INVESTIGATING OCEAN CLIMATE VARIABILITY: THE NEED FOR SYSTEMATIC HYDROGRAPHIC OBSERVATIONS WITHIN CLIVAR/GOOS

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ABSTRACT *- As the necessity for understanding climate variability is increasingly realised, so too is the need to investigate changes in ocean structure and circulation being recognised. Much of the ocean observing system that is being currently planned, rightly focusses on the upper, seasonally-influenced, 2000 m or so of the water column with little attention given to monitoring the demonstrated deeper variability. A predominantly upper-ocean focus would leave future generations facing a lack of good-quality, global-scale, deep-ocean data against which to test model predictions, measure the rate (if any) of secular change, and learn about the nature of deep-ocean variability and how it responds to and influences the global climate system.*

Ship-based hydrographic sampling is one of the oldest observational techniques in physical oceanography, nevertheless remains as the only means of directly measuring the full suite of ocean water properties at high-vertical resolution over the entire water column and hence deriving accurate estimates of net ocean mass and property transports. Here, a subset of previous studies that used hydrographic measurements to describe and build understanding of ocean climate variability are presented as motivation for a programme of repeated sampling within CLIVAR/GOOS. The paper proposes a similar measurement programme that we believe is feasible, cost-effective and vital to future efforts to understand long-term changes in climate.

1 - THE TECHNIQUE AND THE OBJECTIVES

Ship-based hydrographic sampling is predated only by tidal and surface drift observations as a means of observing ocean physics. Nevertheless, it remains today as the only means of directly measuring the full suite of ocean water properties at high-vertical resolution over the entire deep ocean water column. We believe there is a strong case for exploiting these capabilities in a programme of hydrographic observations to address two main requirements:

- to investigate interannual and longer-term variations in the ocean circulation and associated net property transports and their divergences,
- to quantify net changes in water mass inventories and renewal rates on seasonal to decadal time scales, and explore their relationships to estimated ocean transport divergences and air-sea exchanges.

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The variability at the focus of this research is the result of changing patterns of air-sea exchange of heat, fresh water, and momentum, and the consequential changes in ocean circulation. We also consider the associated changes in biogeochemical cycling in the ocean, and of the exchange of natural and anthropogenic tracers between atmosphere and ocean. Many elements of this variability may provide feedbacks to the atmosphere: some involving coupled ocean-atmosphere modes.

Other observational techniques (moored arrays of traditional current meters and of newly developed profiling instruments - the planned ARGO array [ARGO 98] - and deployments of other autonomous vehicles, and acoustic measurements) will also contribute to these requirements.

Hydrographic measurements have unique characteristics that provide the only way of obtaining:

- the highest presently available accuracy of measurements of temperature (0.001K) and salinity (0.002), permitting detection of small but significant changes in deep and bottom watermass properties, and hence also to serve as reference information for profiling floats,
- samples to determine key chemical constituents, (dissolved oxygen, nutrients and a range of transient tracers such as CFCs and Tritium/Helium) which are sensitive to both changes in ventilation rates and in the strength of the biological pump,
- data that are compatible with previous measurements over the past nearly 100 years, thus providing a homogeneous data set from which change can be unambiguously quantified,
- a global inventory of CO_2 in the ocean necessary for quantifying changes in the rate of anthropogenic CO_2 uptake by the ocean and assessing the accuracy of techniques currently used for estimating anthropogenic CO_2 in the ocean,

and most importantly:

- accurate property transport estimates over large-scales, particularly for heat, fresh water, nutrient and carbon fluxes, for which spatial correlations between velocity and property variations contribute to the net flux over full-ocean depth and at small-spatial scale.

Promised for the future are coupled ocean-atmosphere “forward” simulations and models that will assimilate surface and upper ocean temperature/salinity data. These will diagnose and predict the time-evolving ocean circulation and associated property fluxes. How are we to judge these products during their development? For example, were the upper-ocean network to be in place, would the predicted/diagnosed rate of Upper North Atlantic Deep Water production in the 1990s (a time of great variation in Labrador Sea deep convection) be correct? Would the predicted circulation of this water mass (with its multiple recirculation zones linking the western boundary and interior) be realistic? Will the subsequent net water property exports from the Atlantic associated with this water mass circulation be accurately simulated? In short - How will we know if the models are “good” or “bad” - or more precisely, in what ways will they fail?

To address the need for model verification, as well as to support basic research into the mechanisms of climate variability including the time-scales of the oceans’ response to anomalies in forcing (e.g. link from atmosphere to mixed layer; from mixed layer to ocean interior (subduction); from interior back to surface ocean), we strongly recommend that a programme of repeat hydrographic sampling constitute part of any integrated ocean observing system.

The international Climate Variability and Predictability Study (CLIVAR) Initial Implementation Plan [WCRP 98] highlighted the relevance of sustained hydrographic observations particularly as contributions to the study of decadal-to-centennial climate variability both regionally and globally, and hence also to the detection and attribution of anthropogenic climate change. Countries are now starting to implement such measurements within the framework of CLIVAR.

We believe the programme we propose here belongs at least initially as part of the 15-year CLIVAR research study of WCRP and indeed it incorporates measurements proposed in the CLIVAR Initial Implementation Plan. However it is clearly also a contributor to GOOS, particularly as we move towards a time where these repeat sections will become operational agency activities while still maintaining the high data quality standards. Certainly active participation of the operational agencies is key to sustaining the measurement programme over long time.

