Intergovernmental Oceanographic Commission
technical series

28

Bruun memorial lectures, 1982

Presented at the twelfth session of the IOC Assembly,
Unesco, Paris, 10 november 1982

Ocean science for the year 2000

Unesco 1984

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For bibliographic purposes this document should be cited as follows:

I.O.C. Bruun Memorial Lectures 1982:
Ocean science for the year 2000.
IOC Tech. Ser. 28, Unesco, 1984.

ISBN 92-3-102307-1

French edition 92-3-202307-5
Spanish edition 92-3-302307-9
Russian edition 92-3-402307-0

Published in 1985
by the United Nations Educational,
Scientific and Cultural Organization,
7, place de Fontenoy, 75700 Paris

Composed by Germinal, Paris
Printed in Unesco's workshops

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Printed in France

N.J. Campbell

Our second guest speaker this afternoon is Dr. Klaus Hasselmann.

Dr. Hasselmann graduated from University of Hamburg in 1955 and received his doctorate at Goöttingen in Fluid Dynamics, 1957.

He carried out extensive physical oceanographic research studies in the United States at the Institute of Geophysics and Planetary of the Scripps Institution of Oceanography from 1962 to 1966. He is regarded by his colleagues as being the man who successfully solved the problem of ocean wave energy balance.

Dr. Hasselmann is presently the Director of the Max Planck Institute for Meteorology in Hamburg, a position which he has held since 1975.

He is the author of numerous research papers on ocean dynamics and ocean atmosphere modelling for climate.

He is a member of a number of meteorological and oceanographic societies, and has been honoured through invitation to numerous marine research institutions throughout the world.

He is the principal author of the physical oceanography and climate section of the FORE report.

Ladies and Gentlemen, please welcome Dr. Klaus Hasselmann.

Physical oceanography, climate and marine forecasting

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Summary

Understanding the role of the oceans in climate has been repeatedly stressed as one of the most urgent priorities of the World Climate Research Programme. An attack on this problem requires a new approach to ocean modelling and a long-term ocean measurement strategy. This in turn must be guided by the models. New techniques for remote sensing of the ocean from satellites could aid significantly in a global ocean measurement strategy. However, an optimal sampling strategy for long-term ocean measurements based on a combined system of conventional instruments and satellites has yet to be defined. The problems are discussed and illustrated with some results from an ocean climate model.

The FORE report

The Anton Bruun lecturers this year have been invited, as section editors of the report on « Future Ocean Research in the year 2000 », to jointly address the problems and challenges which oceanographers may be expected to face in the next two decades. The contents of the FORE report (IOC 1983) have been discussed in various forums, including the General Oceanographic Assembly in Halifax, July 1982. In considering the role of physical oceanography within the FORE context I shall therefore not attempt a comprehensive summary of the views of the report on this subject. I shall limit myself instead to discussing some possible general developments which may be anticipated as a result of expected advances in technology, considering then the implications of these trends for the structure of future research in physical oceanography. The speculative nature and dangers of such extrapolations into the future have been elegantly expressed in the FORE report itself and need not be reiterated here. It may be recalled only that, almost by definition, the most exiting innovations in research are precisely those which cannot be foreseen. Nevertheless, certain lines of progress can be recognized rather clearly already today, and it may be useful to consider ways in which physical oceanographers can prepare themselves for the changes these imply.

A strong thrust of physical oceanography in the coming decades will undoubtedly continue to be directed towards the role of the oceans in climate. Considerable advances in this field may be expected through the advent of global satellite observing systems, together with other technological advances, such as satellite tracked drifting buoys, sonar floats, automatic stations, expendable instruments and acoustic tomography, which together will make it feasible to obtain long-term measurements of many important ocean parameters on a far more expanded scale than has traditionally been possible.

The same technological developments may be expected to have a strong impact also on marine forecasting, a field of physical oceanography which has gained increasing economic significance in recent years. Quasi-synoptic global data on surface winds and ocean waves obtained from satellites will provide a greatly improved data base for short-and medium-range marine weather and wave forecasting, as required for ship routeing, offshore operations, coastal protection, and other applications. On longer time-scales, sea surface temperature (SST), radiation and surface wind data from satellites will similarly yield the required input for monitoring and forecasting large-scale vacillations of the ocean-atmosphere system, such as El Nino and the Southern Oscillation, or variations in local upwelling regions of interest for fisheries.

With respect to the time-scales and physical processes involved, the problem of long-term climate changes and the prediction of shorter term climate vacillations and marine weather appear to be reasonably well separated. However, the problem areas merge when one considers the required observing systems. Essentially the same satellite and instrument systems are needed in both cases. The problems are similarly non-separable with regard to the data analysis. The same sets of fields (surface winds, SST, fluxes through the air-sea interface, tec.) need to be constructed in both cases. It may be noted in this context that for a continuously operating long-term data collection system the real-time data analysis requirement for marine forecasting applies without significant reduction also for longer term climate studies, since the data stream must be processed at the same rate as it is generated if the data is to be fully utilized (a constant divergence between input and output data fluxes implies a constant data sink !). The optimization of a complex, heterogeneous, multi-national global observing system consisting of different satellites and a combination of conventional measurement systems, together with the rapid, efficient analysis of the greatly expanded data streams generated by these systems, will present major scientific and technical challenges to physical oceanographers in the next decades. The task can be successfully tackled only through a close collaboration between physical oceanographers and meteorologists, since both for climate studies and marine forecasting the ocean cannot be regarded as an isolated system, but must be considered as a component of the coupled system ocean-atmosphere.

In the following we summarize briefly the potentials and open problems of some of the ocean satellites and other observing systems which may become available towards the end of this decade.

Oceanographic satellites

A summary of present capabilities of oceanographic satellites is given in the SCOR Working Group 70 Report (Grower 1983). The report lists the various oceanographic satellites currently being considered by different space agencies for possible launch within the next five to eight years. A more extensive discussion of the operating principles of various remote sensing instruments may be found in Stewart (1984). Many of the techniques were first tested in space aboard SEASAT (which unfortunately failed after 100 days'operation in october 1978) and are discussed, for example, in the SEASAT Special Issues I. (1982) and II. (1983) of the *Journal of Geophysical Research.*

Wind and wave sensors

One of the potentially most useful instruments for both climate studies and marine forecasting is the wind scatterometer, as was flown on SEASAT, and is in discussion for several future satellites. Fig. 1. (from O'Brien 1982) shows the coverage which can be typically achieved by a pair of wind scatterometers viewing to both sides of a polar orbiting satellite within a 24-hour period. The swarth width for each scatterometer is approximately 400 km.

