World Ocean Circulation Experiment

NEWSLETTER

Number 4 May 1987

Features

News from WOCE-IPO

Since the last Newsletter, international planning for WOCE has accelerated. Of particular importance were the Planning Meetings held for Core Projects 1 and 3. The first for Core Project 3 was held at the Royal Society, London on 2-5 September, and was chaired by George Needler and attended by some 50 scientists. It is reported on elsewhere in this Newsletter. The second, addressing Core Project 1 and held in Washington, 10-14 November, was attended by about 70 scientists and was chaired by Carl Wunsch. It will be the subject of an article in the next Newsletter.

New member of the IPO

The IPO is happy to welcome Dr Peter Koltermann of the Deutsches Hydrographisches Institut to its staff. Dr Koltermann is being supported by the WOCE National Committee for the Federal Republic of Germany and is expected to stay at the IPO until 1990.

Additional staff members are being sought from other nations.

The Core Projects remain the central focus of the planning of WOCE and were a major item of discussion at the meeting of the WOCE SSG in Washington 10-14 December. It was decided at that time that the reports of the Planning Meetings for the three Core Projects should be published in the WCP Publication Series as a record of the opinions of the participants in these meetings. Planning of each core project would then be carried on by the working groups that were formed by the SSG. Their membership and terms-of-reference are given below.

The SSG also reviewed progress on the WOCE hydrography and geochemical tracer programme, which had been called the RV WOCE programme. It was decided that the name had been causing problems regarding an understanding of the scope of the programme and it was thus renamed the WOCE Hydrographic Programme, the WHP. In order to address the scientific aspects of collecting the uniform high-quality hydrographic and geochemical tracer data sets required for WOCE, the SSG formed the WHP Planning Committee. Its terms-of-reference and membership are also given below. Consideration is also

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being given as to how best to manage a programme of this size and scope.

The next major step will be the preparation of the first Implementation Plan for WOCE for approval by the SSG at its meeting in November. It will draw heavily on input from the Core Project Working Groups. The Implementation Plan will be presented to nations at an international/intergovernmental meeting to be held in Paris in the fall of 1988. At this time it should be possible to assess whether or not national contributions to WOCE will meet the overall requirements of the international WOCE plan and to identify both areas being adequately addressed and those requiring further resources.

The extent to which WOCE should be involved in programmes to measure the uptake of anthropogenic CO_2 in the oceans has been the subject of discussion within the SSG and the CCCO. It has been agreed in principle that during the WOCE global surveys samples for the measurement of dissolved inorganic carbon and alkalinity will be collected on a non-interference basis during standard hydrographic casts. This should provide a data base against which the future uptake of anthropogenic CO_2 may be measured. The development of the sampling strategy and the analysis of the samples for this programme is being taken to be beyond the scope of WOCE and is being considered by a subcommittee of the CCCO and elsewhere.

The newly constituted working groups are as follows:

Core Project 1 Working Group

Terms-of-Reference:

1. To be responsible to the SSG for the scientific planning for Core Project 1 and to develop plans for its implementation, including contributing to the WOCE Implementation Plan.
2. To consult and cooperate with the working groups for Core Projects 2 and 3, the Numerical Experimentation Group, and those working groups involved with the technical and operational aspects of WOCE on matters of common concern.
3. To keep the Director of the WOCE-IPO informed of significant developments in the planning of Core Project 1. The IPO will supply support staff to the working group to the extent possible.

Members: H. Bryden, A. Clarke (Co-chairman), R. Davis, R. Heath, M. McCartney, J. Merle, Y. Nagata, D. Roemmich, W. Roether, F. Schott, L. Talley (Co-chairman).

Core Project 2 Working Group

Terms-of-Reference:

1. To be responsible to the SSG for the scientific planning for Core Project 2 and to develop plans for its implementation, including contributing to the WOCE Implementation Plan.
2. To consult and cooperate with the working groups for Core Project 1 and 3, the Numerical Experimentation Group, and those working groups involved with the technical and operational aspects of WOCE on matters of common concern.
3. To liaise with international bodies, such as SCAR, that support programmes relevant to WOCE in the Southern Ocean.
4. To keep the Director of the WOCE-IPO informed of significant developments in the planning of Core Project 2. The IPO will supply support staff to the working group to the extent possible.

Members: N. Bagryantsev, J. Crease, A. Gordon (Chairman), P. Killworth, L. Merlivat, W. Nowlin, D. Olbers, A. Piola, W. Roether, A. Sarukhanyan.

Core Project 3 Working Group

Terms-of-Reference:

1. To be responsible to the SSG for the development of a detailed scientific plan and conceptual design for WOCE Core Project 3, The Gyre Dynamics Experiment, including contributing to the WOCE Implementation Plan.
2. To advise the SSG on how best to proceed after completion of the detailed scientific plan for Core Project 3.
3. To consult and cooperate with the working groups for Core Projects 2 and 3, the Numerical Experimentation Group, and those working groups involved with

the technical and operational aspects of WOCE on matters of common concern.
4. To keep the Director of the WOCE-IPO informed of significant developments in the planning of Core Project 1. The IPO will supply support staff to the working group to the extent possible.

Members: A. Clarke, A. Colin de Verdiere, R. Davis, T. McDougall, J. McWilliams (Chairman), R. Pollard, A. Watson.

WOCE Hydrographic Programme Planning Committee

Terms-of-Reference:
1. To be responsible to the SSG for the scientific advice necessary for designing and carrying out the hydrographic-geochemical tracer programmes specified by the WOCE Core Projects.
2. To advise on the accuracy to which measurements should be carried out, the facilities required at sea and on shore, and the capability needed of ships in the programme.
3. To determine the necessary protocols that must be established to carry out the WHP by both dedicated ships and laboratories and national programmes.
4. To advise and consult with the operational arm of the WHP programme on ship scheduling, cruise tracks and the technical aspects of data collection and sample analysis to ensure that the programme is effectively carried out.
5. To advise the SSG whether proposed management structures for the operational aspects of the programme are consistent with the scientific and technical requirements necessary to collect uniform high-quality data sets.

Members: M. Fieux, T. Joyce (Chairman). Y. Nozaki, P. Saunders, R. Weiss, W. Zenk.

George Needler,
WOCE.IPO,
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Wormley, Godalming, Surrey, U.K.

The Core Project 3 Planning Meeting

During 1986 planning meetings were held for each of the WOCE Core Projects. The second of these, for Core Project 3, was held at the Royal Society, London, 2-5 September. Core Project 3, the Gyre Dynamics Experiment, is that part of WOCE that will concentrate on studying the processes which must be better understood if models of decadal climate prediction are to be developed during WOCE. The premise put forward in the Scientific Plan is that by studying certain processes in one ocean basin in sufficient detail it will be possible to make major advances in the modelling of that ocean basin which may be extended to the global ocean.

The basic objective of the meeting was to identify those process studies that should be given priority during WOCE considering WOCE's overall objective of developing and testing models for decadal climate prediction. Since much of the process-oriented physical oceanography being carried out at the present time and foreseen for the future could be argued to have some relevance in this regard, this was clearly not an easy task. The second objective of the meeting was to take a first step towards designing component experiments.

Presentations

The meeting opened with overviews by Peter Rhines, Jurgen Willebrand, and Bill Holland. They reviewed from the theoretical and modelling points-of-view our present understanding of gyre dynamics, the strengths and weaknesses of existing theories and models and the key questions needing investigation. Among the latter were the details of the processes controlling the injection of potential vorticity and water masses into the ocean interior and leading towards their homogenization on isopycnal surfaces as well as the transfer of properties across such surfaces.

To aid discussions several strawman proposals were presented to the meeting. In this regard the North Pacific was discussed by Lynne Talley who reviewed the existing data base and knowledge of the dynamics as a basis for formulating the questions needing to be answered. She then outlined the gyre-scale experiment relying primarily on large-scale surveys to address the issues.

Jim Luyten discussed what is known about the subduction of water masses in the North Atlantic and their changes in properties as they circulate around the gyre, outcrop further to the north, and are once again reintroduced into the interior. He then presented a detailed plan for an experiment to address the initial stages of this process. The general issues of ventilation and subduction were then reviewed by John Woods.

Strawman proposals were also given by Greg Holloway and Breck Owens for the study of gyre-gyre exchange mechanisms and the deep circulation respectively. The latter was to some extent based on considerations of how to test Stommel-Arons type balances in a deep basin. Peter Saunders responded with some comments on this approach.

Two measurement techniques were also presented for consideration. Walter Munk described the latest possibilities for using tomography in gyre scale experiments. Bill Young introduced the possibility of using purposeful tracer releases to study diffusion along and across isopycnal surfaces. Recent successful experiments in small enclosed regions using chemicals that can be detected at extremely low concentrations had renewed interest in this experimental approach. Questions remained as to the appropriate experimental design for their use in the open ocean.