To demonstrate how such data will be of use in future, we summarize below some of the significant results that have derived from hydrographic sampling. They highlight scientific questions to be addressed within CLIVAR/GOOS. Following this overview, we outline a feasible and practical hydrographic sampling programme.

2 - PREVIOUS MEASUREMENTS

2.1 - Oceanic fluxes

As is now widely understood, the oceans and atmosphere jointly move heat from low- to high-latitude in response to the differential radiational heating at the top of the atmosphere. Interestingly, recent analysis of radiation and atmospheric model data by Keith [Keit 95] shows a near equipartitioning of the total meridional heat flux between sensible heat transport in the ocean, sensible heat transport in the atmosphere, and the meridional transport of latent heat (water vapour flux in the atmosphere balanced by fresh water transport in the ocean. See figure 2 of Bryden and Imawaki [Bryd 00]. Thus both fluids have comparable and interdependent roles in balancing the earth’s radiation exchange with space.

The oceans’ contribution to the global heat flux scheme has been estimated as follows: from the residual of the radiation budget and atmospheric flux estimates (e.g. [Tren 94]), through integration of estimated air-sea exchanges e.g. [Jose 99]), and by “direct” calculation of ocean velocity times temperature on ocean sections (e.g. [Brya 62]; [Hall 82]). Thus a principal application for transocean hydrographic section data is the analysis of ocean circulation and the diagnosis of the associated water property fluxes.

Bryden and Imawaki [Bryd 00] and Wijffels [Wijf 00] review present understanding of ocean heat and fresh water fluxes respectively. Although initially viewed with great scepticism (particularly by meteorologists), the direct method has proven to yield far more certain flux estimates (smaller error bars) than other techniques. Moreover, from an oceanographic perspective, co-analysis of the circulation and the fluxes yields information about the mechanisms responsible for the fluxes: water mass modification by air-sea exchange and mixing, overturning (thermohaline) circulations, horizontal (wind-driven) gyre circulations, and Ekman circulations. These are fundamental processes which need to be realistically simulated by ocean models.

Due to the great difference in temperatures above and below the thermocline, estimates of ocean heat flux are relatively insensitive to temperature variations in the abyss (e.g. [Hall 82]). This is particularly true for the Pacific. However, the spatial distributions of other water properties (nutrients and carbon being cases in point) are more structured. Accurate estimation of property fluxes other than heat requires good knowledge of the full-depth circulation and properties. Indeed, the flux divergences of dissolved silica and carbon in the Pacific and Indian Oceans, for example, involve small residuals between northward bottom water and southward deep water transports. Small error in the transport of either water mass can dominate the flux estimate.

One major limitation today on direct ocean flux estimates involves variability in the baroclinic structure of the ocean. A single section occupation may depart from the time-averaged field due to density variability on a host of time scales ranging from ageostrophic internal wave displacements through mesoscale and seasonal variations to interannual, decadal and longer changes. This variability raises two sampling issues:

- collecting sufficient realisations of the density field to accurately quantify the time-averaged circulation and associated property fluxes

- collecting sufficient realisations to quantify the time-varying circulation and associated fluxes

2.2 - The exploration of variability

2.2.1 - General issues and the Pacific Ocean

The World Ocean Circulation Experiment (WOCE) [WCRP 88] programme between 1990 and 1998, together with regional studies in the Nordic Seas and Arctic ocean, the Mediterranean, the Southern Ocean and in continental shelf regions have produced an unprecedented, high-quality, global set of physical and chemical oceanographic observations that characterise much of the ocean in the 1990s. This data set complements previous basin-wide surveys such as those of the International Geophysical Year taken around 1960 and other occasional high-quality trans-oceanic sections from as long ago as the surveys of the FS Meteor in the 1920s [Wüst 64]. In some cases WOCE reoccupied previous sections and these repeated measurements have enabled multi-year changes in temperature and salinity to be documented. The changes measured were of significant magnitude and large horizontal and vertical extent. These are summarised by Dickson et al [Dick 00].

Of those repeated ocean sections, only the lines occupied by Japanese Meteorological Agency scientists in the western Pacific (e.g. [Qiu 92]), and short cross-equatorial lines done NOAA scientists (lately in support of the TAO mooring programme: e.g. [John 99]) have been done over sufficient time and frequency to unambiguously address interannual circulation variability. Other notable, though shorter-term and/or temporally-irregular repeat hydrographic section work has been done across the Antarctic Circumpolar Current (e.g. [Whit 80]; [Rint 97]), in the Northeast Pacific (e.g. [Free 97]) and across the N. Atlantic at 24°N [Bari 99] and 48°N [Kolt 99]. These latter programmes in particular hint at interesting changes in the baroclinic circulation and property fluxes, though they are too short and/or temporally sparse to accurately quantify the dominant time scales of the variability. In the following sections we explore this decadal scale variability at greater length.