The SEASAT scatterometer winds have been compared against accurate wind buoy measure-

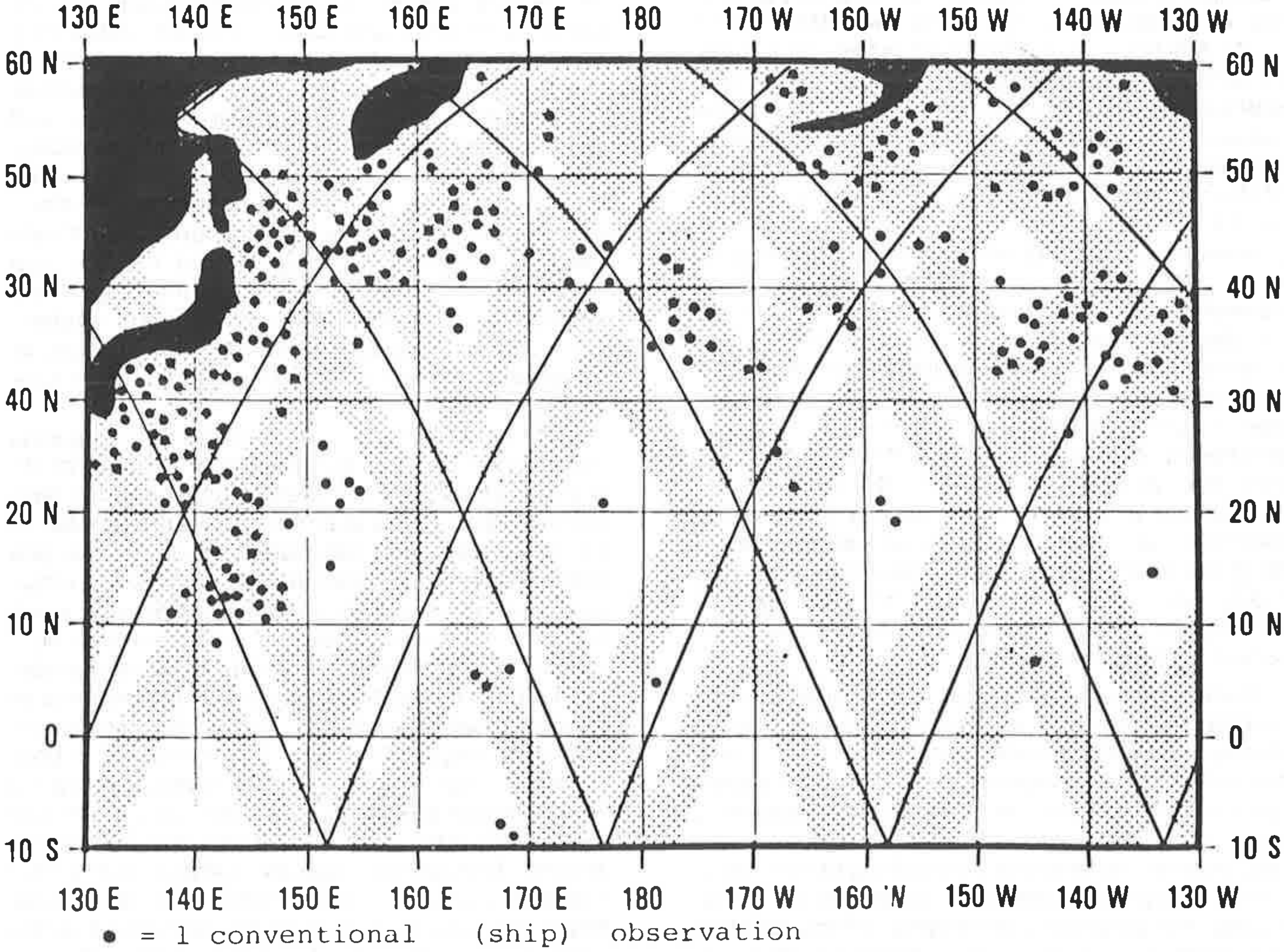


Figure 1. Surface projection of scatterometer data coverage during 24-hour period in North Pacific (from O'Brien 1982).

Figure 2. Comparison of scatterometer wind speeds (upper panel) and wind directions (lower panel) with surface wind measurements in the JASIN experiment (from Jones *et al.* 1981).

