms).

The complete report from the WOCE-AIMS tracer workshop is currently being compiled and should be available from the WOCE IPO by Fall of 1999.

Connecting the Southern Ocean with the Rest of the World: Results from Large-Scale Ocean Models

Anand Gnanadesikan, AOS Program, Princeton University, USA.
a1g@server1.gfdl.gov

One of the key problems in oceanography is understanding how the depth of the oceanic pycnocline is set. In the past fifteen years, work by a number of authors has provided a theoretical framework for understanding the wind-driven pycnocline. Less progress has been made for the deep pycnocline, however. Munk (1966) proposed a picture in which the pycnocline is maintained by a balance between downward mixing of heat and upward advection of dense water. By assuming that the total upwelling was equivalent to the total formation of dense water (~30 Sv), he estimated a pycnocline diffusion rate of order $1\,cm^2\,/\,s$. Bryan (1987) extended this work to an idealised three-dimensional domain with a flat bottom. He showed that the upwelling is consistent with a deep anticyclonic and surface cyclonic flow. The boundary current associated with the surface cyclonic flow advects warm water polewards resulting in a strong poleward heat flux. Bryan then used the assumption first made by Stommel (1961) to link the magnitude of the flow in the boundary current to the pressure gradient. He ended up with a scaling in which the sinking of deep dense water in the northern hemisphere was proportional to the square of the pycnocline depth D

$$T_n = g'D^2 / \varepsilon \qquad (1)$$

where g' is the reduced gravity between the pycnocline and the deep ocean and ε is a frictional resistance. From observations, ($T_n = 18\,Sv$, D ~ 600 m) one can estimate g'/ε to be around $50\,m/s^3$. T_n represents a conversion of light water to dense water. In order for the oceanic density field to be at steady state there must be a counterbalancing conversion of light water to dense water. As shown in Fig. 1, this conversion can either take place in the pycnocline or in the Southern Ocean, where Circumpolar Deep Water is freshened to become Antarctic Surface Water and then warms as it moves northwards. If the conversion of dense to light water within the pycnocline is denoted as T_u and the conversion of dense to light water in the Southern Ocean is denoted T_s, it is possible to derive a simple theory for predicting the depth of the pycnocline (Gnanadesikan, 1999).

The upwelling flux in the pycnocline can be easily solved by noting that an advective-diffusive balance (following Munk, 1968) gives

$$w = T_u / A = K_v / D \qquad (2)$$

where A is the area over which low-latitude upwelling occurs and K_v is the diffusivity within the pycnocline. Then

$$T_u = K_v A / D \qquad (3)$$

The ocean area in latitudes lower than 40° is about $2.5 \times 10^{14}\,m^2$. This means that if D is 600 m and T_u were 18 Sv, K_v would have to be about $0.43\,cm^2/s$. This is much larger than microstructure and tracer release experiments have shown (Ledwell et al., 1993).

In a recent paper (Gnanadesikan, 1999) I revisited this question, looking at the effect of adding a Southern Ocean path for ocean freshening. The upwelling is allowed to either draw up dense water from below the pycnocline, or to be supplied by relatively light water from mesoscale eddies. The additional flux of water has the form

$$T_s = L_x \left(\frac{\tau x}{\rho|f|} - \frac{A_I D}{L_y} \right) \qquad (4)$$

where τ_x is the wind stress in Drake Passage, |f| is the Coriolis force in Drake Passage, L_x is the circumference of the globe in Drake Passage, A_I is an isopycnal mixing coefficient, and L_y is the meridional length scale over which the pycnocline shallows in the Southern Ocean. When put together with eqns 1 and 3, this yields a cubic equation in the pycnocline depth D. Fig. 2 shows a sample solution for $A_I = 1000\,m^2/s$. If the effect of winds is neglected, a high value of pycnocline diffusivity is needed to get a pycnocline of reasonable depth. However, if Southern Ocean winds are included, very little mixing at all is required, in accordance with observations. Gnanadesikan (1999) shows that this model does a qualitatively good job at predicting the response of the pycnocline to Southern Ocean winds and eddy processes within a large-scale model.
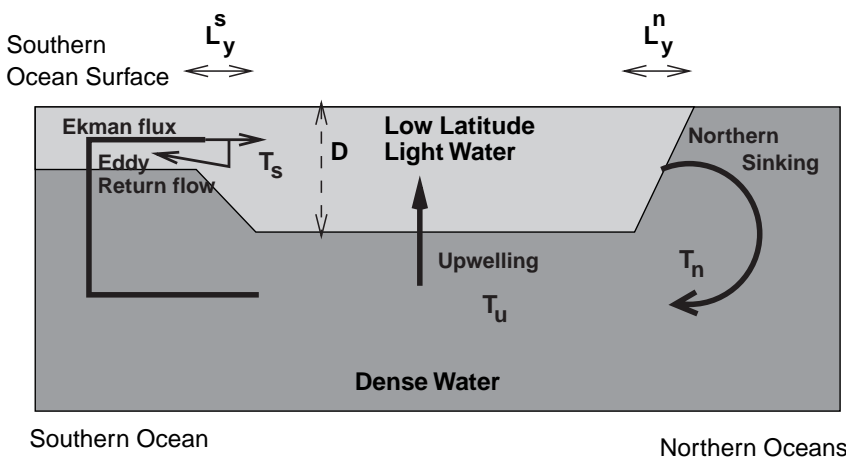