2.2.2 - North Atlantic

The 48°N sections in the North Atlantic show that at all depths, significant and systematic changes in water properties have occurred within the last decade. The seven repeats of the section demonstrate that the boundary current systems, both off the oceanic shelves and on either flank of the mid-Atlantic ridge, are rapid conduits for signals from the water mass formation regions further north. On slower time scales, these boundary current regions communicate with the ocean interior. The resultant large-scale changes in the T/S-properties below the pycnocline contribute to significant changes in the integral heat content on the section. Koltermann et al. [Kolt 99] find significant change in net meridional transport of individual water masses across 24°, 36° as well as 48°N in the Atlantic when comparing 1957-58, 1981-82 and 1992-93. At 48°N they report a variation in meridional heat flux from less than 0.3 to more than 0.6 pW. Based on 4 transoceanic sections at 24°N and seasonal climatologies based on these and other hydrographic data, Baringer and Molinari [Bari 99] suggest a 30% seasonal variation in interior baroclinic heat flux (largely confined to the westernmost third of the basin). It remains to be determined how these circulation and flux changes relate to the time-varying air-sea exchanges over the North Atlantic.

Evolution of the Labrador Sea Water (LSW) has been described thanks primarily to the time series at Ocean Station Bravo [Lazi 80], [Lazi 95]. Relationships between subpolar deep convection and air-sea fluxes have been identified, with decadal variations of LSW properties being well correlated to the North Atlantic Oscillation [Dick 96]. More speculative but nevertheless most interesting are correlations with tropical Atlantic sea-surface temperature (e.g. [Yang 99]). Recent changes in LSW potential temperature and salinity are dramatic, reaching 0.86°C and 0.09 (PSS-78), between 1000 and 1500 dbar. Local changes over the 3500-m water column from 1966 to 1992 are equivalent to a continuous cooling of 8 W/m^2 and the addition of 6 m of fresh water [Dick 96]. The LSW contributes to the North Atlantic Deep Water (NADW) that flows south in a deep western boundary current as part of the global thermohaline circulation. The southward spread of the altered LSW is linked to the theta-S, circulation, and property flux variability observed on repeat hydrographic sections in the North Atlantic Ocean [Bryd 96]; [Joyc 99]; [Kolt 99].

2.2.3 - The Arctic

The inflow of Atlantic Water into the Arctic Ocean represents the northernmost extension of the poleward flow of warm waters. During that northward flow, the warm waters are transformed to colder, denser water masses – as they are exposed to the atmosphere. This heat in turn helps drive the atmosphere.

Though it seems strange to call the Atlantic waters entering the Arctic "warm" at 3°C, they do represent the main heat source for the Arctic Ocean [Aaga 75]; [Vowi 70]. Reports of a dramatic temperature increase in the Arctic's Atlantic Water layer over the last decade by Quadfasel et al. [Quad 91], Anderson et al. [Ande 94], Carmack et al. [Carm 97], Morrison et al. [Morr 98] and Mikhaelevsky et al. [Mikh 99] based on hydrographic station data, and possible thinning of the sea ice cover [McPh 98] hint of major climate change. Is this a manifestation of climate change, or of a natural switch between Arctic circulation regimes as Proshutinsky and Johnson [Pros 97] suggest?

Lacking detailed knowledge of the causes and amplitude of the Atlantic Waters' natural variability, no definitive statements or predictions of the future climatic state are possible. It is clear however that a large increase in the ice-free areas of the Arctic resulting from changes in watermass properties represents a dramatic change to the high-latitude system the documentation of which needs to be continued.

2.2.4 - Southern Ocean and southern hemisphere oceans

By comparing hydrographic data from the middle-late 1960s with WOCE sections from the late 1980s and early 1990s, researchers have found that Subantarctic Mode Water (SAMW) and Antarctic Intermediate Water (AAIW) have freshened on isopycnal surfaces in the Tasman Sea, South Indian Ocean and Southwest Pacific [Bind 94], [Bind 99]; [John 97]. Changes within the SAMW are comparable in magnitude to those in the LSW, which is perhaps not surprising since both water masses are formed by convection at high latitudes and spread equatorward to ventilate the base of the subtropical thermocline. Despite the apparent cooling on isopycnal surfaces, the observations also show warming on isobaric surfaces, consistent with warming and/or freshening in the high-latitude ventilation regions where SAMW and AAIW are formed [Chur 91]. Similar freshening is found near the salinity minimum of North Pacific Intermediate Water, while the Pacific subtropical salinity maxima in both hemispheres have intensified [Wong 99]. Together these changes suggest an increase in the strength of the hydrological cycle, possibly in response to increases in atmospheric greenhouse gas concentrations. However, the two decade interval between the hydrographic measurements allows other interpretations (e.g., aliased interannual variability due to the Antarctic Circumpolar wave; [Whit 96] or longer time-scale oscillations; [Zhan 97].

Antarctic Bottom Water (AABW) is ventilated at various locations around Antarctica, effectively sequestering for long time CO_2 (and other compounds) in the deep sea. (This contrasts with subtropical thermocline ventilation that is largely responsible for short-term sequestration). The cold, fresh AABW mixes with warmer, saltier NADW in the Southern Ocean, creating Lower Circumpolar Water (LCPW) that then spreads north in the Atlantic, Pacific and Indian Oceans as part of the global thermohaline circulation. In the Atlantic, changes in bottom water temperature in the Argentine Basin [Cole 96] and the Vema Channel [Zenk 96] appear to be related to variability in AABW formation [Gord 82]. In the Pacific, LCPW theta-S variability in a northward-flowing deep western boundary current has been traced from the Chatham Rise at 43°S to the Samoa Passage at 10S ([John 94]; [John 97]). Ongoing research is directed towards relating these downstream property changes to variations in high-southern-latitude air-sea exchange and AABW production.