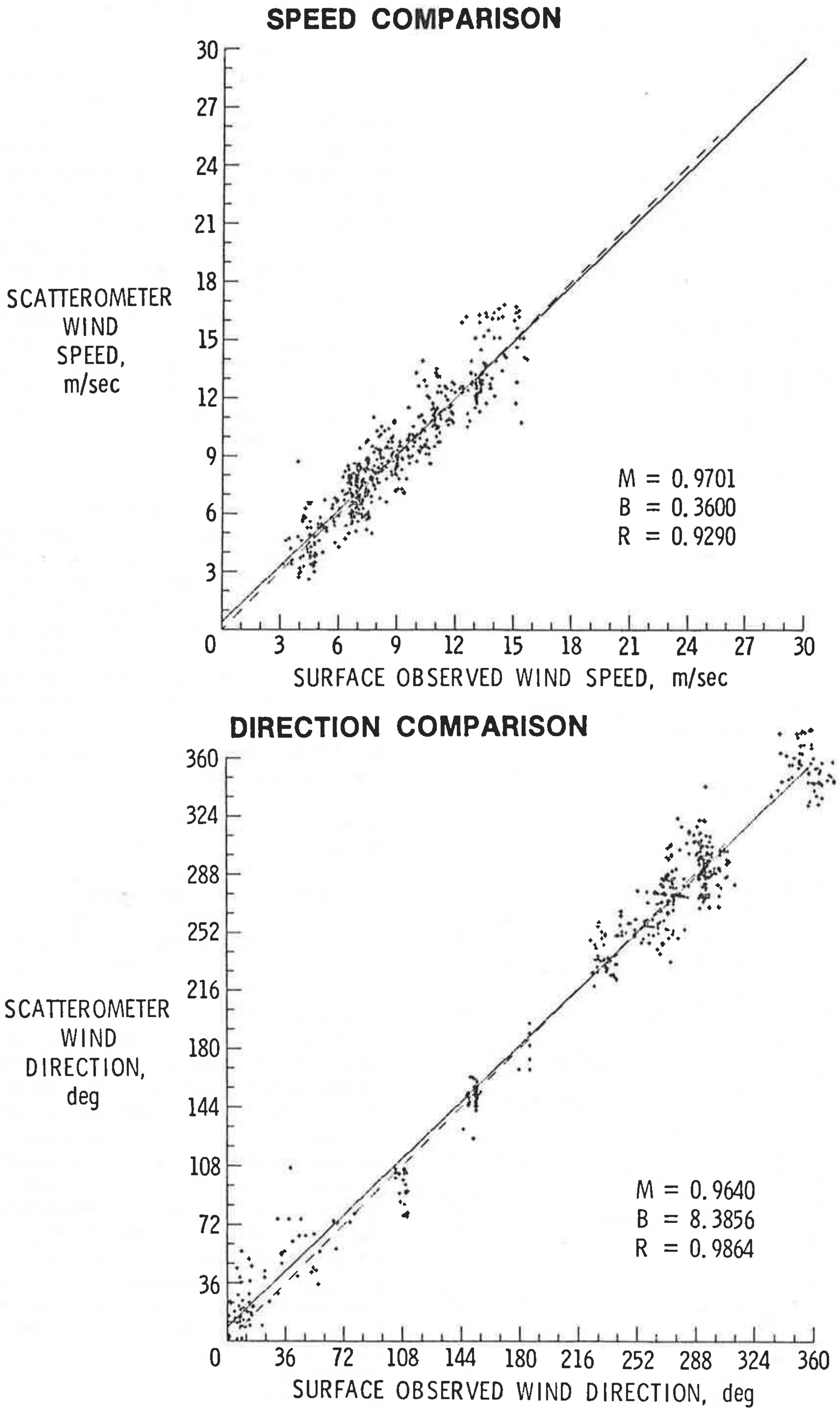


Figure 3 (a) NMC surface wind analysis for 000 GMT 11 september 1970 (from Hoffman 1982)

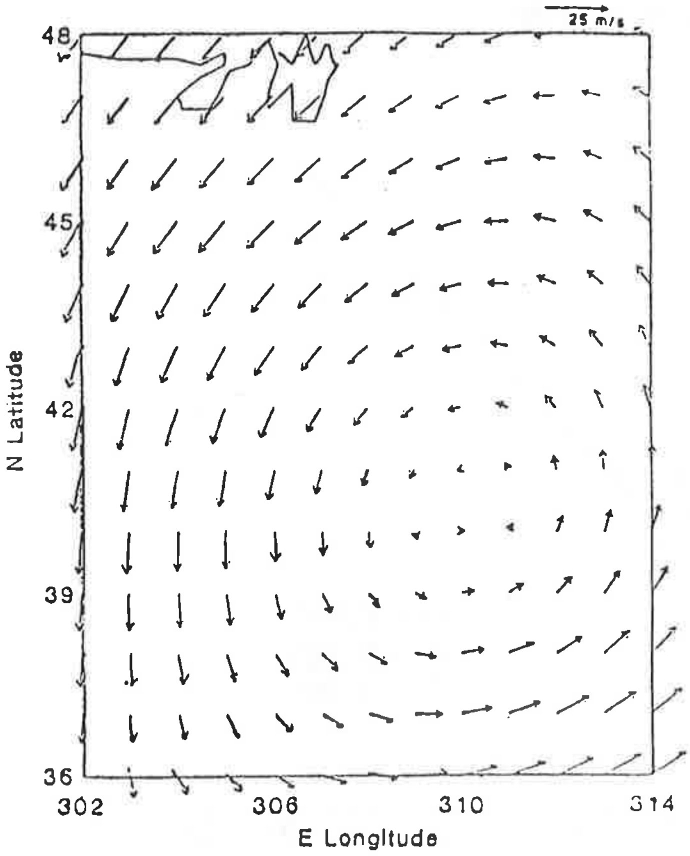
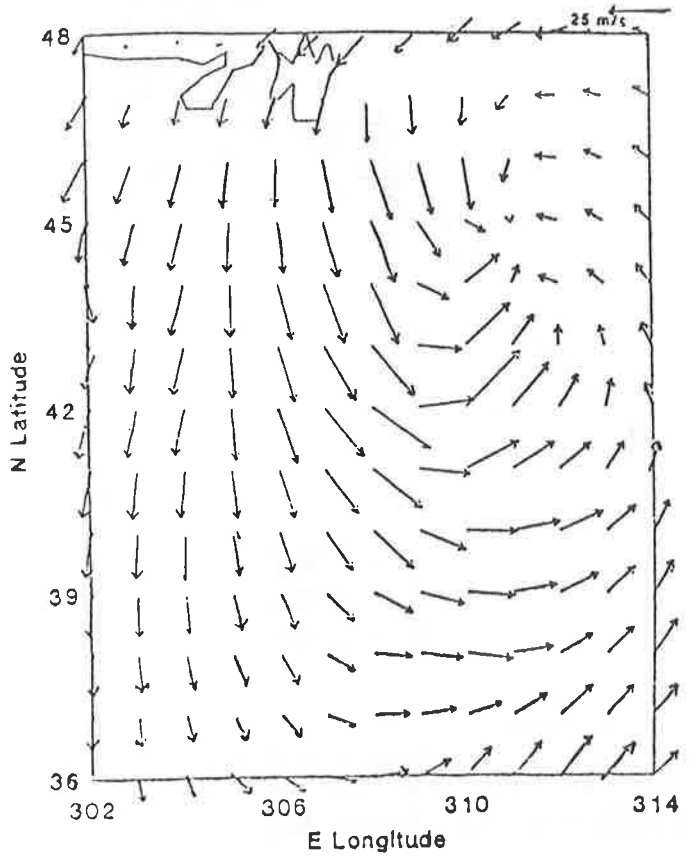


Figure 3 (b) Direct minimization analysis using SASS winds for 0000 GMT 11 september 1978 (from Hoffman 1982).



ments made during the JASIN experiment in the eastern North Atlantic (Jones et al.1981). Excellent agreement (± 2 m/s in wind speed, ± 20° in wind direction) was obtained (see Fig. 2). The usefulness of scatterometer winds for determining the surface wind field is illustrated for a particular case study in Fig. 3 (from Offman 1982). It is seen that without the scatterometer information, the wind field derived from the conventional meteorological observation network (left panel) severely underestimated the most intense regions of the storm, as reconstructed from the full data set (right). (The storm in question was of some practical interest, since it caused considerable damage to the liner *Queen Elizabeth II,* which passed through the storm without sufficient forewarning.)

The great potential of the scatterometer for reconstructing the wind field which drives the ocean circulation and generates the ocean wave climate, or for predicting future surface winds for marine forecasting applications is generally recognized. Nevertheless, the wind scatterometer poses a number of problems which need to be addressed more carefully in the application of such instruments in the future. A single scatterometer or even a scatterometer pair flown on only one satellite does not sample with sufficient density in space and time to avoid aliasing rapidly varying synoptic scale wind systems. Furthermore, the instrument flown on SEASAT was able to determine the wind direction only to within four possible solutions. (Planned future scatterometers will view a given area of the ocean from three instead of two look directions, thereby generally reducing the number of ambiguities to two.) For these reasons the scatterometer data cannot be considered independently of other meteorological data, but need to be imbedded in a general meteorological 4-D data assimilation scheme which provides the analysed surface wind field as one particular output from a complete, dynamically consistent reconstruction of the state of the atmosphere. This is clearly a meteorological rather than an oceanographic task, but the collaboration of oceanographers is essential to develop and apply the actual sensor algorithms.