Figure 1. Basic schematic of the overturning scheme discussed in Gnanadesikan (1999).
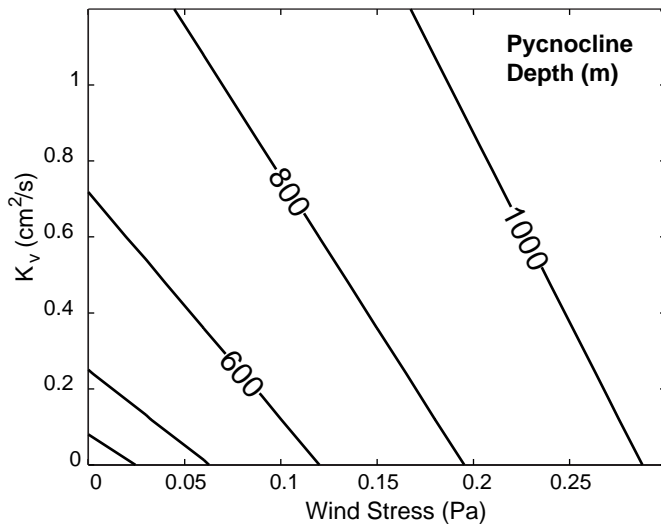
Figure 2. Solutions of the cubic equation in pycnocline depth obtained by setting the northern sinking flux equal to the upwelling flux in the pycnocline plus the net upwelling of deep water in the Southern Ocean. Note that the observed pycnocline depth of around 600 m can be obtained either by having very high vertical diffusion, but low winds, or moderate winds and low vertical diffusion.

What does this have to do with WOCE (and CLIVAR)? What I'd like to emphasise in this article is the contrast between a world where most dense water upwells through the low latitude pycnocline, and one in which most of the conversion of dense water to light water occurs in the Southern Ocean. Observations such as WOCE could help us to make sense of which picture is more accurate. If the Southern Ocean pathway is dominant, this has a number of important implications:

1. It places strong limits on the total productivity of the world ocean. The average silicate content of water at 600 m is ~80 µmol. If 18–20 Sv of this water upwells into the low-latitudes (where surface silicate is low) it would imply 50 Tmol/yr of biogenic silica would have to sink across depths of 500–1000 m in the low latitudes. If the high silicate deep water is brought to the surface in the Southern Ocean, silica production could be far lower.

2. It affects the stability of the climate system. In the absence of Southern Ocean eddies and pycnocline diffusivity, the Northern Hemisphere overturning must simply equal the Southern Hemisphere Ekman transport as long as the NADW is denser than the

AAIW. This means that freshening in the North Atlantic due to climate change would simply cause the pycnocline to deepen, but would not (in the long run) cause the Northern Hemisphere sinking to decline (see also Keeling, subm.). Including eddies, however does cause the overturning to decline slightly.

3. It affects the response of the Antarctic Circumpolar Current to winds. A substantial portion (~75%) of the Circumpolar Current transport within Drake Passage is due to velocity shears occurring above 2500 m (Whitworth, 1983). These shears arise from density gradients across the current. This model suggests that these north-south density gradients are linked to the Southern Ocean winds so that increases in the Southern Ocean winds will produce an increase in the strength of the current. A number of investigations here at Princeton and GFDL, (Toggweiler and Samuels, 1995; Gnanadesikan and Hallberg, subm.) seem to confirm this idea.

What sorts of light can WOCE cast on this problem? I would like to highlight two key areas which would put strong constraints on ocean models:

1. We need a better understanding of what happens to the Antarctic Surface Water after it leaves the Ekman layer. How does it get transformed into Antarctic Intermediate Water and what portion of this flux flows into the North Atlantic?

2. Similarly, we need a better picture of what happens to the North Atlantic Deep Water. How much of it ends up in the Southern Ocean surface and how much moves through the pycnocline? Nutrient based tracers such as PO may be extremely useful in this respect.

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Developing the WOCE and CLIVAR Data Resources: A Report on the WOCE/CLIVAR Data Products Committee in April 1999

N. Penny Holliday, Southampton Oceanography Centre, UK.
penny.holliday@soc.soton.ac.uk

The joint WOCE/CLIVAR Data Products Committee (DPC) held its twelfth meeting at the British Oceanographic Data Centre at CCMS/POL in Bidston, UK. The purpose of the meeting was to continue the development of the integrated WOCE data resource, and to advance the planning of a CLIVAR data, information and products system. The DPC combines both scientists and data managers and for the first time was joined by members of the new CLIVAR Data Task Team, thus meeting as a joint WOCE and CLIVAR group.

Following the enthusiastic reception of Version 1.0 of WOCE Global Data on CD-ROMs (May 1998), the DPC is progressing towards the goal of a fully integrated WOCE data resource by 2002. The next issue of the Global Data (Version 2.0) will be published in mid-2000 and a step closer to that goal. Much of the meeting was spent devising ways to achieve closer links between the various data sets, and to make access for users easier and quicker. The main improvement planned for Version 2.0 is that the user will be able to search all data sets on such common parameters as geographical area, date and time. This facility can best be achieved if all data sets are present in a common file type and only with standardisation of the above header information. There are clear advantages too in standardisation of the variable names.