2.2.5 - Carbon measurements and anthropogenic change

Coupled models of anthropogenic climate change (e.g. [Wood 99]) are revealing large-scale ocean changes spanning the full water column, including changes in the thermohaline circulation and the storage of heat and freshwater. These ocean changes are an integral component of the response of the coupled atmosphere-ocean climate system to increasing levels of greenhouse gases in the atmosphere, and have significant impact on global and regional climate. Indeed predicted changes in the thermohaline circulation are amongst the most important results coming from models of the anthropogenic climate change. Given the coarse resolution of these models and the resulting known flaws, their predictions cannot be completely reliable. This is especially true of those aspects associated with the delicate balance of processes which control the occurrence of deep ocean convection and bottom water production. Attempts to include a biogeochemical component in modelling the global carbon balance are also still rather primitive. It is largely unknown whether the ocean will continue to absorb excess CO_2 passively through sequestering increased surface equilibrium concentrations or whether there might be changes in sequestration due to the biological pump [Sarm 98].

At present, testing of these predictions and the detection of significant change in the thermohaline circulation can only be undertaken by a programme of repeat sections. For example, the suggested recent changes in ocean heat storage (e.g. the North Atlantic papers noted above), imply thermal expansion of the water column. From the sparse but large-scale observations to date, [Chur 00] argued that the average rate of sea-level rise from thermal expansion over the last few decades is of order 1 mm/yr, about the same rate predicted be recent coupled models of anthropogenic sea-level rise. [Wood 99] state that “A monitoring system based on repeated hydrographic sections in the Labrador Sea and at 24°N, and current meter measurements of the Greenland-Iceland-Scotland overflow and the Cape Farewell boundary current, could provide a means of detection of changes in the thermohaline circulation resulting from greenhouse-gas forcing.” These sections need to be repeated at roughly 5 year intervals to separate the signal of decadal variability from climate change [Baco 98]. Inclusion of transient tracer observations will be extremely valuable for both testing these models and detecting changes in the rate of heat and freshwater storage in the oceans. The ability of coupled models to simulate these decadal variations in heat and freshwater storage is an important element in testing and building confidence in predictions of climate variability and anthropogenic climate change. These observations will be needed in particular to test the next much improved generation of coupled models.

A suite of carbon system parameter measurements made on many of the WOCE (in collaboration with the Joint Global Ocean Flux Study – JGOFS) and some of the pre-WOCE sections is allowing the first observation-based global inventories of anthropogenic CO_2 ocean storage to be constructed. To date, these inventories have been published for the Atlantic [Grub 98] and Indian [Sabi 99] Oceans; similar work is proceeding for the Pacific (Richard Feely, pers. comm., 1999). While the overall averages of carbon uptake agree with model results, there are large regional differences between observations and models owing to model faults ([Grub 98]; [Sabi 99]). In addition to the time-evolving inventories, interior carbon ocean flux estimates (both current and pre-industrial) have now been made in the South Atlantic [Holf 98], helping to understand the changing role of ocean transport in the global carbon cycle, generating regional estimate of carbon flux divergences to relate to air-sea flux estimates, and providing another benchmark for model testing. Data are available for similar estimates in the other oceans, but the calculations have not yet been made.

2.3 - Sampling considerations.

While analyses of sections reoccupied years to decades apart reveal intriguing changes in water properties and baroclinicity, aliasing, wherein short-timescale changes mask longer-term trends are a concern. A companion sampling programme to repeat hydrography that employs expendable temperature probes (XBTs) deployed from commercial vessels has been somewhat more effective than widely separated repeat sections in resolving circulation and heat flux variability in time. These efforts have been particularly effective in the Pacific Ocean where the upper ocean (depths sampled by XBTs) appears largely isolated from flows below the pycnocline. A notable example of this work is [Spri 95] study of upper ocean heat content change in the Tasman Sea in which advective divergence of surface waters was found to be a major contributor to the local ocean heat budget that in turn, was correlated to regional (New Zealand) climate variability. Depth restrictions and lack of salinity and other water property information do limit somewhat the science possible with XBTs (though the expendable CTD does in part address the former). Clearly what is called for are symbiotic sampling programmes involving frequent section occupation with XBTs from volunteer ships and complementary hydrographic work at longer time intervals.

In addition to long-line sampling, a handful of time series stations have been maintained for many years (plus a few recently initiated by WOCE and its companion global programmes). These have been valuable for starting to define seasonal to decadal changes in water column properties, with the more frequently sampled time series stations helping to bridge between times when sections were occupied. A good example of this is the manner in which the Bermuda time series station “S” (32.17°N, 64.50°W) [Joyc 96] has enabled an enhanced interpretation to be made of temporal changes on sections at 24°N [Parr 94] and on 52° and 66°W [Joyc 99].