Another difficulty in analysing scatterometer data is that in order to remove the directional ambiguities, and to obtain reliable wind speed values, the local wind sea and swell fields must be known. The backscattered microwave return from the sea surface is determined by the short (cm wavelength) ripples of the sea surface, which are known to be strongly affected by the modulation by longer surface waves (see Stewart 1984); (Keller and Wright 1975); (Feindt et al. in preparation). A reliable algorithm for recovering the surface winds from the backscatter data therefore requires the surface wave spectrum as input. This can be derived only from numerical computations with wave models, which must be driven by the estimated wind field itself, but will also make use of wave data from satellites and conventional instruments. The full interactive problem can clearly be treated only interatively.

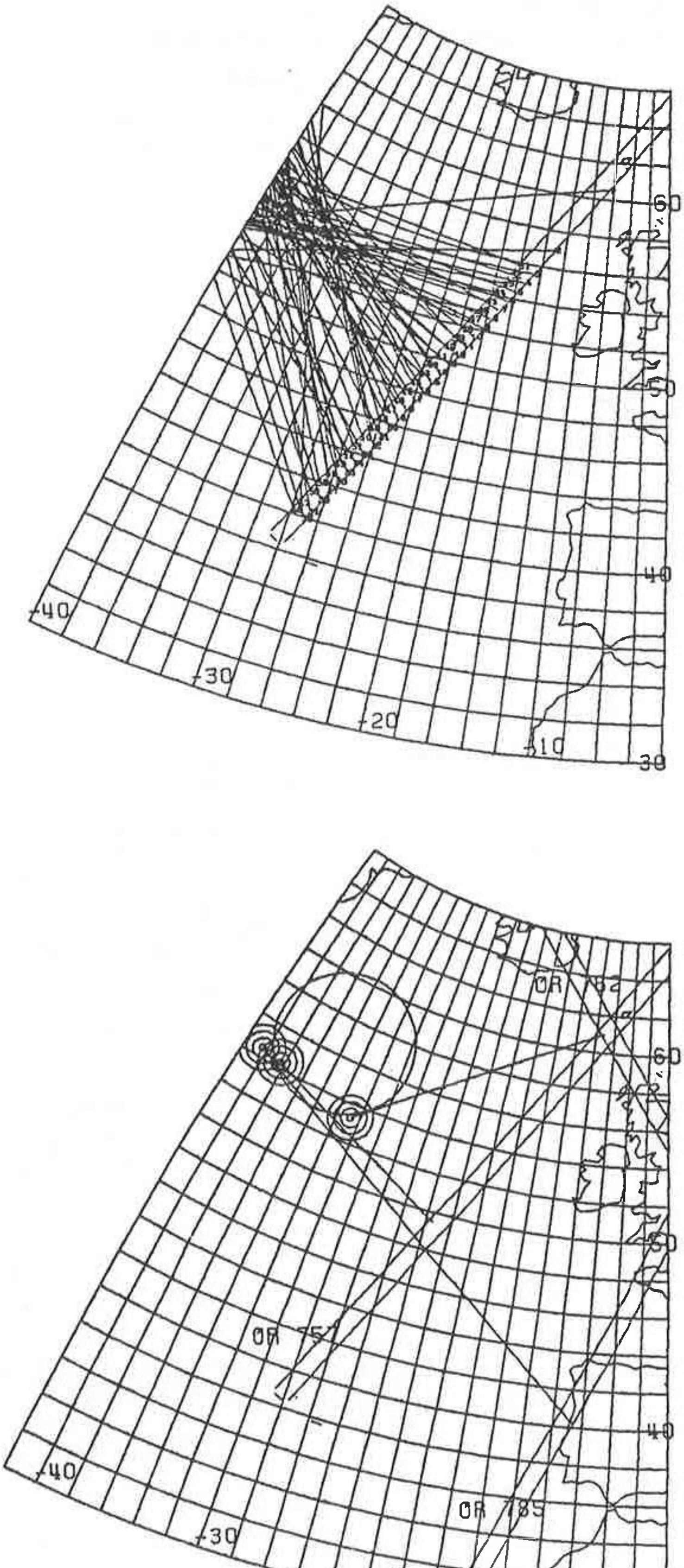
The interdependence of wind and wave data is illustrated further in Fig. 4, which shows the propagation paths of the principal swell components identified in SEASAT synthetic aperture radar (SAR) images obtained along three successive orbits (from Lehner 19844). From the swell rays and the swell wavelengths it was possible to infer the position, time, strength and direction of the maximum winds of the generating storm in the East Atlantic. In this case the usual input-output relation between the wind and wave field was inverted, and useful information on the extreme properties of the wind field was derived from the wave field. Since the inversion technique yields information on the wind fields at an earlier time (because of the finite wave propagation time) the method has natural limiations for forecasting applications and is probably most useful for reconstructing the space-time history of the wind field in data-sparse regions of the ocean for climate studies.

The example illustrates generally the nature of the problems encountered in attempting to extract the full information content from interdependent satellite data. Firstly, individual sensors cannot normally be regarded in isolation, since the algorithms for converting the sensor data to geophysical parameters depend on additional input data which can be obtained only from simultaneous measurements with other sensors, or, more typically, from a reconstruction of the required fields from a mixture of conventional and sattelite data, using models. (In the present example, wind and wave data were available not only from the satellite scatterometer and SAR, but also from the radar altimeter and microwave radiometer, as well as from conventional stations). Secondly, the various geophysical fields derived from the suit of satellite sensors and conventional instruments are normally interrelated dynamically, and an optimal reconstruction of the fields must allow for this interdependency. One is faced therefore with a complex mutidimensional data assimilation problem extending from the development of sensor algorithms to the simultaneous reconstruction of sets of dynamically interacting fields using large scale dynamical models.