The DPC discussed the advantages and disadvantages of NetCDF as a file format that might prove to be the way to achieve integration of the numerous data types. NetCDF is freely available and popular among many modellers, ocean, atmosphere and climate researchers and is used by some WOCE data centres already (see P. McIntosh's article in International WOCE Newsletter No. 31). The principle advantage of NetCDF for the DPC is that it is self-describing, which in plain language means that there is no need to define data formats; each file contains sufficient information for software to be able to read it without the user specifying the format first. There are still concerns about just how practical NetCDF will be for data centres to export data, and for users to access data. Before committing themselves to NetCDF for Version 2.0, the DPC has tasked all the WOCE data centres to make trial data files which members of the IPO and DIU who have little or no experience of NetCDF will use and assess. Before this can happen a working group from the DPC is compiling a comprehensive list of header information, variable names and units etc. that need to be standard. Despite the possible move to a non-ASCII format, the DPC is still intent o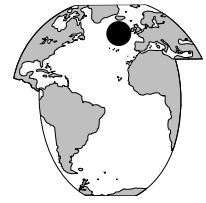n ensuring that the WOCE Global Data are available to all users. NetCDF files are readable by many existing data visualisation and manipulation packages on all platforms, and there exists free software which exports ASCII files from NetCDF.

The future versions of the WOCE Global Data will also be more complete in terms of the data sets they include. Each data centre continues to work hard to increase their holdings and obtain permission from the data providers to make data public. Version 3.0 will be the final archive, and data which are not available at that stage will not be archived as a contribution to the WOCE programme. Lowered ADCP data, and temperature and salinity profiles from profiling floats do not presently have homes within the WOCE data system and the DPC is considering how these data can be archived for WOCE and the future. The US NODC is the WOCE archive centre and is generously providing the resources for the publication of Versions 1.0, 2.0 and 3.0 of the WOCE Global Data, and is actively participating in the discussions on how to create the integrated data resource. NODC is holding continued discussions with data centres on how to transfer the data resource to their databases and archives with all the information intact.

One day of the meeting was taken up with CLIVAR data issues which are rather different from WOCE issues because of their broader scope (oceanic, atmospheric and terrestrial) and the emphasis on rapid delivery of data to users. The Data Task Team must define and develop a data system that will ensure the scientific objectives of CLIVAR are met; no small task and one which requires vision as well as an understanding of the modular yet global nature of the programme. The committee was given a comprehensive guide through the acronym-maze of relevant international climate research programmes and their data management activities, because it is clear that CLIVAR will not exist in isolation but will draw on the expertise and facilities of its companion programmes. As the Task Team defines the objectives of the CLIVAR data system and outlines a model of how it may function, they will draw on their extensive expertise to outline the data streams that make up the CLIVAR data resource. CLIVAR-type observations are already being taken and clearly some tracking of such activities needs to begin straight away before the data system is fully operational.

A list of the DPC terms of reference and members can be found at http://www.soc.soton.ac.uk/OTHERS/woceipo/coms.html. Details of the CLIVAR Data Task Team can be found at http://www.dkrz.de/clivar/data.html

The Atlantic Water Inflow to the Nordic Seas

*Bogi Hansen and Karin M. H. Larsen, Fisheries Laboratory, Faroe Islands;
Svein Østerhus, Geophysical Institute, Norway; Bill Turrell, Marine Laboratory,
Scotland; and Steingrìmur Jónsson, Marine Research Institute and University of
Akureyri, Iceland. bogihan@frs.fo*

The inflow of Atlantic Water to the Nordic Seas (Norwegian Sea, Iceland Sea, Greenland Sea) across the Greenland-Scotland Ridge is of major importance both for the regional climate of the area through its heat import and for the global thermohaline circulation through its import of water and salt to the regions of deep and intermediate water formation. The inflow occurs through three branches (Fig. 1), but previously only the weakest of these, the inflow west of Iceland, has been systematically monitored by current measurements.

The "Nordic WOCE" programme was established as a joint Nordic component of WOCE which focused on the exchanges across the Greenland-Scotland Ridge. One of the main aims of the programme was to measure fluxes of water, heat and salt in the Atlantic inflow. The field phase of the Nordic WOCE programme was finished in mid-1997, but the equipment acquired within the programme has been used within the MAST-funded VEINS (Variability of Exchanges In the Northern Seas) project in a continuing study with similar objectives.

Velocity and water mass observations

The Iceland-Scotland region is a heavily fished area. This has severely limited previous observational efforts to measure the fluxes over the Greenland-Scotland Ridge.

The Nordic WOCE programme therefore has relied upon Acoustic Doppler Current Profilers (ADCPs) which may be moored at depths below the intensive fishery or in protected frames on the bottom while still being able to measure velocity profiles covering most of the Atlantic water layer.

As part of the programme, ADCPs have been moored at 8 semi-permanent sites on two sections that cross the two main branches of Atlantic water inflow (Fig. 2). Over the Scottish slope region, our own observations have been supplemented by ADCP data obtained from the North-western Approaches Group through a data exchange agreement.

In addition to the moored equipment, CTD-observations have been carried out by research vessels from the Faroese Fisheries Laboratory and the Marine Laboratory in Aberdeen at least four times a year. Fig. 3 shows the average salinity distribution on the two sections together with typical velocity distributions indicating cores over the slopes.