From the circulation schemes and property distributions emerging from these and other analyses, the basin-scale fluxes of properties within the ocean are being estimated, exchanges between the ocean and atmosphere are being quantified, and the interplay of temporal and spatial variability is being explored. Unarguably, the hydrographic sections are a key element of these analyses and it seems clear that the unique nature of repeated sections and time-series stations gives them high priority for meeting many of the objectives of CLIVAR and GOOS.

3 - SUGGESTED HYDROGRAPHIC SAMPLING STRATEGIES.

3.1 - Monitoring water mass properties and volumes

As we have seen, major modes of ocean variability at seasonal to interannual (and longer) time scales are manifested in changes in the properties and distributions of water masses and variations in the strengths and positions of water mass/gyre boundaries. Information on future changes in the upper ocean will be in part derived from the combination of the ARGO profiling float array and satellite altimetry. We believe occasional basin-scale repeated hydrographic surveys will provide a means to quantify the full-water-column evolution of water masses in time. The resultant temporally-sparse sampling for intermediate and deep waters (below ~2000m) will not match that possible for the upper ocean with profiling float technology. However, changes in the inventories of these deeper water masses generally occur on longer time-scales than those waters that are in more local contact with the atmosphere. Moreover, the pathways of deep water mass movement are so constrained by topography that locations of key monitoring sections can be specified and straightforwardly monitored.

It is proposed that a set of the hydrographic sections, many of them repeats of WOCE Hydrographic Programme sections, be occupied at regionally relevant intervals of between 3 to 10 years to provide broad-scale global coverage of ocean variability. The sampling time interval should allow adequate resolution of the local ventilation time-scales of the water column below the main thermocline, with ARGO attacking the shallower, shorter-timescale variability. Moreover, the hydrographic sections will provide the only real ground truth, beyond pre-deployment calibrations, for ARGO float salinity measurements. Analysis of repeat sections discussed previously demonstrates that there is significant water-mass variability, usually down to intermediate waters, and even to deep and bottom waters in many locations. So in some places a comparison of ARGO-float T-S relations to historical data assuming invariance will be questionable over the entire float profiling range.

Station spacing on the proposed sections should wherever possible approach eddy-resolution (typically 50km but closer over significant topographic features), in order to allow accurate circulation estimates to be made, and to avoid aliasing of eddies and other variability into the climate signal. While such aliasing is less likely for temperature and salinity changes along isopycnals, changes on isobaths are more difficult to determine from sparsely sampled sections [John 97].

In addition to temperature and salinity, oxygen, nutrient, and CO_2 data will be useful for investigating possible biogeochemical variability, both that dependent and independent of the physical oceanography. Transient tracers (in addition to carbon) should be measured on these sections to estimate fluxes for comparison with the upper-ocean programme estimates, to investigate ventilation variability, to document changes in tracer inventories for quantifying variability in water mass formation rates, to assess changes in carbon fluxes and uptake, and by comparison with actual hydrographic time-series, to evaluate current methods of anthropogenic carbon estimation [Grub 96]. These re-occupations should be co-ordinated with other sustained observations, process studies, and modeling activities.

Meridional sections are most useful for separating “gyre wobble” (variations in the strength and location basin-scale circulations) from real volumetric change, and tracking the invasion of newly-created subpolar water masses into the subtropical and tropical gyres. Meridional sections should be occupied in the western basins of all three oceans in both hemispheres. Extension of these sections into the Labrador, Weddell, and Ross Seas is desirable to investigate links between these water-mass formation regions and the deep waters downstream. In the southern hemisphere, intermediate and subpolar mode waters enter the subtropical gyres at the eastern sides of the basins. Meridional sections there, would also be useful, being closer to the sources of these water masses. In addition, an eastern basin meridional section in the North Pacific might be warranted given the width of the basin, as well as the formation of eastern subtropical mode waters there.

Repeated occupation of zonal lines allows detection of variability in the rates, pathways, and properties of deep and intermediate waters carried equatorward from the high latitudes. Ideally, they should be located downstream of the deep and intermediate water formation regions. Significant and recent ventilation of equatorward-flowing deep water is found at high latitudes in the North Atlantic, South Atlantic, South Pacific, and South Indian Oceans. A circumpolar belt of zonal sections between 30°S and 45°S would be most useful for quantifying variability in properties, fluxes, and pathways of these water-masses from the Southern Ocean northward, as well as the return flows of older waters. The possibility of occupying a similar circumpolar section at higher (approx. 60°S) should also be considered to document water property variations as well as to document changes in the meridional currents as they transport newly-formed waters away from the continent.. In the North Atlantic, zonal sections across the major circulation gyres will quantify changes in formation rates (e.g., [Fine 95]) and their impact on the circulation (e.g. [Curr 98]). Common to these lines is the real possibility of change in deep shear, deeper than accessible by present float technology. Although the North Pacific is far removed from deep-water formation sites, deep variability cannot be excluded and still remains to be explored on decadal scales. North Pacific Intermediate Water does exhibit such variability [VanS 93].

The high priority sections that address these sampling issues are shown in Fig. 1 and listed in Table 1. Importantly, the proposed array of profiling floats, fixed time-series stations, and XBT repeat lines with their higher frequency sampling (see below) will be necessary to place the repeat deep hydrographic sections in temporal context. In turn, the full-depth, high-spatial-resolution, extensive water sample data from the repeated sections will constrain/enhance estimates of circulation variability, water mass renewal rates, and property fluxes based on the upper-ocean measurements.