The ocean circulation

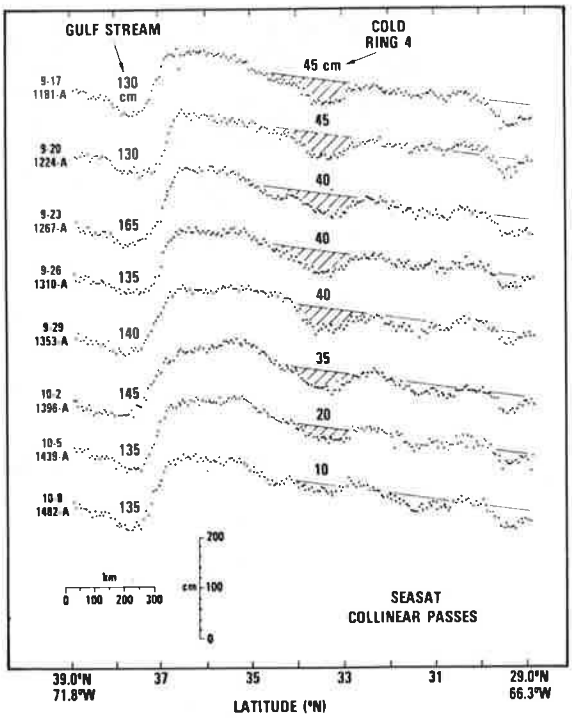
Another important area in which satellites and new developments in measurement technique can be expected to bring significant advances in the future is global ocean circulation. Serious efforts are currently being undertaken by physical ceanographers to design a World Ocean Circulation Experiment (WOCE) directed towards this goal. The experiment should begin in the late eighties, when it is hoped that the required satellites will become available, and extend over a period of at least five

Figure 4 Propagation patterns of swell components observed along a SEASAT orbit (left) and reconstruction of principal scales and strength of generating wind field from the data from this orbit and two other orbits (right) (from Lehner 1984).



years. In addition to surface winds, SST and radiative fluxes, satellites yield essential data on the sea surface topography. After substraction of the geoid (which can be determined by other means) the sea surface topography yields the surface geostrophic current, thus providing the essential integration constant of the standard geostrophic current calculation which has proved so difficult (virtually impossible on a global scale) to obtain by conventional measurements. Fig. 5 shows successive sea surface profiles through the Gulf Stream obtained with the SEASAT radar altimeter (from Cheney and Marsh 1981, see also Wunsch 1981). The current can be clearly identified by the almost one metre change in surface elevation across the stream. An eddy is also seen to the south of the current. Fig 6 shows the rms eddy activity (rms surface height displacement) for the Western North Atlantic during the SEASAT operation period derived from the altimeter measurements (from Menard 1983).

Figure 5 Successive altimeter tracks passing through the Gulf Stream and a cold ring. The tracks span a period of 21 days (from Cheney and Marsh 1981).



Radar altimeters are most readily applicable to the study of time variable, small and intermediate-scale ocean circulation features such as the western boundary currents and eddies shown in these figures. Measurements of the large-scale time variable features or the mean ocean circulation pose more stringent requirements on the determination of the satellite orbit and the geoid. However, the feasibility of obtaining quantitative information also on these scales is illustrated by a comparison of the large scale (low pass filtered) global absolute dynamic topography derived from SEASAT altimeter data with the classical picture of the dynamic topography inferred from density data (see Fig. 7, from Tai and Wunsch, in press). In view of the very short period of only 100 days for the altimeter measurements, the general agreement is quite satisfactory.

To complete the description of the ocean circulation, satellite sea surface topography measurements need to be augmented by conventional mea-

Figure 6 Variability of sea-surface topography from SEASAT radar altimeter in the NW Atlantic (from Meanrd 1983).