The importance of using neutral surfaces for the analysis of the distribution of various oceanic properties was raised by Trevor McDougall. He showed differences that would arise in the interpretation of potential vorticity and mixing. John Marshall made some unifying remarks concerning the subtropical recirculation, bottom forcing, and gyre exchange.

Working Groups

After the presentations, the meeting was divided into groups to address limited aspects of the meetings objectives. It was decided that the most effective division would be three working groups to examine the processes needing consideration in Core Project 3 in the oceanic surface layer, the ocean interior, and the deep circulation. Several plenary sessions were held to ensure the meeting as a whole was kept informed of the progress and that as comprehensive and uniform approach as possible to the total issues was being reached.

The Working Group on the oceanic Surface Layer, which was chaired by Jim McWilliams, decided there are at least three reasons for carrying out experiments within the Gyre Dynamics Experiment. These are to elucidate particular processes important to the circulation, to assess or calibrate a sparse measurement scheme used globally (Core Projects 1 and 2), and to provide data sets for either forcing models of a limited ocean region or comparing with their solutions. Suggestions were made for experiments for each of these categories.

A pair of process studies might be addressed to the question of convection in winter, one in a subpolar region of deep water formation and one in a subtropical region of mode water formation (for example, 18° water in the North Atlantic). In both cases the experiment should encompass significant spatial inhomogenicity and a full winters cycle. Issues to address would be the patchiness and intermittency of convection, the mass fluxes involved, the fate of the water formed over several months, the preconditioning of the region, surface fluxes during convection, the fraction of water ventilated, and the structure of the small-scale turbulence.

The front between subtropical and subpolar gyres is a region of intense variability and of anomalous fluxes with the atmosphere, between gyres through the meandering and breaking of the surface current, and horizontally and vertically in the vicinity between fronts through secondary circulations. It was identified as needing study. The scale of an experiment would be several hundred kilometres horizontally, several hundred metres vertically and would need to last several months in order to span the principle scales of variability and to obtain representative estimates of mean fluxes.

The processes of ventilation and subsequent restratification and subduction of newly formed water masses requires attention. Experiments already planned for the North Atlantic were noted and it was unclear whether further subduction experiments would be needed in this region or elsewhere.

The estimation of the global surface fluxes of momentum, heat and salt is both difficult and of great importance for WOCE. Although calibration of the estimation procedures will be needed through a variety of local measurements of limited extent, there will also be a need for the more uniform and complete sampling of a full basin in order to take advantage of data averaging and compositing and the constraints of physical budgets.

Similar considerations arise from the need for surface buoyancy and forcing fields for ocean circulation models of a complete ocean basin that will be required for incorporation and comparison with model solutions in substantially more detail than will be available globally from Core Project 1. Other important objectives concern climatological studies of ocean-atmosphere interaction, the seasonal cycle and the exchange between the surface boundary layer and the ocean interior, and the need to bridge the sampling and modelling gap between process studies and the global experiment. The extent of measurements should be at least from the equator to the ice margin in one basin. The resolutions put forward for further consideration were 250 km in the horizontal and 2 months in time.

Lastly, the working group considered the wind-driven, ageostrophic component of velocity that is important in the upper-ocean boundary layer evolution, transport, and exchange with the atmosphere and interior ocean. Its bulk properties (horizontal transport and integrated divergence) should be closely related to the surface wind stress, although this is not well verified. Verification of the space and time-scales over which the theoretical relationship is valid and tests of whether the vertical shear can be adequately modelled and estimated from the global observing system are required.

The Working Group on the Interior Circulation, chaired by Mike McCartney, also faced the question of the balance between gyre-scale and the more traditional localized process-oriented experiments. Also considered was the need to carry out a comprehensive experiment of one ocean gyre in order to determine its dynamics and to provide a base for comparative studies with others.

In order to focus the work, some of the group’s initial discussion concerned the definition of an oceanic gyre. This allowed considerations of intense return flows, western boundary currents and their separation, Sverdrup interiors, cross-gyre exchanges, and the extent of regions of exchange with the surface layers and the deep circulation.

The working group identified six scientific goals for studies of the interior circulation. These are:

1. the need to obtain a complete quantitative description of the general circulation and the property fields of a subtropical gyre for the period of the Gyre Dynamics Experiment;
2. the determination of the varieties and degrees of connectedness between the subtropical gyres and the adjacent tropical, subpolar and deep circulations,
3. the assessment of the seasonality of various elements of the subtropical gyre circulation;
4. the determination of the balances of mass transport, potential vorticity, heat, salt, and tracers in the various physical regimes of the subtropical gyre;
5. the determination of the buoyancy flux and balances and the processes of maintenance of the main thermocline with an understanding of their differences in regions of strong negative buoyancy flux versus weak negative or even positive flux;

6. and the assessment of the roles of bottom roughness and bottom slope in the interior gyre vorticity balance.

To meet the first three of these goals it was agreed that the gyre would need to be surveyed in some detail in order to obtain a data base for mapping the general circulation and the property fields of the subtropical gyre, the deep circulation underneath it and the adjacent parts of the tropical and subpolar circulations. Primary tools would be hydrographic sections and simultaneous reference level calculations using acoustic doppler profilers and floats (surface and deep). The horizontal and vertical resolution of the sections would be such as to resolve the dominant eddy-scales and they would form a net with a maximum 1000 km spacing in the interior and less where pattern scales are much smaller.

Ideally such a grid would be occupied at least four times to get an indication of seasonal changes but this goal could be partially met by occupying some key sections and closed boxes more frequently. In addition, the acquisition of long time series of some selected stations or groups of stations at even greater frequency could help examine the time variability.

The last three of the stated goals concern more the dynamical nature of the interior circulation rather than its overall description. For these goals the gyre survey described above will not be sufficient and more detailed experiments on sub-gyre scales will be necessary. The working group foresaw a series of experiments in smaller "control volumes" designed to examine particular dynamical questions that would involve some number of the measurement tools available. These include floats and drifters of various kinds, detailed hydrography, current meters, pressure gauges, inverted echo sounders, acoustic tomography, satellite altimetry, and purposeful tracers.

The Working Group on the Deep Circulation, chaired by Russ Davis, expressed the opinion that the relative infancy of the theory for the deep circulation dictated a somewhat more descriptive experimental approach than was suitable for the better understood dynamics in and above the thermocline. While experiments could be designed to examine specific processes of the deep circulation, a major goal of the Core Project 3 experiments should be obtaining accurate and well-resolved pictures of the hydrographic, tracer and velocity observations in a well-resolved area that should be large enough to define changes in the deep general circulation but yet small enough that it could be well-sampled.

One of the critical processes needing study is that of topographic form stress that may represent a very significant exchange of momentum with the bottom. Two observation strategies were suggested to directly measure this effect. Firstly, from the measurement of the deep velocity by current meters, say 100 m from the bottom for a year, the average bottom pressure gradient could be estimated from geostrophy and the bottom stress or torque calculated. Secondly, the bottom pressure might be measured by altimeter measurements and a geoid determined on the length scales of the topography combined with hydrographically determined changes of pressure with depth. The need for experiments in a number of dynamically different regions was seen.

Estimates have shown that frictional dissipation of abyssal eddy kinetic energy may remove a significant proportion of the wind energy of subtropical gyres. In addition, the structure of deep boundary currents can also provide important diagnostic information for assessing the adequacy of eddy-resolving ocean circulation models. Thus, studies of the deep currents in various high eddy energy areas are indicated.

Diapycnal mixing remains one of the crucial uncertainties in models of the ocean circulation with results highly dependent on the choice of the diffusion coefficient and it being impossible to use a constant diffusivity and obtain both a realistic thickness for the thermocline and meridional heat flux. Thus, the spatial dependence and parameterization of mixing remains a key question. The working group felt that the possibility now exists that diapycnal mixing may be measurable using a long-term deliberate tracer release. It was noted however that the feasibility and strategy for such an experiment was not clear and that release experiments will not determine the vertical diffusion of active tracers such as temperature and salinity, which affect density, or of potential vorticity. Double-diffusion, cabbeling, the nature of neutral surfaces and the dynamically active role of potential vorticity may be significant. Thus, further studies using purposeful tracers and other techniques for quantifying diapycnal mixing processes were recommended.

The analysis and prediction of property fields on the large-scale also depends on knowledge of the lateral flux by smaller scale motion. The large-scale diffusivity is however fully determined by the single-particle lateral diffusivity which can be estimated from the trajectories of pseudo-Lagrangian floats passing through an area. The floats could also be used to determine the mean flow. No direct additional requirement for descriptions of lateral mixing were identified.

The working group spent considerable effort considering a “well-measured” basin experiment that would directly measure the large-scale balances in order to determine the relative importance of specific processes in eddy-resolving models and the adequacy of parameterizations in those with less resolution. Measurements of the horizontal velocity would be made directly with floats and current meters with vertical shear being provided by hydrography. Float dispersion would be used to bound lateral diffusive transports and purposeful tracers to help determine them in the vertical. The fields of various conservative and non-conservative tracers would be determined and used to infer the vertical velocity.