3.2 - Measuring oceanic fluxes

As we have reported, the ocean shares with the atmosphere the task of global-scale redistribution of heat, fresh water and other key variables (including CO_2) in the earth’s climate system. WOCE occupied a number of (generally zonal) hydrographic sections with the intention of determining the oceanic fluxes of heat, chemical tracers, and fresh water. These so called “flux sections” were close to the zero-zonal-wind-stress latitudes in the North and South Pacific and Atlantic Oceans and in the South Indian Ocean, thus minimising uncertainty in the Ekman transport and associated property fluxes. Boundary current arrays of current meters at the western and in some cases eastern ends of each section have provided independent current measurements to determine barotropic transports in shallow regions to which the property transports are sensitive. Synoptic flux calculations have already been carried out on some of the one-time sections, and thanks to the availability of repeated occupations of the North Atlantic line, study of the variability and errors in the flux determination has begun (e.g. [Bari 99]; [Kolt 99]). However, much of the planned repeat sampling was not done during WOCE.

Since the global climate system is likely to be sensitive to any significant changes in these fluxes through changes in the flux divergences between sections, and since we have as yet only a poor understanding of the magnitudes of the variations in fluxes or flux divergences, we thus recommend that:

- flux sections be repeated during CLIVAR and that, as suggested above, these should be re-occupations of lines sampled during WOCE,
- the basic sampling should involve full-depth temperature and salinity measurements at eddy-resolving spacing. Experience in WOCE has shown that direct, absolute velocity measurements can improve the determination of transports and fluxes. Consideration should therefore be given to using ship-mounted and lowered ADCP sensors and accurate navigation systems.
- once every 3-10 years the full suite of water properties should be measured along these heat flux lines as part of the basin-scale surveys to allow inventories and flux estimates for water properties such as CO_2 and nutrients,
- these lines be repeated at intervals chosen to determine interannual and decadal scale changes in oceanic fluxes, and be tied with more frequent sampling networks (e.g. floats, moored instruments, XBT sampling ...) to quantify seasonal and other high-frequency variability. If possible, the occupations of these sections should be co-ordinated to reduce ambiguities in interpretation at basin- and possibly global-scale.

See Fig. 1 and Table 1 for proposed flux lines to be occupied by CLIVAR/GOOS.

3.3 - Monitoring of major choke points and boundary currents

Transport monitoring of the earth’s major current systems is most conveniently carried out either where they pass through bathymetric constrictions or on sections that lie between convenient ports. Repeated occupations of sections across several of the major current systems and boundary regimes have been initiated and we recommend that these be continued. They include sections crossing the Antarctic Circumpolar current, monitoring the Indonesian throughflow and the exchanges between the Atlantic Ocean and both the Mediterranean and Nordic seas, Fig. 1.

Western boundary currents play a major role in determining basin-scale property fluxes and may provide early indications of climate-induced changes in ocean circulation. For this reason, monitoring of these boundary currents is seen as important for CLIVAR. In order to provide frequent measurements of absolute transports, the monitoring will take many forms (moored arrays, electric field measurements, XBTs, ship-mounted ADCP, satellite altimetry). Hydrography is an appropriate contributor to such monitoring activities and is unique in providing evidence of water mass property changes in both the surface boundary currents and their undercurrents. Several boundary currents have been monitored over recent years, and continuation of these programmes will help identify future change, Fig. 1 and Table 1.

3.4 - Time series stations

Despite providing dramatic evidence of ocean change on interannual to multi-decadal time scales (e.g. [Lazi 80], [Lazi 95], [Joyc 96]; [Curr 98]), traditional time-series hydrographic stations constitute a small component of the present ocean observing system. The costs of regularly maintaining a vessel on station are high, and consequently, all but Station M (southern Norwegian Sea: [Øste 96]) of the original rapid-sampling weather ship network have been discontinued. However, measurements at a handful of these original sites (station Bravo in the Central Labrador Sea and Papa in the NE Pacific, for example) [GCOS 97] have been maintained through aperiodic site visits by research vessels. Present sampling frequency ranges from bi-monthly to annually, varying inversely with logistical difficulty of sending a research vessel to the site. As part of WOCE and JGOFS, a few new stations have been initiated in this operation mode (off Hawaii: HOTS, and the Canary Islands: ESTOC, [Llin 94]). The Panulirus station off Bermuda (also known as Station S) that has provided important evidence of long term change has been maintained and enhanced by these programmes. In the equatorial Pacific, short meridional CTD (and now ADCP) sections currently collected to intermediate depth while servicing the TAO moorings constitute time-series sampled at roughly semiannual period starting as early as 1979

Based on the few existing time series records, it can be argued that interannual variability in both physical and biogeochemical properties is universal. The significance of this variability is still being assessed. However for most regions of the oceans, we have no long, well-resolved records to document subsurface property changes on interannual and decadal time scales, let alone trends on century time scales. To better document and understand interannual variability of subsurface ocean properties and change of ocean baroclinicity, we argue that within CLIVAR a global observation network of time-series stations, including the continuation of those already underway, be instituted. Highest priority must be given to maintaining those few stations that presently exist in regions of climatically important ocean variability. General requirements and justifications have been recently published [GCOS 97]. Existing time series stations that we feel should be continued by CLIVAR are indicated on Fig. 1 and Table 1.