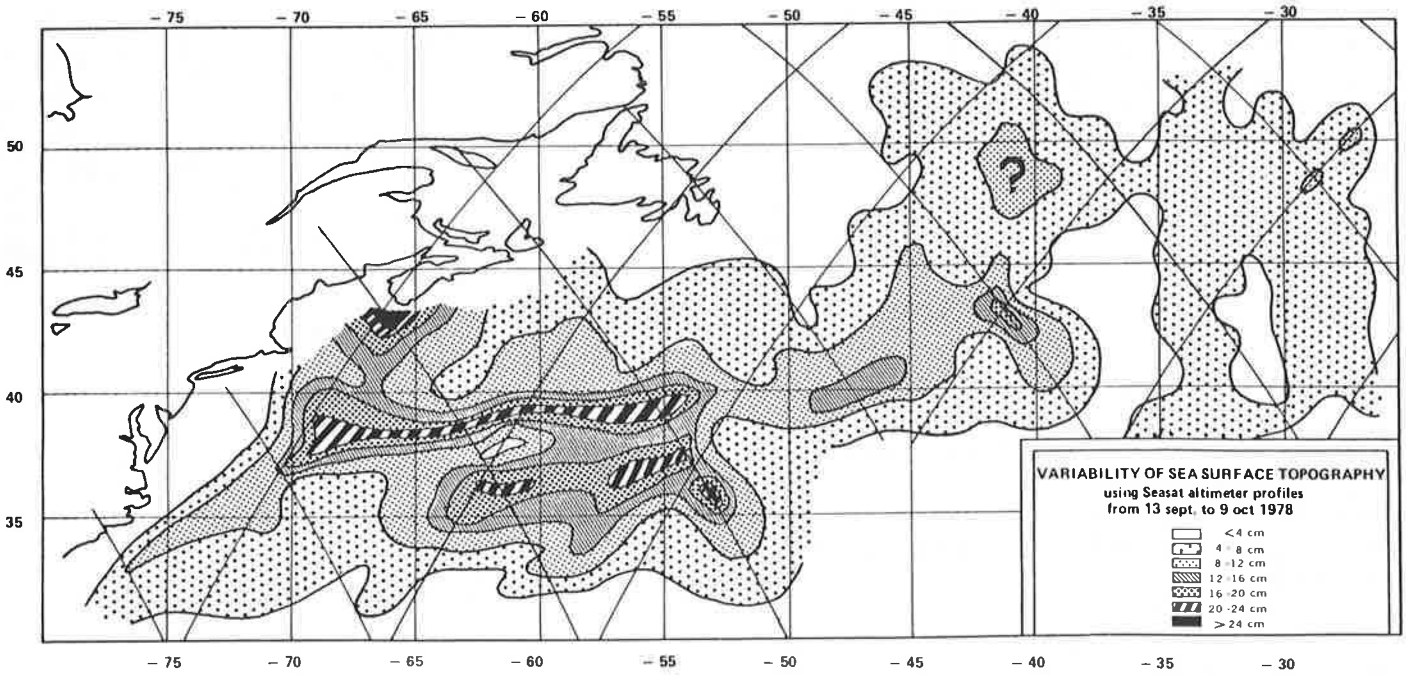
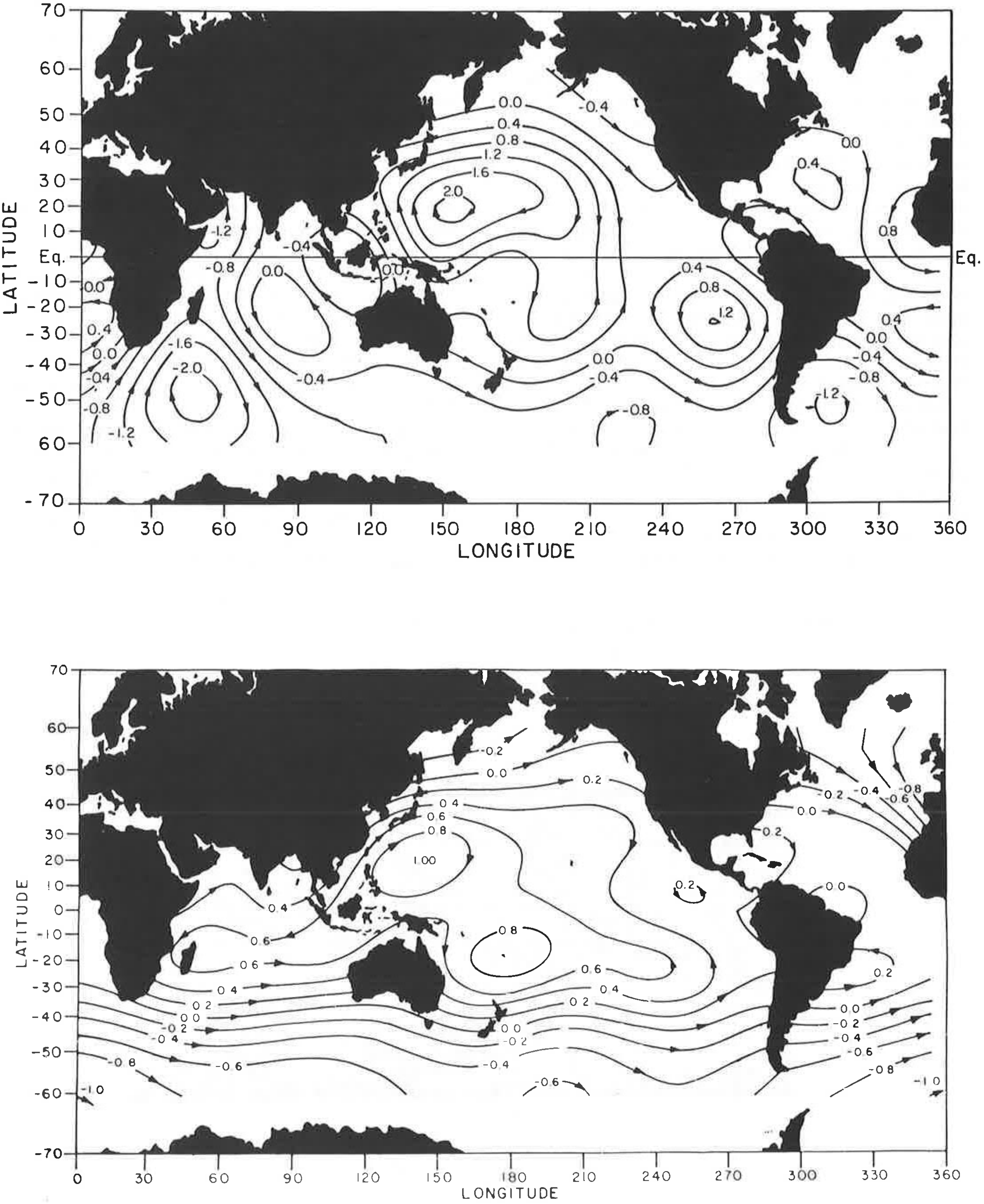


Figure 7 Large-scale (low-pass filtered) global dynamic topography derived from the SEASAT radar altimeter (a) and density data (b) (from Tai and Wunsch, in press).