Flux calculations

To estimate the Atlantic water flux through the Iceland-Scotland Gap, each of the two sections in Fig. 3 was divided into boxes, each of which was assigned typical
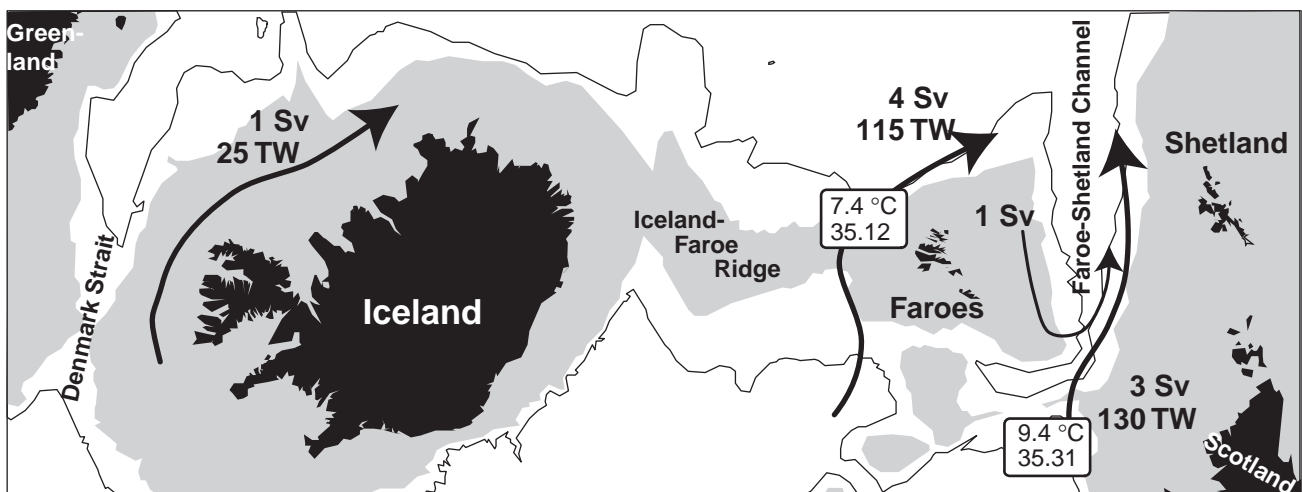
Figure 1. The Greenland-Scotland Ridge separates the Nordic Seas from the North Atlantic and the rest of the World Ocean. Areas shallower than 500 m are lightly shaded. The three Atlantic water inflow branches are indicated by arrows with indication (rounded values) of the flux of Atlantic water (in Sv = 10^6 m^3 s^{-1}) and heat (in TW = 10^{12} W, relative to 0°C) in each branch together with typical temperature and salinity of the water transported. About 1 Sv from the Iceland-Faroes inflow recirculates into the Faroe-Shetland Channel and joins the flow along the Scottish slope.
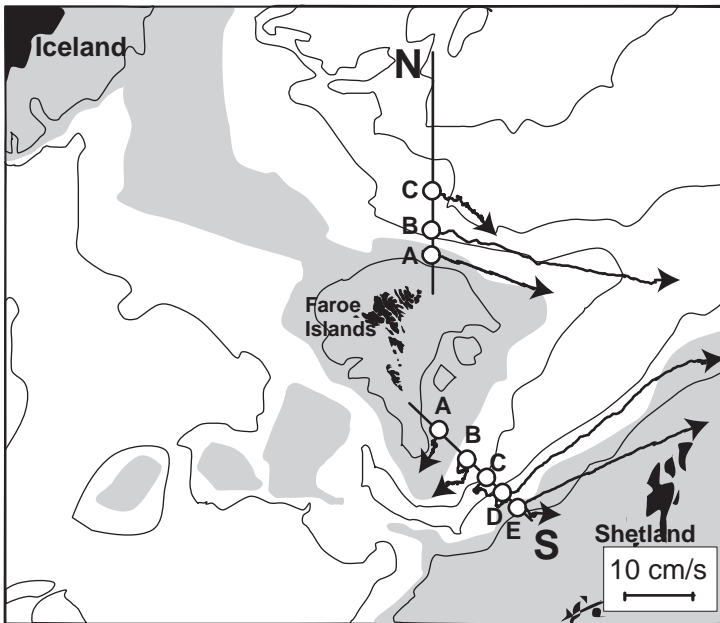
Figure 2. The 8 Nordic WOCE ADCP mooring sites for measuring Atlantic water inflow are marked by circles on the two black lines indicating standard sections N (North) and S (South). The traces going out from the mooring sites are progressive vector diagrams for one deployment at each site adjusted for deployment length (4 to 12 months) to indicate velocity in the scale shown in the lower right-hand corner.

values for temperature, salinity, and velocity perpendicular to the section as determined from the observations. The content of Atlantic water in each box was determined from temperature and salinity by assuming the water to be a mixture of three water masses: Atlantic water (T>7°C, S>35.1), Deep water (T<0.5°C, S=34.9), and more shallow water from the East Icelandic Current (T=2.5°C, S<34.85). From this, the total flux of Atlantic water, its heat flux, average temperature and salinity may be determined by summing all the boxes.

The results of the flux calculations have been added to Fig. 1 and they indicate that the Iceland-Faroe branch (the Faroe Current) dominates in transporting water while the Faroe-Shetland inflow dominates in terms of heat and salt flux.