Traditionally, time-series stations have been occupied using research vessels to make standard hydrographic casts, but the costs to maintain/constrain such a vessel are prohibitively high. The only practical means to expand the observation network globally seems to be to use autonomous instruments. The recent development of moored profiling CTD systems and self-maneuvering devices including gliders and AUVs now being tested, are likely to relax the logistical constraints on ships and manpower for time-series stations. CLIVAR/GOOS should embrace these technical developments to support the existing measurements as well as implementing new automated time series stations. Cruises to deploy and/or service these instruments offer the opportunity to conduct more comprehensive hydrographic sampling. This traditional sampling will be valuable for sensor calibration purposes, for the collection of biogeochemical and transient tracer data, and to survey about sites to provide a spatial context. New stations should target areas of known water mass formation and modification that are not presently observed. Additionally, stations bracketing major baroclinic currents should be initiated to efficiently investigate variability in baroclinic transport. A white paper discussing a Global program of Eulerian Observatories (GEO) that relies heavily on the new technologies is available at http://uop.whoi.edu/geo.html. The stations that are proposed for CLIVAR/GOOS are also indicated on Fig. 1 and in Table 1.

4 - CLIVAR AND/OR GOOS?

Our understanding of ocean variability on basin scales is still emerging and will be refined over the next decade as historical data are exploited and as coupled ocean atmosphere models begin to identify possible driving mechanisms of large scale ocean variability and the related effects of that variability on climate at regional and global scales. We believe that future research to build knowledge of ocean variability will continue to require scientific scrutiny to ensure the highest possible data quality, ongoing research to refine the techniques for quantifying oceanic property fluxes, the use of multiple observational techniques (including hydrographic sections and stations) to determine the optimum observational strategy. For these reasons, any hydrography programme will sit most comfortable within the remit of CLIVAR (a research programme) rather than GOOS. However there are key aspects of these measurements (e.g the use of hydrographic sections to make CO_2 inventories) that are not identified in the current CLIVAR programme. This calls for developing an umbrella structure to more closely link the future global programmes and optimize the ocean sampling scheme.

5 - ACHIEVABILITY

The programme outlined above appears ambitions, and indeed it will require substantial resources. However, the high value of this activity in addressing pressing climate issues means that many elements of the proposed programme are already incorporated in national plans for CLIVAR (and GOOS) and are therefore in some sense already committed. The co-ordination of observations in order to derive maximum benefit from the occupations of several sections in an ocean basin within a short time frame would naturally be the responsibility of the appropriate CLIVAR Implementation Panel (Atlantic, Pacific/Indian, Southern Ocean).

It should also be borne in mind that while we have in many cases identified particular sections with the achievement of single objectives, each line will contribute to multiple objectives. In similar fashion national scientific priorities may dictate the occupation of sections not identified in this paper. In some cases these may be located to fill “holes” in data coverage. However, until such time as ocean data assimilation techniques are sufficiently advanced in their ability to provide “state estimation” for entire ocean basins, we recommend reoccupation of previously sampled lines in order to minimise ambiguity in the determination of ocean variability.

A summary of the requirements in terms of number of stations suggested for each ocean basin is presented in the tables. Countries that have already indicated interest in or made commitments to the sampling are identified. They show that for the Atlantic ocean almost 70% of the requirements are already “committed” this drops to of order 30% for the Pacific and Southern Oceans and to a small percentage for the Indian Ocean.

These tables should be treated with some caution as we have not been able to contact all potential contributors in the compilation.

6 - OPERATIONAL REQUIREMENTS

Quantification of subtle changes in water properties and circulation dictates sampling with high-accuracy and spatial resolution. Procedures set in place for WOCE regarding the documentation and methodology for achieving the highest possible data quality should be followed wherever possible. These observations would be unique and valuable contribution to CLIVAR/GOOS but such data will also be useful to researchers outside the immediate hydrographic community. This implies the need for a greatly-accelerated data flow as compared to the WOCE Hydrographic Programme. This should initially be achieved the using existing mechanism of TESAC messages submitted to the WMO global telecommunication system. As such these would be an immediate and important contribution to GOOS.

Beyond that the full data sets (following final data processing) need to be made available to researchers and to operational agencies via the data system that CLIVAR is in process of establishing.

7 - SUMMARY

- High quality, full depth hydrography (including measurements of nutrients, transient tracers and CO_2) are an essential component of the CLIVAR research programme and can make a unique contribution to GOOS.

- The primary motivation for such measurements is to enhance our understanding of the climate system and to extend our monitoring of climate change.

- To be of greatest value these measurements should be of high quality and should be collected in such a way that their quality can be assessed.

- An observational strategy based on repeats of previously-occupied trans-ocean sections is best able to document changes in oceanic properties and fluxes.

- The measurements complement other elements of the observing system (ARGO floats, time series stations, boundary current arrays and sections).

- The global hydrography will sit most comfortably within the CLIVAR research programme.

- Rapid delivery of such data to both the operational agencies and to researchers should be a key criterion for the development of the CLIVAR data delivery system.

- A significant fraction of the proposed programme is already included in national plans for contributions to GOOS and CLIVAR.