A potential site for the well-measured basin experiment was identified as the Brazil Basin because of its limited size and eddy activity, strong meridional flow and water mass contrasts, and heat fluxes that reverse with depth. It was noted however that there are logistic and scientific reasons to have the well-measured deep basin underlie any large-scale Core Project 3 measurements, such as were suggested by the other working groups, and that these seemed unlikely to overlie the Brazil Basin. The potential advantages and disadvantages of a separate self-contained deep basin experiment were left unresolved.

Summary

The above can only present an overview of the lively discussions that took place during the Core Project 3 meeting. The report of the meeting will contain more details.

Although much remains to be done to develop a coherent scientific plan for Core Project 3, several elements are emerging. Of these, perhaps the most surprising is the strong emphasis placed by all the working groups on gyre or basin-scale experiments using many of the same tools as will be used for Core Project 1, the Global Description, but in a way as to provide much more detail of the fields being observed. The working groups noted reasons for overlapping coverage of the larger-scale experiments in the surface, interior and deep-ocean but the extent to which overlapping should be an overriding criteria in their location was not resolved. Similarly, the advantages and disadvantages of locating the more traditional limited-area process experiments recommended for Core Project 3 within the basin (or basins) selected for the larger-scale coverage was not determined. It is however clear that reasons for some isolated process experiments will exist.

The problem of choosing a location for the majority of the elements of Core Project 3 was to some extent avoided in order to focus discussions on which processes need to be studied in order to meet the WOCE goals of model development. However, with the exception of the deep Brazil Basin Experiment mentioned above, it was at least implicitly assumed, as it is in the WOCE Scientific Plan, that there are many reasons for locating most of Core Project 3 in the North Atlantic.

Future planning for Core Project 3 was discussed and a Core Project 3 Working Group was formed to carry forward the enthusiasm and ideas expressed. Its terms-of-reference and membership were confirmed by the SSG in December and are referred to elsewhere in this newsletter.

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A Finite Element Approach to the Hydrographic Surveying of an Ocean

At the recent planning meeting for Core Project 3, the Gyre Dynamics Experiment, I gave a brief presentation summarizing the discussions of the working group on the gyre interior. At one point I showed a sketch of a generic subtropical gyre, which included several triangles in which intense experimental efforts would be made. The idea was that these were located in various differing physical regimes of the gyre. From the back of the audience came a comment that it was starting to look like a finite element model. This stuck in my mind, and back at my office while preparing the working group report, I developed the following finite element approach to doing the hydrographic survey work that presumably is a necessary adjunct to the gyre dynamics experiment. It could also find application in the global survey (Core Project 1) and the Southern Ocean Programme (Core Project 2).

A prime goal of the survey will be to collect data at sufficient horizontal resolution to allow the mapping of property fields (including relative dynamic height). The simultaneous collection of acoustic doppler velocity estimates for a surface reference level field adds a new dimension to this survey (maps of absolute dynamic height). It is unlikely that the amount of data required for mapping will be acquired in synoptic fashion. Instead the data will be collected over a period of years. A second goal is to obtain sufficient repeat sampling and even time series to explore seasonality and questions of representativeness of single realizations of sections. In scale these might range from seasonal reoccupation of large areas of the gyre, through even higher frequency repeat surveys of specific control volumes within which specific process experiments are carried out, down to specific station lines and individual stations at which we try to determine the average field.

The classic approach to such an extended survey has been to make long lines of hydrographic stations, continent to continent (or island). This approach (which I certainly have used myself!) generally has the features of logistical efficiency through minimization of deadhead steaming, and of being able to add some overall mass balance constraint to the budgeting for the section. The usages of an individual section seem relatively straightforward, particularly if the section is eddy-resolving. Things become more difficult when sections from different times are combined, for example for mapping or estimating flux divergence. You find yourself rejecting (or otherwise contouring through) points near the intersections of sections. You wonder in the end how much of the map is a contouring of spatial differences and not temporal differences. Using the various control volumes defined by the net of sections, the non-synopticity limits the application of powerful integral constraints due to the uncertainty of the storage term inside the box.

The alternate approach is to build the net of sections piecewise from individually synoptic control volume elements. For the present purpose I will use triangular elements and the generic rectangular subtropical ocean used for the gyre dynamics experiment discussions. The grid would be distorted (conformally mapped if you will) to “fit” the geometry (including bathymetry) of a particular real ocean, including a variable scale to the elements used in various regions reflecting the scale of the synoptic general circulation field. First I will describe using triangles in efficient combination to give a synoptic survey element doable in 30 days. Second I will describe using a gyre filling set of these synoptic elements to produce a non-synoptic picture of the gyre that is actually a mosaic of synoptic “tiles”. Last I will describe a multiple ship approach that allows complete local synopticity to the resultant maps, although as a whole the field remains non-synoptic.

For illustration I will suppose that the basic survey plan includes a section net composed of zonal lines at latitudes

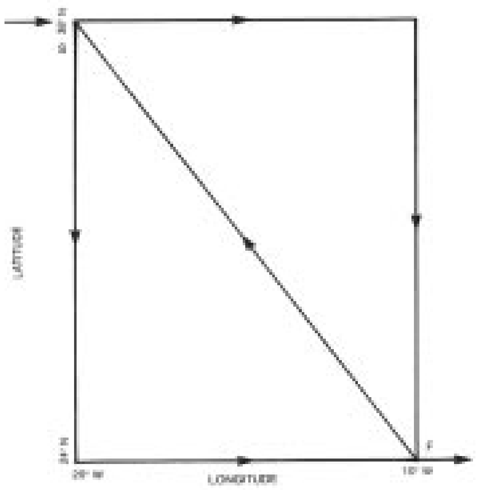

Figure 1. Rectangular survey element formed from two synoptic triangles. At 10 knots, with 30 nm station spacing along the track, and at 3 hours per station it will take 28 days from start (S) to finish (F).

of 12°, 24°, 36° and 48° and meridional lines at intervals of about 10° longitude. The basic triangles will then have north-south sides of 720 nm, and east-west sides ranging from 587 nm at 120 to 401 nm at 480 (for which I use a rough average of about 500 nm. Two contiguous triangles (Figure 1) then form a convenient single cruise leg: 3300 nm of steaming distance taking about 14 days at 10 knots, with about 110 full water column stations at 30 nm spacing, taking 14 days at 3 hours per station, for a total of 28 days. Two control volumes are thus obtained, with maximum synopticity since the diagonal leg is the last leg of the first triangle and first leg of the second triangle. This should allow the most effective combining of the hydrographic and acoustic doppler measurements through exercising the powerful constraint of mass conservation for each triangle (Joyce et al., 1986). The diagonal could be either of the two possibilities, with the selection depending on the expected pattern of the general circulation and the bottom topography, as well as practical matters like steaming distances to ports. The diagonal would be the most sensible line for deploying floats to maximize their impact on the subsequent interpretation of this pair of triangles.

An example of a generic ocean surveyed by this method is shown in Figure 2, using a longitudinal width of 70° (a narrow ocean like the North Atlantic). The 42 triangles thus indicated would require about 585 ship days exclusive of the time needed to steam to and from the triangles (which presumably would be put to some good use like XBT's or float launching - things that don't require much additional ship time). There would be about 2310 stations, separated into 21 synoptic "tiles", from which a non-synoptic mosaic can be constructed. Each of the four zonal and eight meridional sections is non-synoptic, but a composite of non overlapping synoptic segments. Of those twelve sections, all but the four defining the outside of the domain are completely occupied twice. The 12° and 48° sections could be separately repeated, possibly with additional triangles for exploring the connections of the subtropical gyre to the subpolar and tropical circulations. The meridional sections at the ends of the domain would be shallow sections following the shelf break to close the mass balance for these triangles, and are probably logistically easy to repeat if desired. The points where four of the rectangles meet are each occupied from four to eight times (depending on the orientation of the diagonals). Thus the basic survey

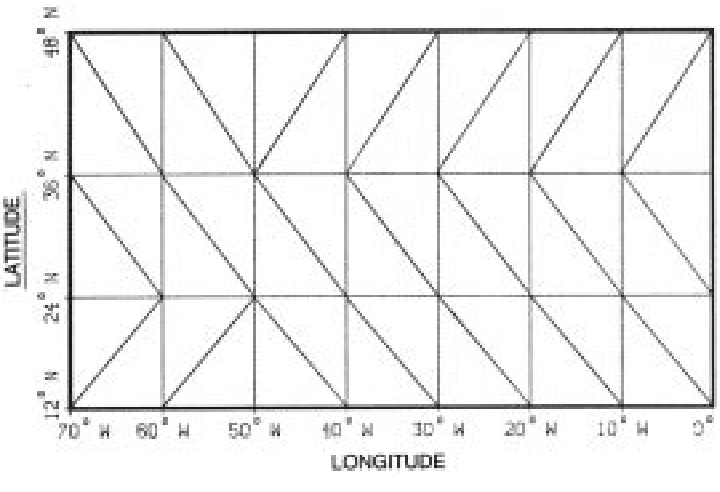

Figure 2. The mosaic of synoptic tiles that results from surveying a generic subtropical gyre with one ship using the survey element shown in Figure 1. The individual meridians of longitude and parallels of latitude in the interior are sampled twice. The survey represents about 2310 stations and about 585 ship days exclusive of steaming time to and from port stops. Each rectangle is synoptic, but adjacent triangles may be displaced in time.

achieves a good start at the repeat sampling and time series that the overall programme will require.