Budgets

In addition to the Iceland-Scotland inflow, Fig. 1 includes the inflow west of Iceland, based on Kristmannsson (1998). This gives a total Atlantic water inflow to the Nordic Seas around 8 Sv with a total heat flux around 270 TW (1 TW = 10^{12} W). These estimates are preliminary, awaiting more detailed analysis of the co-variation between the temperature and velocity fields and between different branches of the inflow as well as additional data being acquired in the ongoing VEINS programme. They are slightly lower than but not inconsistent with Worthington's (1970) conjecture.
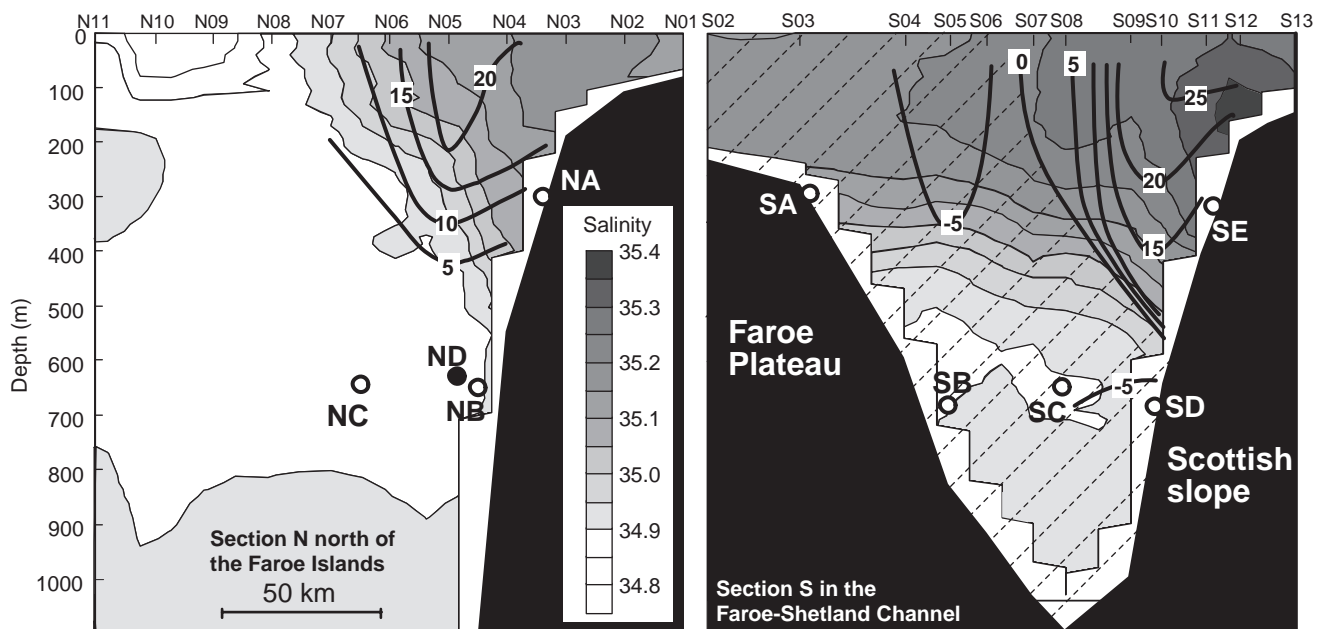
Figure 3. Salinity and velocity on section N and S (Fig. 2). The shading indicates average salinities from 8 CTD cruises on section N and 19 cruises on section S. Thick lines indicate typical velocity perpendicular to the section in cm/sec, positive towards the east (section N) or northeast (section S) based on ADCP observations in the period 1995–1998. Hatched area on section S (right) indicates negative flow (towards the south-west). Quasi-permanent ADCP sites are indicated by open circles. Black circle indicates a special ADCP deployment (ND) from November 1997 to June 1998.
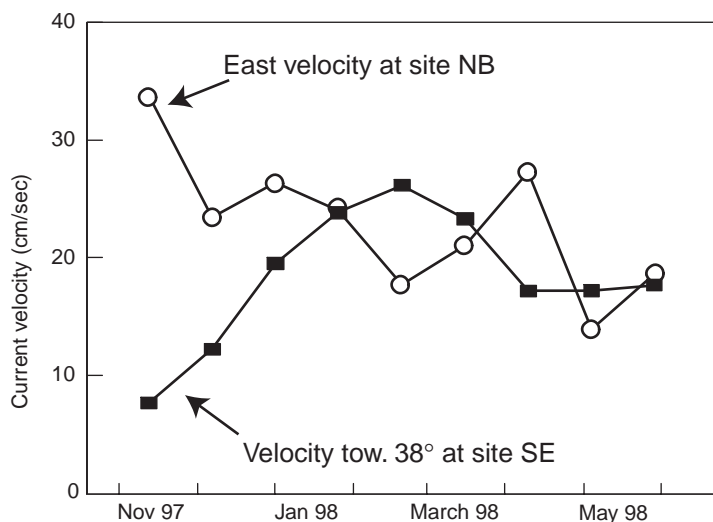
Figure 4. Current velocities at 200 m depth at sites NB and SE (Fig. 3), averaged over 25 days, measured simultaneously in the period 30 October 1997 to 11 June 1998.

Including a Bering Strait inflow around 1 Sv (Roach et al., 1995), a total of 9 Sv are found to enter the Arctic Mediterranean (Nordic Seas + Arctic Ocean). Two thirds of this inflow, 6 Sv, return to the Atlantic as deep overflow according to the best available evidence (Hansen et al., 1998), leaving about 3 Sv to exit in the upper layers of the East Greenland Current and through the Canadian Archipelago.

The deep overflows are mainly driven by the density distribution set up by the thermohaline processes, forming deep and intermediate water in the Arctic Mediterranean. They require a compensating inflow which apparently dominates the total inflow, indicating that thermohaline processes dominate over direct wind-forcing in driving the Atlantic inflow. The overflows do not appear to vary

greatly on time-scales shorter than a few years (Hansen et al., 1998); but the in- and outflows have to balance on short time-scales (weeks), as noted by Worthington (1970).