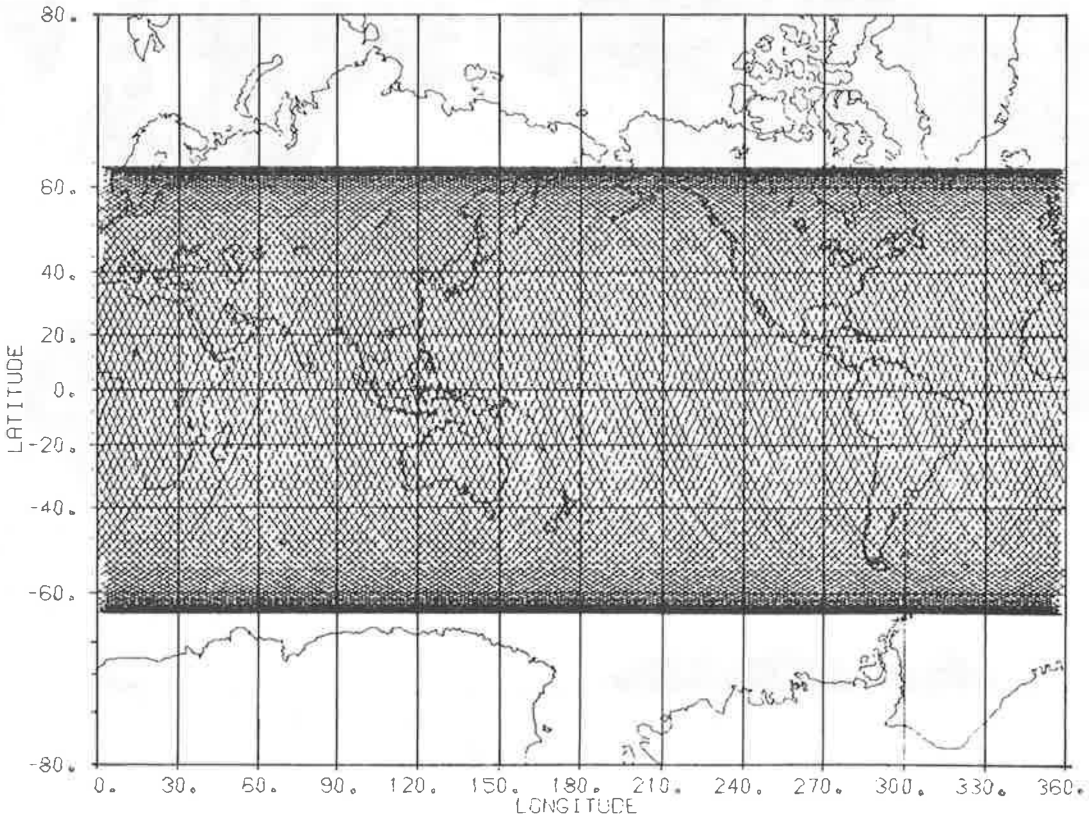


surements, particularly measurements of the density stratification. The later determine the baroclinic component of the currents (the thermal wind) while the sea-level data (together with the density data) establish the barotropic current, i.e. the vertically integrated mass transport. It is a fortunate coincidence that the separate measurement techniques are well matched to a natural separation of the time scales of these two modes of the ocean circulation. In most regions of the ocean, the baroclinic adjustment of the interior density stratification to changes in the external forcing occurs at least two orders of magnitude slower than the barotropic response of the sea surface (several years compared with severals days or weeks). Faster baroclinic response times occur, however, in the equatorial regions, in regions of intense currents and in the seasonal thermocline. The rapid rate of satellite altimeters makes it possible to study the fast global barotropic response with an acceptable space-time sampling trade-off, while the more slowly varying interior density distribution may be established (although with poorer spatial resolution) through ship surveys and other conventional techniques. Fig.8 shows the global sea-surface topography coverage achievable with a polar orbiting satellite for a 10-days repeat orbit, which provides a reasonable compromise between space and time resolution for the barotropic variability. However, aliasing is not entirely negligible, and a two-satellite system would yield a significant improvement in sampling density (and also measurement accuracy).

In regions of more rapid baroclinic response, such as equatorial and frontal regions, more frequent hydrographic surveys or equivalent measurements within the water column are needed to study the baroclinic flow and its interactions with the barotropic circulation. A quasi-automatic method for continously monitoring the interior hydrographic structure in these regions of the ocean would clearly be highly desirable. Acoustic tomography shows considerable promise of providing at least some of the information needed by continuous remote measurement. In this technique, the temperature structure over an extended region of the ocean is inferred by inverse modelling from the travel times of acoustic signals for a variety of ray paths through the regions (Behringer et al. 1982). The technique has been successfully tested for an approximately 400 km square box of the Atlantic south of Bermuda. It can be extended in principal to measure both the temperature structure and the current field through use of two way propagation.

Other techniques wich may contribute significantly to our understanding of the global ocean circulation are satellite-tracked drifting buoys, deep-ocean sonar floats, automatic ship-of-opportunity sampling systems, and moored continuous profiling instruments. The best combination of these different measurement techniques, howe-

Figure 8 Sampling density of a radar altimeter during a 10-day period for a polar orbiting satellite.



ver, and the optimal deployment strategy for each measurement system still has to be established. Although the advent of sattellites and other advanced instrumentation has brought the study of the dynamics of the global ocean circulation within the potential reach of large-scale experimental programs, such as the World Ocean Circulation Experiment, concerted theoretical and numerical modelling efforts will be needed on the part of the oceanographic community to develop effective measurement and data analysis strategies for such undertakings.

The nature of the questions to be addressed can be illustrated by considering one of the most important quantities affecting the ocean circulation and the interaction of the ocean with the atmosphere in climate studies : the net heat flux from the atmosphere to the ocean. A comparison of the measured heat flux for the Atlantic (Bunker 1980), Fig. 9, with the heat flux computed from a global ocean circulation model (Maier-Reimer et al.1982), Fig. 10, shows good general agreement for the North Atlantic, but a very poor correlation for the South Atlantic. The ocean model reproduces the mean temperature and salinity distributions, current fields and tritium distributions rather satisfactorily, so that there is not obvious reason to suspect the model heat flux comutations *a priori.* Does the discrepancy nevertheless reflect an error of the model, or are the data incorrect ? What measurements are needed to resolve the discrepancy ? Does a test of the model for the time averaged heat flux have any immediate bearing on the validity of the model for computing variations of the oceanic heat flux and heat storage on time scales of a few months to a few years relevant for WOCE ? Should investigations of the variability of the oceanic heat flux on this time-scale be weighted heavily towards the tropical oceans, as suggested empirically by the pronounced large-scale coupled ocean-atmosphere anomaly signals observed in the equatorial regions, and supported theoretically by the strong response of atmospheric models to tropical and sub-tropical SST anomalies (and as proposed in the Tropical Oceans-Global Atmosphere (TOGA) experiment) ? These and similar basic questions clearly need to be addressed through an extensive numerical modelling program in which the sensitivity of different types of models are tested for different types of parameterization, coupling and external forcing.

Figure 9 Net surface heat flux into the ocean (from Bunker 1980).