What I like the most about this approach besides the impact on the control volume constraints on the combining of the geostrophic shear with the acoustic doppler measurements, is the notion of synoptic tiles in a mosaic map. All the non-synopticity of the data collapses onto the boundaries between contiguous sampling rectangles; isopleths in one rectangle intersect the shared boundary at different locations than the same isopleths in the other triangle. This doesn't get smeared throughout the domain as it does in physically overlapping data sets.

There will be locations where it is deemed desirable to achieve more repeat sampling or time series occupations of sections or stations than this survey alone will provide. One sensible way to approach this would be to repeat sample some of the individual tiles of the survey mosaic. This might be to look at seasonal or interannual variability, or to determine the long term mean, or because a mesoscale process experiment is being done within the control volume.

There are other variations on this approach that are intriguing. Here is one. Have the three zonal swaths be made by three ships in parallel operations, so that each 10° longitude width meridional band is synoptic, and as the ships progress zonally across the ocean, local synopticity is attained since successive bands are at roughly one month intervals. The entire map would then be synoptic snapshots as before, but contiguous rectangles would join much more smoothly, since all adjacent data would be close in time, even though the entire survey would take $^{2}/_{3}$ rds of a year to complete. In this three ship mode, there probably is no point in doing the repeat occupations of the common boundaries of the rectangles. Instead, both diagonals are occupied, to provide even more contour control inside the rectangles. Figure 3 shows a modified one month survey element for the three ships (the "extra" leg assigned to the poleward ship, where the convergence of meridians shortens the distances needed to produce the 12° x 10° grid). If there were any more than a couple of weeks break scheduled between successive longitude

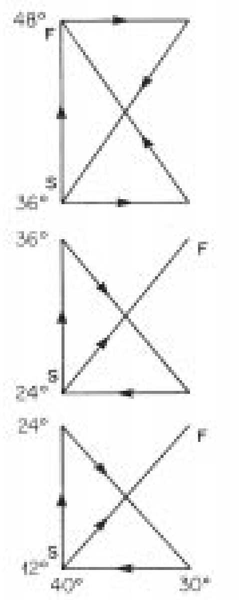

Figure 3. Rectangular survey elements for three ships operating in concert to synoptically survey a meridional swath, and march progressively across an ocean. Each swath represents about 316 stations and would take about 28 days to complete.

bands, then the open side of each rectangle should be occupied to synoptically close the system. The time to complete the 70° wide ocean in this three ship mode is 560 days (taking 187 days to do with three ships doing the work), again exclusive of the time to steam to and from port. Figure 4 shows the arrangement of the 2284 stations that this survey involves for the 70° wide ocean. This survey does not have the repeat occupations that the first plan achieves, but the extra diagonals give a better spatial resolution in compensation.

An example of an intermediate design phase for such a survey technique applied to the North Atlantic is shown in Figure 5. It has been presumed that even though the focus is on the subtropical gyre, some level of surveying will be made in the adjacent segments of the tropical and subpolar gyres. The dense sampling grid of 12° x 10° has been used, with the three ship swath mode for the subtropical regime and the single ship mode for the high and low latitudes. In this intermediate stage the basic grid has been distorted at the basin edges to better "fit" the ocean shape. Cruise legs that would be shortened by the intersection with the continental shelves, have had their length restored to the nominal month by adding extra crossings of the boundaries (all estimated assuming the shallow stations along the shelf break take only a half hour). The next iteration might include additional crossings of the Gulf Stream system between Cape Hatteras and Bermuda to achieve more complete coverage of the recirculation system. It also certainly would involve further distortion to conform better to the large scale bottom topography. Further alterations would reflect island and other port locations, and the minimization of deadhead steaming distances. Another approach might be to rearrange so as to have the "diagonals" line up with satellite orbit ground tracks, if actual coincidence of altimeter and hydrographic/acoustic doppler data sets were deemed important.

The author welcomes comments on the tradeoffs between the classic long lines approach and the present control volume approach, and examples of either approach applied to specific oceans or basins. To return to my original motivation, which is the ocean survey for the Gyre Dynamics Experiment, the next step would be to select several control volumes in different dynamical regimes that would be repeat sampled and be the sites of more intensive process/dynamic experiments.

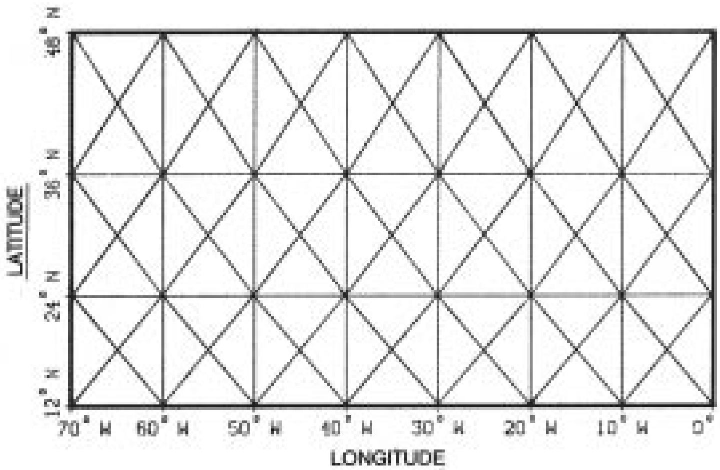

Figure 4. The mosaic of synoptic tiles that results from surveying a generic subtropical gyre with three ships marching progressively across an ocean using the survey elements shown in Figure 3. The survey represents about 2284 stations and about 560 ship days exclusive of steaming time to and from port stops.

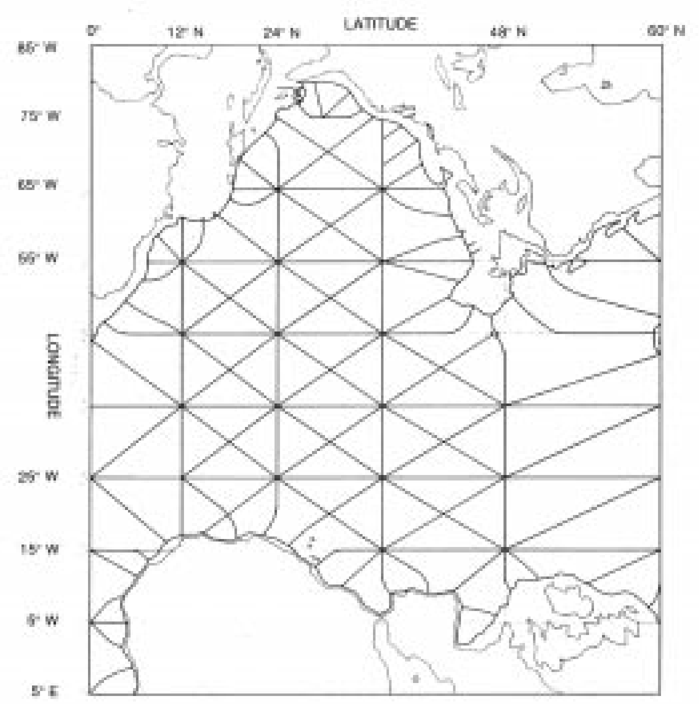

Figure 5. An intermediate design stage for the mosaic survey of the North Atlantic. Survey elements intersecting the continents are closed by steaming along the 200 meter isobath. Intersecting tracks at the boundaries have been separated to provide more crossings of the boundary regime and turned to cross the continental shelf at right angles. The complete survey represents on the order of 3400 stations and would take about 830 ship days to complete, exclusive of the steaming time to and from port stops. A final adjustment of tracks could result from minimizing this steaming time, as well as further consideration of the expected circulation fields and the bottom topography.

These might include:

- Western boundary current and recirculation, high transport regime.
- North Atlantic Current bifurcation and subpolar mode water convection.
- North Atlantic Current separation and interaction with Labrador Current and Deep Western Boundary Current.
- Eastern gyre interior.
- Central gyre interior.
- Tropical-subtropical western boundary interaction.