If these qualitative arguments are valid, only small variations should be expected in the total Atlantic inflow on monthly time-scales. Fig. 4 shows along-slope current velocity at one site close to the core in each of the two main branches. Both sites do show fairly large monthly (25 days) variations; but there is an indication of a counter-phase relationship in the two branches. These results are therefore not inconsistent with a fairly constant total inflow, but with rapid shifts between the branches, perhaps influenced by wind.

Using simple Ekman dynamics, increased south-westerlies (high NAO index) might be expected to concentrate the inflow more along the continental slope and this may be one explanation for the high correlation found further downstream off the Norwegian coast between NAO and the width of the Atlantic flow (Blindheim et al., submitted). A more rigorous basis for assessing these conclusions is the main focus of the ongoing observational effort.

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The Overflow Through the Faroe Bank Channel

Svein Østerhus, Geophysical Institute, Norway; Bogi Hansen and Regin Kristiansen, Fisheries Laboratory, Faroe Islands; and Peter Lundberg, Stockholm University, Sweden.
svein@gfi.uib.no

The Faroe Bank Channel is more than 200 m deeper than any other passage across the Greenland-Scotland Ridge (Fig. 1). It is therefore the main outlet for the densest overflow of cold water from the Arctic Mediterranean (Nordic Seas + Arctic Ocean) to the North Atlantic and is estimated to carry about one third of the total overflow flux across the ridge (Hansen et al., 1998). Since 1988 the Faroese Fisheries Laboratory has monitored the hydrography of the channel with regular CTD cruises along a standard section south-east of the sill. Since 1995 the

Nordic WOCE and later the VEINS programmes have maintained a 75 kHz ADCP (Acoustic Doppler Current Profiler) mooring in the channel, located on the sill. To study the cross-sectional variation of velocity, an experiment was mounted in 1998 where the long-term ADCP mooring was supplemented by two additional 75 kHz ADCPs, one on either side, on a section crossing the channel during a special deployment period lasting about two months from July to September 1998. This was combined with CTD observations along the ADCP section on three cruises.

Vertical profiles

Fig. 2 shows the average velocity profiles from four ADCP deployments at the central mooring site of the channel covering a period of almost three years as well as a sample temperature profile from that site obtained during the special deployment period. Cold water dominates the deepest 200–300 m of the channel and at the central site this cold water flows north-westwards in a current with average velocities exceeding 1 m/sec in the core, centred about 120 m above the bottom.

Cross-sectional variation

The cross-sectional variation is shown in a velocity section across the channel for the July-September 1998 special deployment period in Fig. 3. This figure shows the high speed core to be located on the south-western side of the channel along the slope of the Faroe Bank. On that side of the channel, the overflow current only extended a little more than 200 m above the sill. On the Faroe side of the channel, the velocities in the bottom core were smaller, but the flow extended much higher onto the slope of the Faroe Plateau. Fig. 3 also shows the temperature distribution
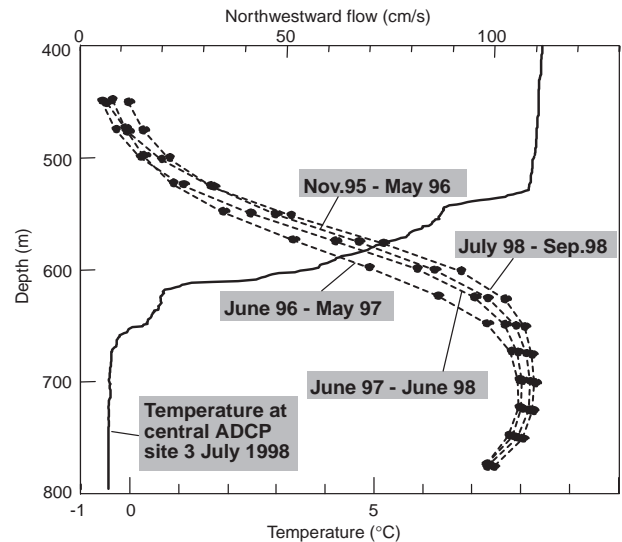
Figure 2. Vectorially averaged velocity profiles along the axis of the channel (towards 304°) for four ADCP deployments in the middle of the Faroe Bank Channel. Each filled circle indicates the average velocity in a 25 m layer (bin) from measurements every 15 or 20 minutes. The continuous curve shows the temperature profile from a CTD cast at this site.

across the channel on one occasion. To a large extent the isotherms followed the velocity field.

Flux calculations

To utilise the long-term observations at the central ADCP site, the flux of the deep water through the channel has been calculated by dividing the cross-sectional area of the channel into a number of boxes, each of which is assumed to have the same along-channel velocity as one of the 25 m bins (depth intervals) measured by the ADCP at the central site. The flux calculations have been done both with horizontal boxes (no cross-sectional variation) and with boxes designed on the basis of Fig. 3.

The total water transport through the depths of the channel is of some interest, but more important is the flux of specific water masses. The water in the cold core may be classified into two different water masses (Hansen et al., 1998): Norwegian Sea Deep Water (NSDW) colder than

Figure 1. Map of the bottom topography (left). Inserted map shows region around the Faroe Bank Channel and ADCP mooring sites indicated by circles. On both maps, areas shallower than 500 m are lightly shaded. Arrows indicate the path of the overflow through the channel. Section below follows the crest of the Greenland-Scotland Ridge along the trace shown on the map.