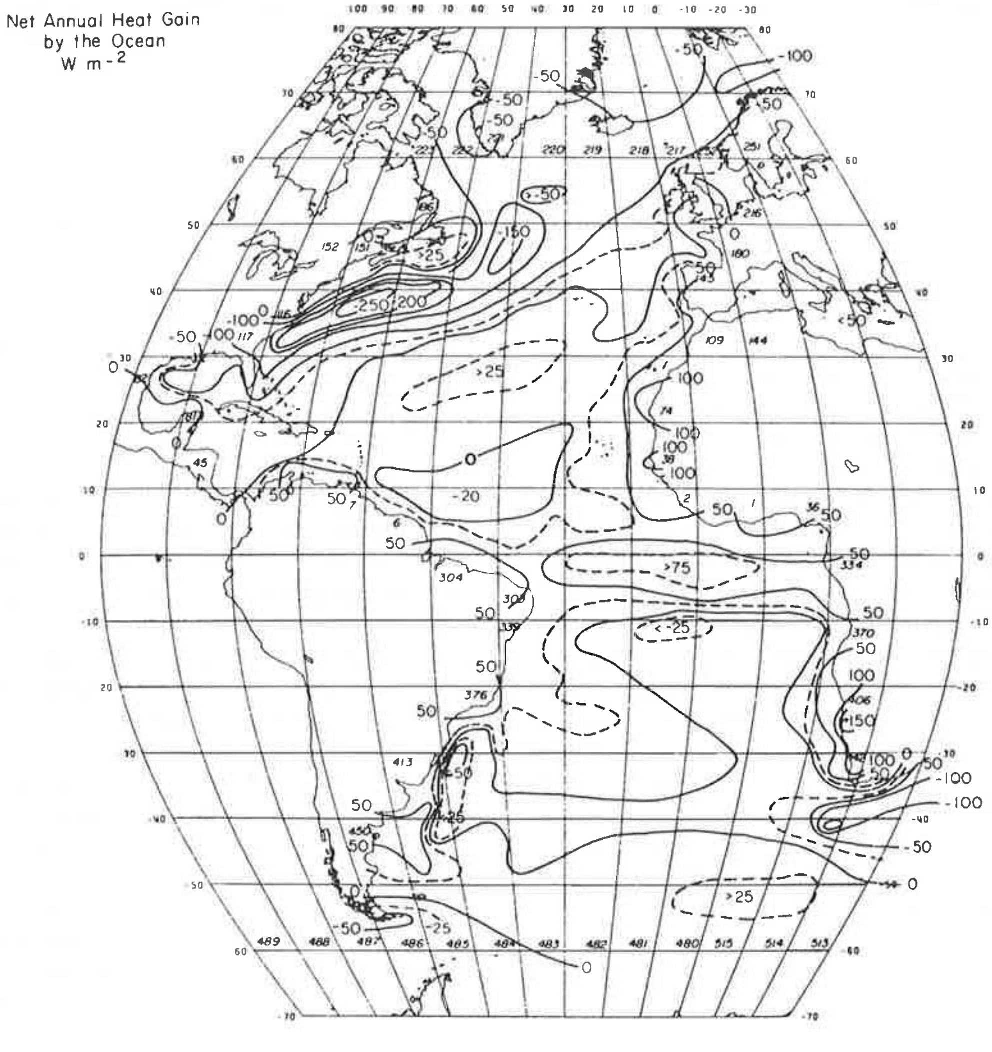
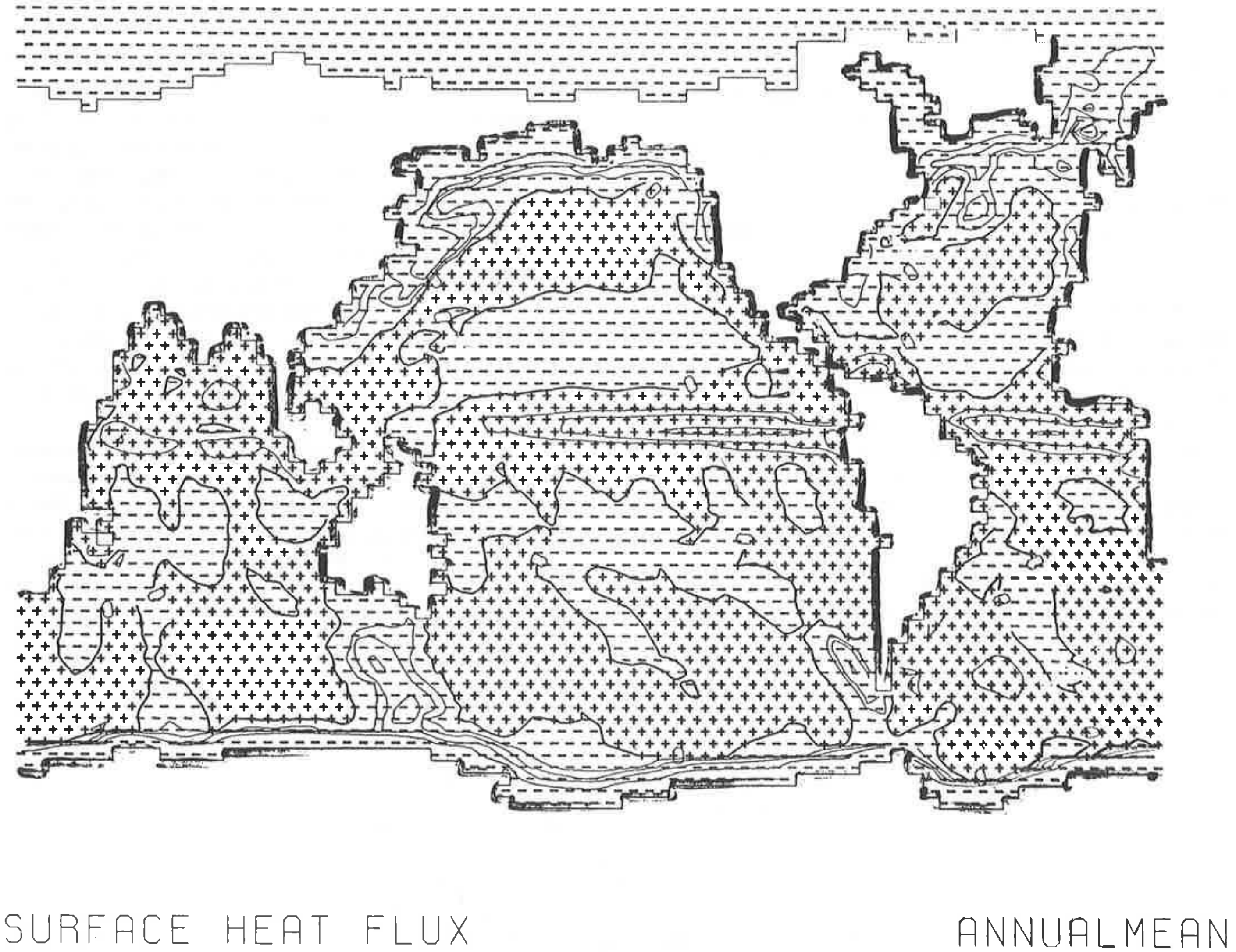


Figure 10 Net surface heat flux into the ocean computed with a global ocean circulation model (from Maier-Reimer *et al.* 1982).



Conclusions

The coming decades in physical oceanography will witness the advent of new measurement techniques for observing the oceans on a greatly expanded scale, both globally and regionally. The sensors from these advanced observing systems will produce continuous streams of data at rates significantly higher than physical oceanographers have been accustomed to work with. Ideally, research in physical oceanography has been carried out in the past in a sequence of logical steps : an oceanographic expedition is first planned, then carried out, the data is analysed, interpreted, and on the basis of these results, a new expedition is planned, and so forth. Physical oceanographers have nevertheless traditionally suffered from the fact that these logical steps are not always well separated in practice, and that the individual researcher is constantly engulfed in undigested data from previous expeditions while already planning the next. This complaint could achieve new dimensions when extensive, high data rate, continuous observing systems come into operation. The traditional style of oceanographic research may need to be basically restructured. Oceanographic analysis centres will need to be established, analogous to present meteorological analysis and forecast centres, with the routine task of continuously analysing the incoming data streams. As in meteorological analysis centres, the analysis will require the application of rather complex models in order to reconstruct dynamically consistent fields.

To interpret and apply the data, an ensemble of research and application models will be required, including global ocean circulation models, high resolution limited area models for particularly active regions of the ocean circulation, and global and regional marine forecasting models. In many applications, the ocean must be viewed as a subcomponent of the coupled ocean-atmosphere system, and a close collaboration of physical oceanographers with meteorologists will be necessary. Experience with data processing and numerical modelling in a continuous, quasioperational mode is still very limited in the physical oceanographic community. However, a successful response to these challenges can open the way to a new era in physical oceanography, in which the global ocean, as today the atmophere, is treated in its entirety, both in the study of the complex role of the oceans in the global climate system and in the global prediction of marine weather.

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