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Global Circulation Studies: The need for data submission and exchange in WOCE

The March 1986 WOCE newsletter presents the reader with an interesting contrast between the data needs of the ocean modelling community and the requirements of observational scientists involved in ocean profiling. In his report of an ad hoc meeting to discuss density profiling Joyce discusses some very important requirements of observational scientists for stable and reliable temperature, salinity, depth and oxygen sensors. In this age of solid state electronics, we sometimes forget that while our electronic profiling systems have evolved dramatically over the past 30 years, they are still lacking in some very fundamental aspects. As pointed out by Joyce there are many basic instrument improvements which can and should be made. Hopefully in these improvements some emphasis will be placed on the development of uniform standards that will allow future ocean profiles, collected by a variety of instruments, to be intermixed and analyzed together. The present variety of sensing systems, while offering competitive improvements, does not ease the intermixing of even basic ocean profile data. The lack of common standards and format, such as were available for bottle station data, has contributed to the general decrease in the global coverage of ocean profiles.

This introduces the dichotomy between the needs of deep ocean profiling, the precise, accurate profiles of high vertical resolution and the needs of the ocean modelling community for comprehensive coverage in time and space. Clearly, with an oceanographic community of the present size it is not reasonable to expect all global measurements to have the levels of accuracy required for water mass studies in the deep ocean. There is an apparent conflict between the need in instrument developments for automated and simple systems that adapt well to use on ships-of-opportunity and the need for more reliable and consistent systems for deep ocean profiling. Only routine measurements made from volunteer platforms have the potential of fulfilling the need for repeated wider spatial and temporal coverage.

Assuming for a moment that both the need for accurate deep profiles and for less accurate but widely distributed ones can and will be met, either by private industry or by the oceanographic community itself, then an even more fundamental problem needs to be addressed. This is the need for investigators to have access to any and all data germane to any particular WOCE study, including both newly collected and historical data. Traditionally oceanographic data exchange has been either by the direct exchange between individual investigators as part of a larger project, or independent agreement. Or by the use of a central data agency where the data have been submitted by the originating investigator.

There are fundamental differences in these two forms of data exchange. While the former is often the more reliable way to receive data of known quality, it is not a generally useful procedure for large amounts of varied data. It would be an exhausting exercise to personally assemble a global XBT or hydrographic data file. It is much more convenient to assume that central data agencies are functioning properly and that such global collections are available upon request. The problems with this assumption are many. Painful past experience has demonstrated that it is difficult, and often impossible, to either submit or receive data from central agencies. Often data carefully edited and prepared cannot be read by the central agency, even when converted to the agency’s format. Data are frequently misplaced. When an investigator has succeeded in getting his data accepted by an agency, he sometimes finds that he cannot independently request these same data and get them back. In requesting data it can be difficult to determine to what stage the data set has been updated and how many more data points might be available but are yet to be converted to the standard format. Upon plotting up the distribution of the data received, one frequently finds that some well known data set is missing.

All of these problems have led many oceanographers to circumvent the national data agencies in acquiring data from and in providing data to other investigators. Oceanographers are generally well-informed by the many coordination meetings, the wide-spread use of computer mail and the continuing emergence of newsletters such as this one for WOCE. Taking advantage of this close communication oceanographers have done amazingly well in locating and exchanging data needed for many different, and often originally unrelated studies. Still this informal system has many frailties that would likely render it inoperative in the expanded need for data exchange dictated by the global aspects of WOCE. Some data collection programmes that are prime candidates for rapid data exchange may not make their data generally available and only route the data to selected requestors. Other data sets may be unknown to an investigator requiring coverage in a certain region or period of time. Data exchange between individual scientists also means that data editing and format conversion must be done either by the data originator or the data user.

For the more extensive data collection programmes envisaged for WOCE, it would be much more convenient if the data could be acquired not from each data originator but rather from a central data agency. This assumes the central agency can perform its function in a reliable manner. With this assumption, fulfilled data agencies will be the appropriate centres for the submission of, and later requests for, all types of oceanographic data. The extensive data tracking procedures being planned for WOCE will make it possible to follow the collection and submission of oceanographic data and for interested investigators to locate and request appropriate measurements.

This all sounds great but requires not only some major changes in the central data agencies but a fundamental change in the way many of us view data exchange and data submission. We must update our attitude and approach to data submission and exchange, be willing to clean up and submit our data to a central agency and to ensure the future disposition of these data by encouraging that all exchanges be made through the central agencies. Timely submission of data will be a necessity as will be its processing and distribution. Some new system needs to be developed to guarantee scientific credit or some other form of acknowledgement for the use of data submitted to a central agency but not yet fully utilized by the originating investigator. In the more routine, monitoring-like programmes the community should acknowledge the initiation and maintenance of the data collection while the data themselves become part of the larger community and aren’t tied up for an extensive period of time by the originating investigators. In this way oceanographers could approach the attitude of the meteorological community to routine weather observations; their value is acknowledged and their collection endorsed but they are not the domain of any single set of scientists.

Only through efforts of this kind can the limited resources of the observational oceanographic community be effectively pooled to approach the global data requirements envisioned in WOCE. A similar global approach to <u>in situ</u> oceanographic observations, is required for their synthesis with satellite sensed observations, which have the primary advantage of global coverage. While specific regional comparisons between <u>in situ</u> and satellite data will be helpful in evaluating the remotely sensed measurements only global combinations of such regional comparisons will be capable of answering the overall questions of accuracy and utility of the satellite observations. This global synthesis has the added benefit of providing the data for use with numerical models.

It seems clear that, if an approach such as is outlined above is not taken by the observational community, the modelling groups will develop their own mechanisms to provide the data sets they need in order to run and evaluate their models. Thus, it is appropriate to consider these issues as we anticipate the substantial increase of data during WOCE.

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Sea Ice Issues related to the WOCE Southern Ocean Programme

The presence of sea ice in the polar oceans has several prominent climatic impacts, making it essential to consider sea ice in any thorough study of polar and global climate. In the Southern Ocean, where a major WOCE effort is directed, sea ice extent ranges from a minimum of approximately 4 x 10^6 square kilometers in February, when the ice is confined largely to portions of the Weddell, Bellingshausen, and Amundsen seas, to a maximum of approximately 20 x 10^6 square kilometers in August and September, when the ice surrounds the Antarctic continent and extends northward to 55-65°S (Figure 1). Both the large amount of wintertime sea ice and the substantial seasonal cycle in the sea ice cover contribute to the impact of the ice on the regional oceanography and meteorology. Of necessity, the planned WOCE efforts in the Southern Ocean include examination of the sea ice cover from both theoretical and observational standpoints. This article identifies several of the important impacts sea ice has on the rest of the climate system, then illustrates how sea ice can be observed from satellites, complementing and extending the much more spatially and temporally limited in-situ field observations, and how it can be examined through numerical modelling.

Climatic Impacts of Sea Ice

Among the most important of the climatic impacts of sea ice is that sea ice serves as a strong insulator, restricting exchanges of heat, mass, and momentum between ocean and atmosphere. In fact, the winter turbulent heat exchanges from the surface to the atmosphere are often reduced by over an order of magnitude, from hundreds to tens of watts per meter squared, as a result of the presence of a sea ice cover; and wind-driven waves are often nearly eliminated, a fact well appreciated by individuals on ships maneuvering in sea ice laden waters.

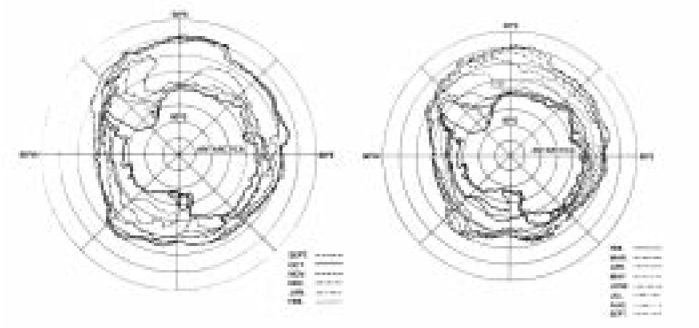

Figure 1. Monthly Southern Ocean ice edge positions, averaged over the four years 1973-1976 from satellite passive microwave data. [From Zwally et al., 1983.]

Maykut (1978) has calculated the effect of sea ice of various thicknesses on the seasonal cycle of sensible and latent heat fluxes from the surface to the atmosphere, using a simple model of heat transport through the ice, along with climatological data on air temperatures and incoming radiation. His results, illustrated in Figure 2, indicate that both sensible and latent heat fluxes are reduced to near 0 when the ice thickness reaches 1 meter or more.

Sea ice also has a strong effect on the surface shortwave albedo, as indicated by the whiteness of the ice cover in contrast to the dark ocean surface. Reasonable albedo estimates for ice-free ocean, bare ice of thickness 1 meter or more, and ice

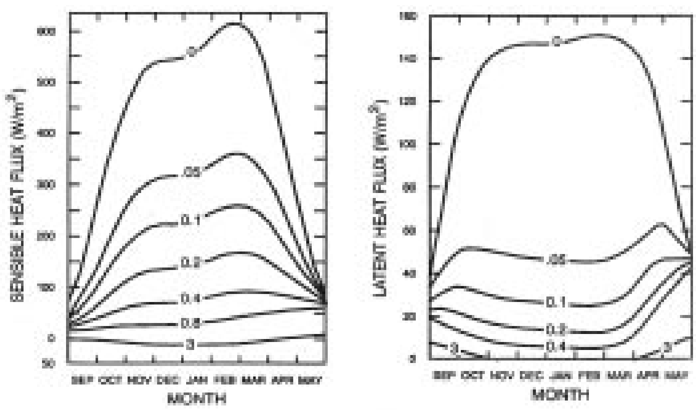

Figure 2. Seasonal variations in the sensible and latent heat fluxes from the surface to the Arctic atmosphere for various sea ice thicknesses (in meters). [Redrawn from Maykut, 1978.]