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We recognise that we may not have included all potential contributions to the proposed measurement programme and that a dialogue needs to be continued with laboratories and agencies involved in these activities.

TABLE 1 - List of recommended long/open-ocean hydrographic sections for CLIVAR/GOOS with country expressing interest/commitment to the sampling where known.

* Number of stations implies 50km spacing (closer over topography).

• Boldface indicates funding applied for or already assured.
Normal type implies expression of interest.

Atlantic Ocean (including Arctic and Nordic seas)

Section	**WOCE Ref**	**Stns in Section***	**Frequency recommended**	**Commitment**	**Country•**
Trans-Arctic	-	70	10 years		
Norway-Greenland 75°N	-	40	Annual	Occasional	**Norway**
Labrador Sea	AR7W	30	Annual	Annual	**Canada**
Greenland-UK	AR7E	30	Annual	2 years	**Germany/** Netherlands
UK-Rockall-Iceland		40	Annual	Annual	**UK**
48°N	A2	75	2-3 year	2-3 year	**Germany**
36°N	A3	130	10 years	10 years	UK
24°N	A5	110	2-4 years	10 years	UK
7.5°N	A6	85			
30°S	A10	120	5-7 years		
40°S	A11	130	5-7 years	10 years	**UK**
20°W (N Atlantic)	A16	130	5-7 years	10 years	**UK**
Cape Farewell-Spain		100	2 years	2 years	**France**
52°W (N Atlantic)		90	5-7 years	10 years	USA
66°W (N Atlantic)		60	5-7 years	10 years	USA
0° (S.Atlantic.)	A13	120	5-7 years		
30°W (S.Atlantic.)	A23	100	5-7 years		
	Total	**1460**			

Pacific Ocean

Section	WOCE Ref	Stns in Section*	Frequency recommended	Commitment	Country•
50°N	P1	120	5-7 years	Occasional	**Canada/ Japan**
24° or 30°N	P3	180	5-7 years		
32° or 43°S	P6/P7	220	5-7 years	5-7 years	**Australia** (West part)
137°E (3°N-30°N)	P9	75	Annually /quarterly	Annually	**Japan**
144°E (Equat-35°N)	P10	85	Annually	Annually	**Japan**
155°E	P11	110	5-7 years		
165°E (3°S – 45/50°N)	P13	100	Annually	Annually	**Japan/ Australia (S)**
170°W (S Pacific)	P15	80	5-7 years		**Australia**
150°W (N Pacific)	P16	280	5-7 years		
110°W	P18	200	5-7 years		
	Total	**1450**			

Indian Ocean

Section	WOCE Ref	Stns in Section*	Frequency recommended	Commitment	Country•
32°S	I5	150	5-7 years		
55°E (Arabia to Antarctic)	I7	200	5-7 years		
95°E (Bangladesh to Antarctic)	I9	130	5-7 years		
Australia-Bali	I10	35	Biannually	5-7 years	**Australia**
	Total	**515**			

Southern Ocean

Section	WOCE Ref	Stns in Section*	Frequency recommended	Commitment	Country•
Drake Passage	S1	30	Annual	Annual	**UK**/Spain
S Africa to Antarctic (0°-20°E)	S2	80	Annual		
Tasmania to Antarctic (115°E)	S3	50	Annual	2 years	**Australia**
Weddell Sea (AA Penins. to 0°	SR4	35	5-7 years		
115°E Australia-Antarctic	I9 (part)	50	Biannually	Biannually	**Australia**
Circumpolar (60°-70°S)	S4	350	10 years		
	Total	**595**			

TABLE 1. B - TIME SERIES STATIONS

Existing stations (upper) to be continued and suggested (lower) new stations

Station	**Position**	**Responsibility**
S/BATS	Bermuda	**Bermuda/U.S.**
Station and line Papa	NE Pacific	**Canada**
Mike	Norwegian Sea	**Norway**
HOTS	Hawaii	**U.S.**
ESTOC	Canary Is	**Spain/Germany**
Bravo	Labrador Sea	**Canada**
Pacific Equatorial sections	165°E, 140°W and 110°W	**U.S.**
Station W	(40°N 70°W)	U.S.?
NE Atlantic	Poss (55°N, 20°W)	U.K./EU?
Weddell Sea	(63°S 50°W)	U.S.?
N.Pacific	Poss (30°N 135°E)	??
SE Pacific	Poss (50°S, 90°W)	??

TABLE 1. C - OCEAN CURRENT MONITORING SECTIONS

Location	**Purpose**	**Method**	**Commitment/ interest**
Florida Strait	Florida current	E-M	**USA**
NY to Bermuda	Gulf Stream	XBT/ADCP	**USA**
East coast US	DWBC	Moorings,hydro	**USA**
E Greenland	Denmark Strait o'flow/ E. Greenland current	Hydro, moorings	**France, Germany**
UK-Greenland Gap	Nordic Sea Exchanges	Hydro,moorings	**Nordic group**
Gibraltar	Med water	Hydro, acoustics	**France**, Germany
Brazil Current	Brazil current	Hydro + ?	
	Agulhas Current	Hydro + ?	
Kuroshio	Kuroshio	Hydro, moorings, altim	**Japan**
Leeuwin Current	Leeuwin current	Hydro +	
E Australia Current	E Australia Current	Hydro +	

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