-0.5°C, and Norwegian Sea Arctic Intermediate Water (NSAIW) between -0.5°C and +0.5°C. In the literature, water colder than 3°C is often termed "Iceland-Scotland Overflow Water" (ISOW).
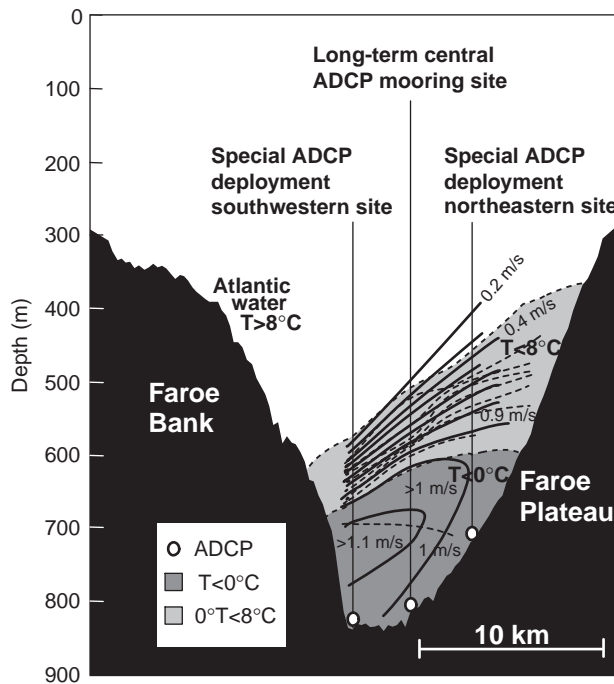

Figure 3. A section across the channel in the sill region with average along-channel velocity distribution (solid lines) from the special deployment period and temperature distribution (dashed lines) from a CTD section obtained at the end of that period. Water colder than 0°C is darkly shaded while water between 0°C and 8°C is more lightly shaded. Circles indicate ADCPs.
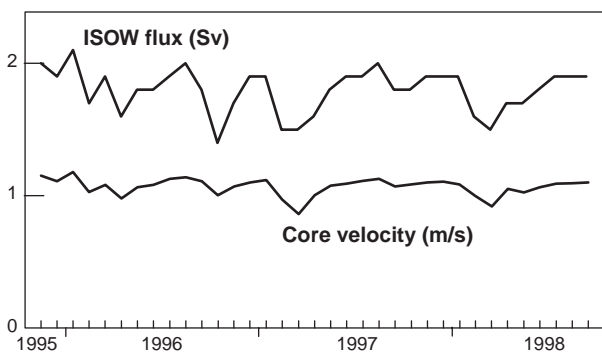
Figure 4. Monthly averaged along-channel velocity at the core, 117 m above the bottom, at the central ADCP site and the volume flux of ISOW water through the Faroe Bank Channel from November 1995 to September 1998 assuming constant cross-sectional velocity variation and temperature field.

The content of each water mass in the boxes associated with each ADCP bin can be determined from the temperature. Figs. 2 and 3 indicate a relationship between the temperature field and the velocity field. Further study is required to clarify on what timescales these two fields co-vary. In this preliminary calculation we have tried both a constant watermass distribution and one that co-varies with the velocity distribution.

Long-term fluxes of the overflow

Using the almost three year long series from the central ADCP site, average fluxes have been calculated to 2.5 Sv for the total volume flux below 450 m depth, 1.9 Sv for ISOW, and 1.5 Sv of water colder than +0.5°C (NSDW + NWSAIW).

These estimates are preliminary, since a detailed analysis of the data sets has not been carried out; but they were not found to depend critically on assumptions of cross-sectional variation or the coupling of the velocity and temperature fields. They are therefore not expected to be drastically revised by the more refined analysis in progress. These estimates are largely consistent with previous, less data intensive, estimates (Borenäs and Lundberg, 1988; Saunders, 1990).

The temporal variation of the core velocity at the central ADCP site and of the transport of Iceland-Scotland Overflow water (ISOW) throughout the period are shown in Fig. 4. On a monthly timescale, fairly large variations are seen, but no systematic seasonal signal is obvious in the data. The figure also has a slight indication of a decreasing trend in ISOW transport. This would be consistent with long-term trends that have been reported for the region (Østerhus and Gammelsrød, in press; Turrell et al., in press) and for the Faroe Bank Channel itself (Hansen and Kristiansen, in press), but as yet the ADCP measurements in the Faroe Bank Channel are of too short duration to allow any conclusions on this important question.

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The Development of Seawater Standards for Dissolved Nutrients

P. S. Ridout, Ocean Scientific International Ltd., UK. paul.ridout@oceanscientific.co.uk

Quality assurance is an essential part of any chemical analysis. The measurement of nutrients in seawater has posed a number of difficulties particularly in terms of matrix interference and calibration. Ocean Scientific International, who produce the IAPSO seawater standards for Practical Salinity, have been working for some years to develop seawater calibration standards for dissolved nutrients. This article describes that development and the current availability of reference materials and standards.

Certified reference materials

The International Council for Exploration of the Seas (ICES) has expressed an urgent need for the development of certified reference seawater for dissolved nutrients. Unfortunately, this expression took place almost a decade ago at the meeting of the IOC-IAEA-UNEP Group of Experts on Standards and Reference Materials (GESREM) and no such material has appeared to date.

A certified reference material (CRM) is a material or substance, one or more properties of which, are sufficiently well established and certified to be used for the calibration of an apparatus. In many laboratories, a CRM is analysed, as a sample, to determine the accuracy of analysis as part of a quality assurance scheme. In the case of nutrients, the ideal CRM would be a natural seawater which has been analysed, by more than one method, for dissolved nutrients, with confidence limits provided for the determinands.