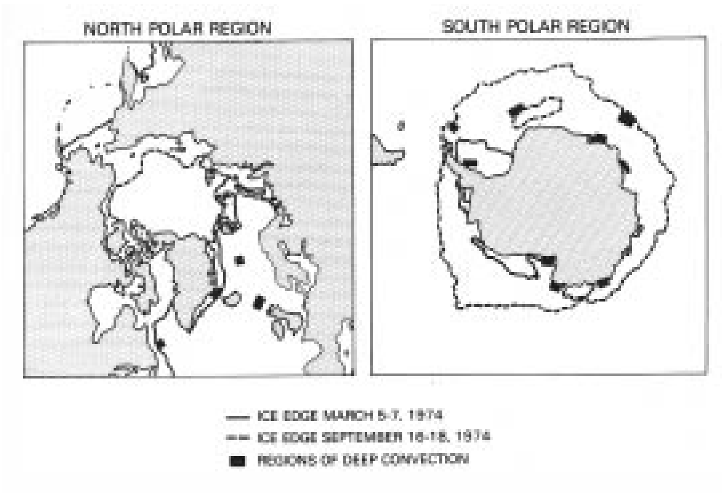

Figure 3. Regions of deep convection from Killworth (1983) replotted onto polar projections along with the ice edge positions on March 5-7, 1974, and September 16-18, 1974, determined from satellite passive microwave data. [From Parkinson, 1985.]

with a fresh snow cover are 5-15%, 70-85%, and 90-98%, respectively. In spring and summer, as melt ponds form on the sea ice or the snow becomes wet and dirty, the albedo of the ice can decrease significantly, toward the much lower open-ocean values.

Another consequence of the existence of sea ice is the downwelling occasionally induced by salt rejection during ice formation and aging. As ice forms and ages, salt rejection tends to increase the density of the oceanic mixed layer directly below the ice. Depending upon the initial local density structure of the ocean, this can lead to a deepening of the mixed layer and at times to deep convection and even bottom water formation. In fact, although observations are limited, it is likely that much of the world's bottom water forms initially in polar latitudes, in the region of the sea ice cover. When plotted on polar projections along with approximate seasonal maximum and minimum ice edge locations (Figure 3), many of the regions of deep convection identified by Killworth (1983) in a paper specifically on deep convection are seen to occur in the vicinity of either the landward or the seaward ice edge. In a study using satellite and in-situ observations to examine coastal polynyas along the Antarctic continent, Cavalieri and Martin (1985) find that the observed shelf water salinity elevations are associated with the average size of nearby coastal polynyas and thereby conclude that these coastal polynyas are the sources of the brine needed for generating the dense Antarctic shelf water, thus contributing to the formation of Antarctic bottom water. Antarctic bottom water in turn has a significant impact on the bottom water of the globe as a whole.

Sea ice also plays an important role in the surface horizontal transports of heat and salt. In particular, the net equatorward flow of the ice away from the Antarctic continent provides an equatorward flow of very cold, relatively fresh water, sometimes referred to as negative heat and salt transports produced by the ice motion. This net equatorward flow (and the associated fact that, on average, the release of energy during ice formation occurs in more poleward latitudes than the absorption of energy during ice melt) has a tendency to reduce regional temperature contrasts.

Satellite Imaging of Sea Ice

Useful imaging of sea ice by satellites has been done with a variety of satellite sensors. Among these are the Multispectral Scanner and Thematic Mapper on the Landsat satellite series, the Very High Resolution Radiometers (VHRRs) and Advanced Very High Resolution Radiometers (AVHRRs) on the NOAA satellite series and on Tiros-N, the Electrically Scanning Microwave Radiometer (ESMR) on Nimbus 5, the Scanning Multichannel Microwave Radiometer (SMMR) on Nimbus 7, and the Synthetic Aperture Radar (SAR) on Seasat. The Landsat sensors, VHRRs, and AVHRRs record in the visible and infrared wavelengths, whereas the ESMR and SMMR are passive microwave sensors, and the SAR is an active microwave sensor.

Each of the instruments mentioned above has various advantages and disadvantages for sea ice observations. For instance, although Landsat images have the advantage of good spatial resolution of approximately 80 meters, allowing individual ice floes to be readily

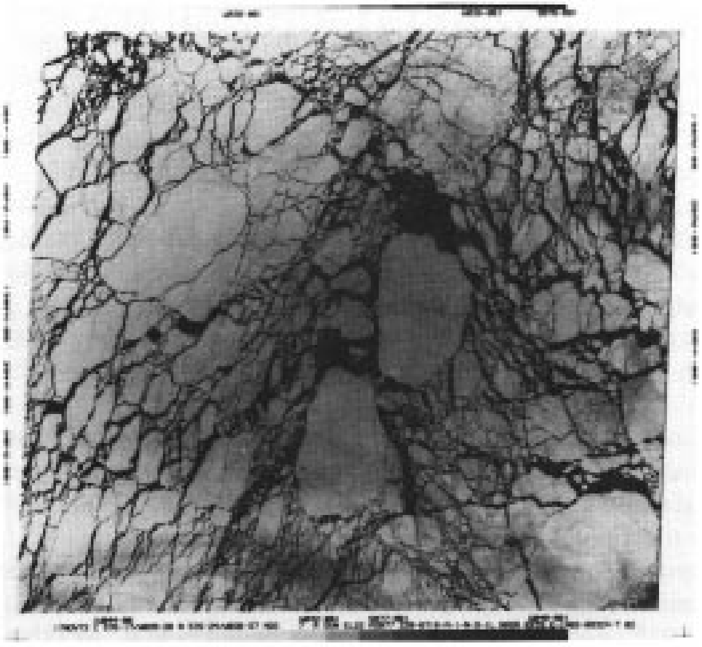

Figure 4. Landsat image of sea ice within the Weddell Sea, November 17, 1973.

distinguished (e.g. Figure 4), they have three major disadvantages relative to the passive microwave images from ESMR and SMMR: Landsat images have much poorer temporal resolution, with repeat orbits coming every 18 days compared to approximately every day for the ESMR and SMMR; they are obscured by cloud; and they are useless during hours or months of darkness. On the other hand, passive microwave data have a much coarser spatial resolution of about 30 kilometers, so that whereas the Landsat images can be used to determine floe shapes and sizes and to track individual ice floes, the passive microwave images cannot. The Seasat SAR data had a resolution of 25-40 meters and, in contrast to Landsat data, were not hindered by cloud or darkness. SAR data revealed details ‘of ice morphology, structural changes, and drift. AVHRR images have a resolution of approximately 1.1 kilometers and are, like the Landsat images, obscured by cloud. The reader is referred to Freden and Gordon (1983), Kidwell (1983), and Fu and Holt (1982) for more details on Landsat, AVHRR, and the Seasat SAR, respectively.

Passive microwave data have major advantages for determining large-scale sea ice conditions and for climate studies. Because of the sharp contrast in microwave emissions between sea ice and open water, microwave data can be used to estimate the areal fraction of sea ice coverage (or sea ice concentration) through a basically linear conversion from microwave brightness temperatures to sea ice concentrations (Zwally et al., 1983). In regions with a mixture of ice types the ice concentration estimates are less accurate than in regions with only one ice type plus open water, because different ice types have different microwave signatures; but in the Southern Ocean most of the ice is believed to have a fairly uniform microwave signature, facilitating the interpretations. With passive microwave data it becomes possible to provide images of sea ice extent and approximate ice concentrations for the entire Southern Ocean (Figures 5 and 6), and to do so on a routine basis, with a frequency of every few days. Such large-scale mapping could not be done with current Landsat, AVHRR, or SAR data. Thus, while the latter sensors can and have been used effectively for detailed local studies, it is passive microwave data which allow the seasonal cycle and interannual variations in the sea ice cover as a whole to be routinely monitored by satellite imagery. Multichannel microwave instruments such as the SMMR have improved the determination of sea ice concentration over that possible from the single-channel ESMR and allow the possibility of determining additional variables such as ice temperature, ice type, snow cover, and surface melting (Cavalieri et al., 1984).

During the intensive observing period for WOCE, in the early 1990s, there should be available visible and infrared data from Landsat and NOAA satellites, passive microwave data from the Special Sensor Microwave Imager (SSMI) on the satellites of the U.S. Defense Meteorological Satellite Program (DMSP), and active microwave data from SARs on the European Space Agency’s Remote Sensing Satellite (ERS-1), the Canadian/U.S. Radarsat, and the Japanese Radar Satellite.

Numerical modelling of Sea Ice

Large-scale numerical modelling of sea ice is generally based on energy balance calculations for simulating ice

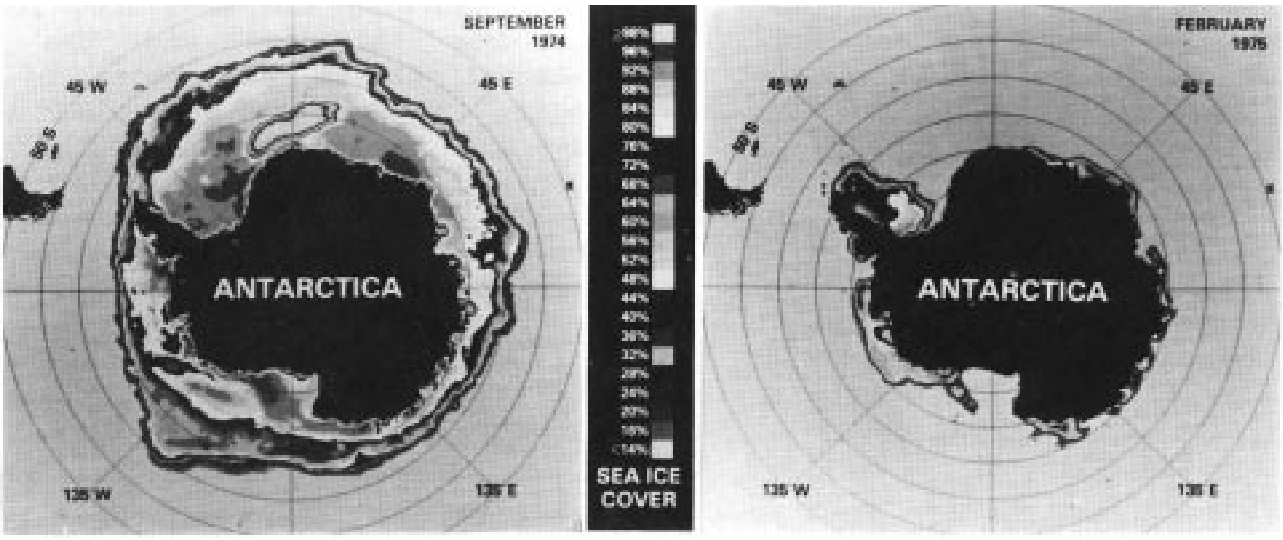

Figure 5. Seasonal extremes in Southern Ocean sea ice cover illustrated by maps of the September 1974 and February 1975 ice concentrations, as determined from data of the Nimbus 5 ESMR. The September image clearly shows a prominent Weddell polynya centered at about 0°E, 67°S. [From Zwally et al., 1983.]

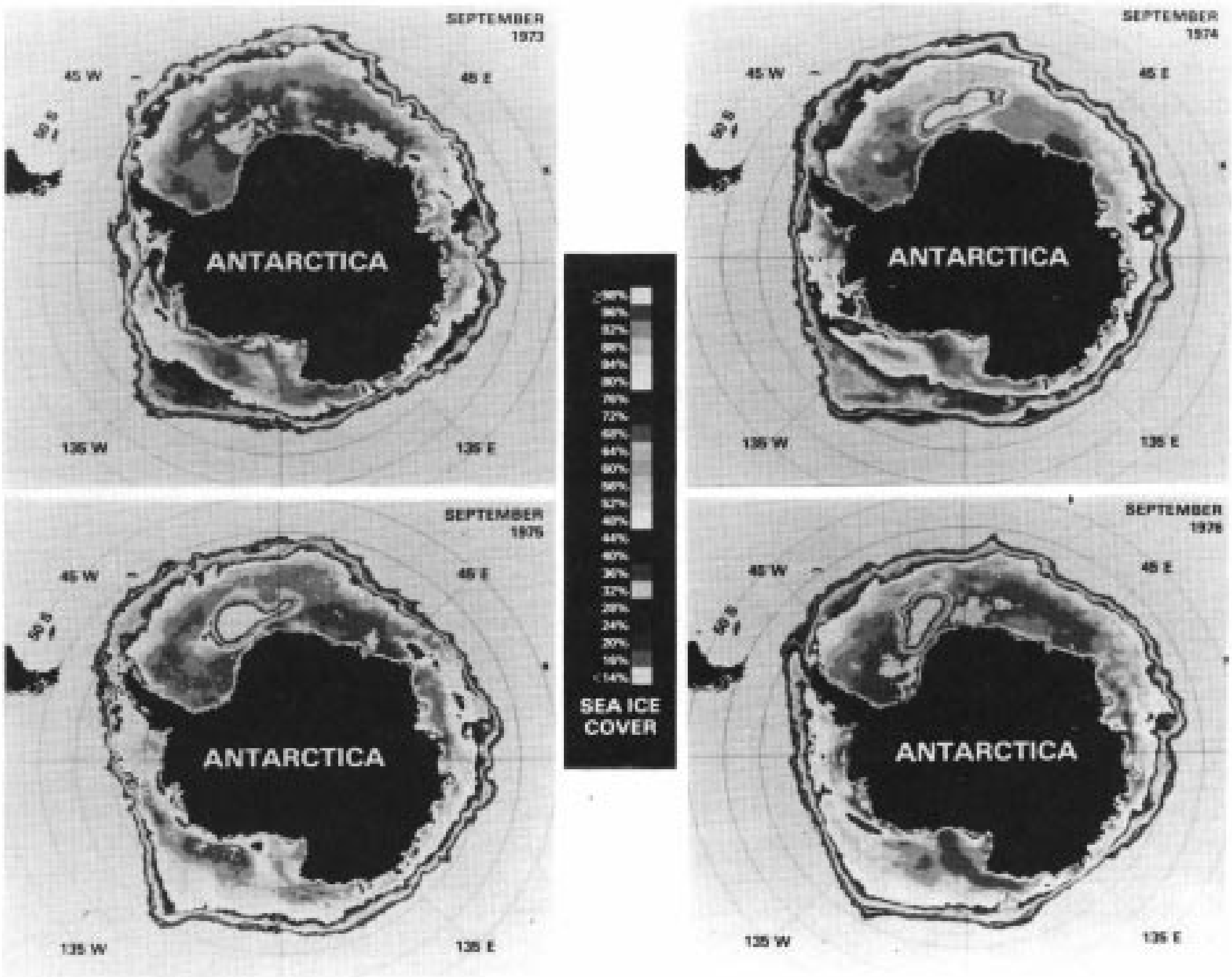

Figure 6. Interannual variations in Southern Ocean sea ice **cover** illustrated by maps of September ice concentrations in 1973, 1974, 1975, and 1976, as determined from data of the Nimbus 5 ESMR. [From Zwally et al., 1983.]

thermodynamics and a momentum balance for simulating ice dynamics. For the thermodynamics, the relevant fluxes at the upper surf ace of the ice (or of the snow if a snow layer overlies the ice) are the incident and reflected solar radiation, the incident and reflected longwave radiation from the atmosphere, the emitted longwave radiation from the ice or snow surface, the sensible and latent heat fluxes, the conductive flux through the ice or snow, and the flux due to surface melting of the ice. At the bottom surface of the ice the relevant fluxes are the oceanic heat flux from the water to the ice, the conductive flux through the ice, and the flux due to melting or freezing at the ice/water interface. Calculations balancing these various energy fluxes allow determination of the temperature and thickness of the ice at each grid square of the model. Details of the calculations for a large-scale, three-dimensional sea ice model and a complete set of formulations for the fluxes can be found in Parkinson and Washington (1979). Maykut and Untersteiner (1971) present a more elaborate but one-dimensional model of the vertical growth and decay of sea ice at an individual point, and this might also prove of value during WOCE, for detailed local sea ice studies.

For simulating ice dynamics, ice motions are generally agreed to be predominantly controlled by five stresses: wind stress from above the ice, water stress from below the ice, and the stresses induced by the Coriolis effect, the dynamic topography (or ocean tilt), and internal ice resistance. These, then, are the five stresses included in the momentum balance. Of the five stresses, the one due to internal ice resistance has probably generated the most controversy amongst sea-ice modellers. The ice has been treated variously with viscous, elastic, plastic, elastic-plastic, or viscous-plastic constitutive equations for use in the ice-resistance term. The reader is referred to Hibler (1979) for a review of some of these treatments and for the details of the ice dynamics calculations using a viscous-plastic approach.