One of the main problems encountered in the production of a CRM, has been the stability of the product. Biological and chemical activity can lead to changes in the nutrient concentrations in short periods of time. Various forms of chemical preservatives have been used which include organic solvents, formalin, potassium cyanide, sodium fluoride, various acids and mercuric chloride (see Kirkwood, 1992).

The use of additives is generally undesirable as it changes the matrix of the reference. In addition, mercuric chloride, the most commonly used poison, is known to degrade the efficiency of the cadmium reduction columns on some nitrate analysers. There are also problems associated with the handling and transport of solutions containing such toxic elements. As a result, some workers have investigated the use of heat as a means of preserving the nutrient concentrations in seawater (Aminot and Kerouel, 1991). Uncertified reference materials have been produced for dissolved nutrients in seawater by the Quasimeme Project (see Topping, 1997). These materials which comprise seawaters, spiked with nutrient salts, are provided as part of a laboratory performance study. The Quasimeme Project preserves mixed nutrients in seawater by autoclaving the samples.

Although reference materials are important in quality assurance, the preparation of working standards is a fundamental component of any chemical analysis. Ocean Scientific International Ltd. (OSIL) studied the feasibility of producing commercially available working standards for nutrients in seawater. A number of products were already available from other sources, but none offered natural seawater matrix at salinity 35.

The need for nutrient standards

The need for seawater nutrient standards has intensified in recent years, with international programmes such as WOCE, requiring high-quality nutrient data to be collected at sea. Most shipboard analyses are carried out using automated chemistry systems which measure nutrients colorimetrically. The kinetics, and often the ultimate colour intensities of the chemistry of these techniques, are generally affected by the presence of seawater matrix salts. Elimination of these salt effects requires that working calibration solutions are prepared in natural low nutrient seawater (LNS) rather than in demineralised water. The WOCE protocol produced by Gordon et al. (1992) stated a preference for the production of working standards in natural low nutrient seawater (LNS), but recognised that artificial seawater may suffice when LNS was unavailable. In continuous-flow analysis, LNS can also be used as a refractive-index blank. This is to correct for a false positive absorbance signal, generated by the refractive effects within the flow cell when saline samples are run with a demineralised water baseline and inter-sample wash.

Low nutrient seawater

The first requirement of a standard for nutrients in seawater, is the seawater matrix itself. It must be significantly lower in nutrients than the required standard concentration. This is particularly difficult for open ocean measurements where analyte levels can be lower than 1_Molar as a result of the surface-water depletion by plankton. Low Nutrient Seawater (LNS) can be prepared naturally or artificially. OSIL regularly collects relatively large quantities of seawater from the mid-Atlantic Ocean for operation of the IAPSO Standard Seawater Service and investigated methods for depleting the nutrient content. Chemical removal, using co-precipitation techniques with iron and aluminium compounds, were found to be effective in terms of nutrient depletion, but the subsequent removal of the precipitate proved difficult and costly. Biological depletion using an inoculum of plankton to create an artificial 'bloom' in the bulk seawater was occasionally successful but was unreliable due to the difficulty in controlling the conditions for growth.

Table 1. Marine Nutrient Standard Kits			
Code	Analyte	Matrix	Concentration (_M)
NSSPO	Phosphate	Deionised Water	100
NSSNI	Nitrite	"	100
NSSNA	Nitrate	"	1000
NSSSI	Silicate	"	1000
LNS	All nutrients	Ocean Water	<1_M S = 35

As a result, OSIL has now standardised on a practice of measuring each batch of bulk seawater for dissolved nutrients and reserving the very low measuring batches for bottling. This LNS has the advantage of being naturally depleted which, combined with our processing/bottling regime, gives rise to a very stable product. The LNS fulfils all the needs of a seawater matrix for the preparation of standards, carrier solution and RI blank.

Standards preparation

Initial attempts to produce 'mixed' nutrient standards in LNS gave rise to the problems of preservation. Although we were able to stabilise the product using mercuric chloride, this was considered undesirable, by many users, for the reasons described earlier. Another problem, which arose, was defining the most useful working concentration of the nutrients. It became obvious that it would be commercially uneconomical to produce the wide range of standards necessary to meet all user needs.

The problems described above led to the production of a range of marine nutrient standard kits (MNSK). These comprise concentrates of single nutrients in deionised water, together with bottles of Low Nutrient Seawater (LNS) - (Table 1).

The user dilutes the concentrate with the LNS to provide working standards. This method overcomes problems of preservative as the concentrates of single nutrients in deionised water and the LNS, are stable for long periods. However, once diluted, the working standards should be used immediately after preparation. The concentrate method also allows the users to define their own working concentration range, thereby overcoming the need for a wide range of products. Although a confidence is given for the nutrient levels in the concentrates and the LNS, the final working standard concentration is dependent on the dilution made by the user.

Performance evaluation

Although our standards may be used as working calibration standards, many laboratories make up their own standards using nutrient salts and incorporate our standards as quality assurance (QA) samples. As a result of user requests, we now offer Performance Evaluation (PE) samples for dissolved nutrients and salinity. These PE samples are supplied, 'unknown', to analysts who include them in a normal analysis run. After analysis, the measured value for each PE sample is forwarded to our laboratory where a certificate is issued showing the true value and the analytical error.

The need for a certified reference material still exists for nutrients in seawater. However data quality for marine nutrients can be improved by the careful selection of standards, carrier solutions and performance evaluation samples. Further information may be obtained by contacting OSIL (paul.ridout@oceanscientific.co.uk).

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United Kingdom.

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