Figure 7 presents bimonthly results from a dynamic/thermodynamic model of the sea ice cover of the entire Southern Ocean, showing the simulated contours of sea ice thickness and the simulated seasonal growth and decay of the ice cover. Few if any other sea ice models have been applied to the Southern Ocean as a whole, but smaller-scale simulations with dynamic/thermodynamic models have been done of the Weddell Sea region. In one, Parkinson (1983) examined the formation of

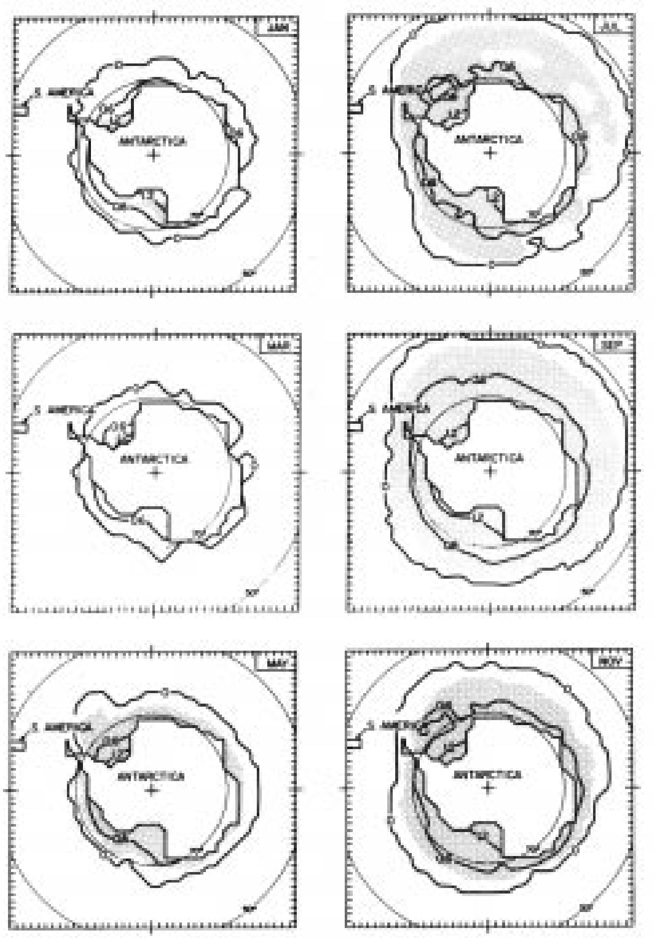

Figure 7. Bimonthly sea ice thickness contours (in meters) simulated with a dynamic/thermodynamic model. Stippling indicates areas with simulated ice concentrations exceeding 90%. [Rearranged from Parkinson and Washington, 1979.]

a simulated Weddell polynya and established that the simulated polynya forms as a result of the wind fields used as input to the model. In the other, results of a set of simulations by Hibler and Ackley (1983) indicate that including ice dynamics in the calculations, which requires considerably more computer time than calculating ice thermodynamics alone, is more important to model results in summer than in winter (Figure 8).

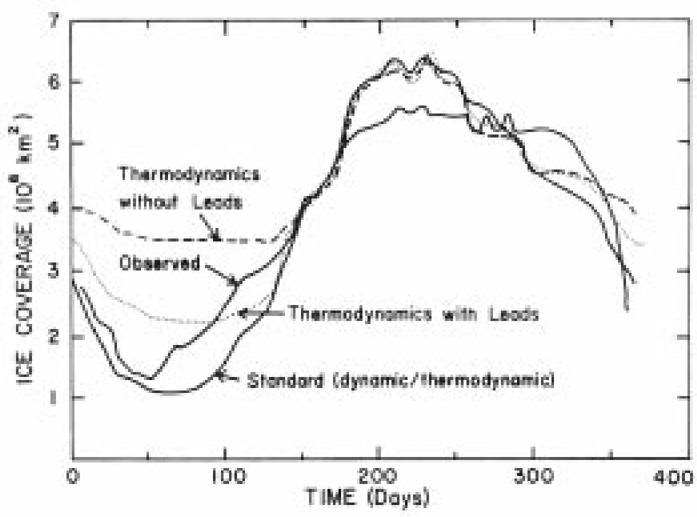

Figure 8. Seasonal cycle of sea ice coverage in the Weddell Sea as observed and as simulated with a dynamic/ thermodynamic numerical model and with the thermodynamics portion of that model. [Redrawn and relabelled from Hibler and Ackley, 1983.]

In the long run it is important to create detailed global models coupling ice, ocean, and atmospheric calculations. Initial attempts in this direction have shown, as expected, that the simulation of sea ice in coupled models is hindered by the various flaws in the calculated ocean and atmospheric fields. For instance, far too little Southern Ocean sea ice is calculated by Washington et al. (1980) due to unrealistically warm atmospheric temperatures. However, coupled calculations are essential in order to simulate the full scope of the interactions between the various climatic components, and consequently the WOCE plans include coupled ocean/ice/atmosphere models. Encouraging results in coupling ice and ocean have been obtained by Hibler and Bryan (1984) in a simulation for the North Atlantic, where they considerably improve the location of the simulated sea ice edge by incorporating into the model warm ocean currents from the south.

Concluding Comments

Sea ice is an important component of the atmosphere/ocean/ice climate system. It can be routinely observed from space through a variety of satellite sensors and it has been modelled numerically with a range of computer models. Although we have learned much about sea ice in the past several decades, much still remains unknown. Important sea-ice-related issues to be examined during WOCE include the determination of heat flux values between ocean and atmosphere and the impact of sea ice on them, the formation and maintenance of coastal and other polynyas, and the impact of the vertical salt flux during sea ice formation, particularly on mixed-layer deepening and bottom-water formation. Each of these will likely involve a combination of in-situ observations, satellite data, and numerical modelling.

References

Cavalieri, D. I., P. Gloersen, and W. J. Campbell, 1984: Determination of sea ice parameters with the Nimbus 7 SMMR, Journal of Geophysical Research, 89, 5355-5369.

Cavalieri, D. J., and S. Martin, 1985: A passive microwave study of polynyas along the Antarctic Wilkes Land coast, Oceanology of the Antarctic Continental Shelf, S. S. Jacobs, ed., Antarctic Research Series 43, American Geophysical Union, Washington, D. C., 227-252.

Freden, S. C., and F. Gordon, Jr., 1983: Landsat satellites, Manual of Remote Sensing, R. N. Colwell, Ed., American Society of Photogrammetry, Falls Church, Virginia, vol.1, 517-570.

Fu, L. L., and B. Holt, 1982: Seasat Views Oceans and Sea Ice with Synthetic Aperture Radar, JPL, Publication 81-120, Jet Propulsion Laboratory, Pasadena, California, 200pp.

Hibler, W. D., III, 1979: A dynamic thermodynamic sea ice model, Journal of Physical Oceanography, 9, 815-846.
Hibler, W. D., III, and S. F. Ackley, 1983: Numerical simulation of the Weddell Sea pack ice, Journal of Geophysical Research, 88, 2873-2887.
Hibler, W. D., III, and K. Bryan, 1984: Ocean circulation: its effects on seasonal sea-ice simulations, Science, 224, 489-492.
Kidwell, K. B., 1983: NOAA Polar Orbiter Data (Tiros-N, NOAA-6, NOAA-7, and NOAA-8) Users' Guide, Satellite Data Services Division special report, National oceanic and Atmospheric Administration, Washington, D. C., 138 pp.
Killworth, P. D., 1983: Deep convection in the world ocean, Reviews of Geophysics and Space Physics, 21, 1-26.
Maykut, G. A., 1978: Energy exchange over young sea ice in the central Arctic, Journal of Geophysical Research, 83, 3646-3658.
Maykut, G. A., and N. Untersteiner, 1971: Some results from a time-dependent thermodynamic model of sea ice, Journal of Geophysical Research, 76, 1550-1575.
Parkinson, C. L., 1983: On the development and cause of the Weddell polynya in a sea ice simulation. Journal of Physical Oceanography, 13, 501-511.
Parkinson, C. L., 1985: Possible sea ice impacts on oceanic deep convection, North Atlantic Deep Water Formation, T. Bennett, W. Broecker, and J. Hansen, eds., NASA Conference Publication 2367, National Aeronautics and Space Administration, Washington, D. C., 39-41.
Parkinson, C. L., and W. M. Washington, 1979: A large-scale numerical model of sea ice, Journal of Geophysical Research, 84, 311-337.
Washington, W. M., A. J. Semtner, Jr., G. A. Meehl, D. J. Knight, and T. A. Mayer, 1980: A general circulation experiment with a coupled atmosphere, ocean and sea ice model, Journal of Physical Oceanography, 10, 1887-1908.
Zwally, H. J., J. C. Comiso, C. L. Parkinson, W. J. Campbell, F. D. Carsey, and P. Gloersen, 1983: Antarctic Sea Ice, 1973-1976: Satellite Passive-Microwave Observations, NASA SP 459, National Aeronautics and Space Administration, Washington, D. C., 206 pp.

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Contributions should not be cited without the agreement of the author.

We hope that colleagues will see this Newsletter as a means of reporting work in progress related to the Goals of WOCE as described in the Scientific Plan. The SSG will use it also to report progress of working groups, and of experiment design and of models.

The editor will be pleased to send copies of the Newsletter to Institutes and Research Scientists with an interest in WOCE or related research.