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Satellite Monitoring of the Ocean for Global Climate Research [and Discussion]

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Satellite monitoring of the ocean for global climate research

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The study of climate embraces a broad range of timescales, from weeks to millions of years. This paper concentrates on the narrow spectral band ‘several weeks to several decades’ chosen for study in the World Climate Research Programme (WCRP). The programme is divided into three streams, concerned with climate variation on timescales of several weeks, several years and several decades, respectively. The aim is to discover how far it is possible to predict natural climate variation and man’s influence on climate in each of these spectral bands. It is believed that an improved understanding of, and an ability to monitor and model, the World Ocean will be critical to the success of the WCRP in each stream. International experiments are now being planned to achieve these improvements. Satellite monitoring of the ocean offers a number of advantages for these experiments, including the following: global coverage, accuracy and consistency, novel products, tracking and communication. The paper reviews specifications for monitoring the ocean in the context of the WCRP and assesses the extent to which satellite monitoring will help towards meeting these requirements. The special needs of two major projects, the World Ocean Circulation Experiment (WOCE) and the Tropical Ocean and Global Atmosphere (TOGA), are described. The prospects seem good for a new generation of ocean-observing satellites suitable for climate research in the next decade. They will be crucial to the success of the World Climate Research Programme.

Introduction

The climate of a planet is its atmospheric response to solar and internal heating. The response mechanism involves not only the atmosphere, but also the other elements of the planetary climate system. The existence of the World Ocean makes Earth climatologically unique among the planets of the solar system. It is difficult to think of any problem in global climatology, regardless of the timescale involved, that does not centrally involve the ocean. Examples of ocean–climate interaction, based on the review by Woods (1983), are given in table 1. In this paper I shall concentrate on the shorter timescales commensurate with human activities and therefore offering potential benefits if they could be predicted. The World Climate Research Programme (WRCP 1980–2000) has been established by the World Meteorological Organization (WMO) and the International Council of Scientific Unions (ICSU) with the following aims:

(1) to determine to what extent climate can be predicted;
(2) to determine the extent of man’s influence on climate.

Highest priority is being given to climate variation on timescales of ‘several weeks to several decades’. The underlying assumption is that it might be possible one day to achieve some kind of prediction of climate changes with sufficient lead time for industry and public services to prepare for them. Meteorologists have had considerable success in forecasting the weather by systematic global observations fed into computer models based on the laws of dynamics and physics. It is hoped that an appropriate combination of global observations and dynamic-physical models can also provide the basis for climate prediction. But it is not yet certain whether that is going to be possible. An intense research programme including model development and data collection is being planned for the remaining years of this century (Houghton & Morel 1983).

TABLE 1. THE INFLUENCE OF THE OCEAN ON GLOBAL CLIMATE CHANGES WITH DIFFERENT TIMESCALES

timescale	climatological phenomenon	ocean contribution
order 10^9 years	evolution of the atmosphere	chemistry and biology
order 10^9 years	evolution of the continents	sedimentation and coastal erosion
10^8–10^9 years	evolution of the biosphere	spreading from the ocean to the land
10^7–10^8 years	continental drift opens and closes narrow sills between ocean basins	global energy cycle modified by the interchange of water masses between ocean basins via narrow sills; for example: opening of the Drake Passage, closing of the Meso-American gap between Pacific and Atlantic, opening of the overflow from Arctic Ocean to Atlantic Ocean, temporary closing of the Straits of Gibraltar (leading to desiccation of the Mediterranean)
order 10^8 years	interval between ice ages	evaporation supplies water for the polar glaciers;
order 10^7 years	duration of ice ages (due to continents drifting near the poles)	biology changes atmospheric CO_2; deep convection in polar seas creates the ocean cold water sphere, thermally isolating the upper ocean
10^4–10^5 years	fluctuations in ice ages due to variations of the Earth's orbit	sea level changes affect biological processes modifying atmospheric CO_2 sea surface a few degrees cooler 18000 years ago at the maximum glaciation
centuries	little ice age	unknown
decades	heating by CO_2 pollution	accommodation of CO_2 by ocean chemistry and biology halves the greenhouse effect ocean thermal lag delays by several decades the temperature rise in the atmosphere
years	inter-annual variability including the Southern Oscillation	teleconnections in ocean due to El Niño, Gulf Stream, etc. sea ice variation mid-latitude heat content anomalies in the oceanic boundary layer
months	the regular seasonal cycle, including: the meridional migration of the Westerlies and Trades; the monsoons	seasonal heat storage in the upper ocean global circulation of about 1 % of the solar heat input land–sea difference of annual temperature range waxing and waning of sea ice cover
days	weather	sea-surface temperature distribution; sea ice distribution

The programme strategy for the World Climate Research Programme (WCRP 1983) is divided into three streams, each concerned with a particular range of timescales:

stream 1, timescales of order months;
stream 2, timescales of order years;
stream 3, timescales of order decades.

The ocean is important for all three streams. An oceanographic programme (WCRP-O, where the O stands for oceanography) is being planned with specific activities devoted to each of the three WCRP streams. Many of the activities are being organized by research groups in a single institute, or at several institutes in one country, or involve informal collaboration between groups in several countries. International organizations like ICES (the Inter-governmental

Council for Exploration of the Sea), Unesco and the Nato Science Committee, are actively supporting the international aspects of these activities.

Experience in GARP (the Global Atmospheric Research Programme) showed that more formal co-ordination is needed in the case of major international experiments such as GATE (the GARP Atlantic Tropical Experiment, in 1974) and FGGE (the First GARP Global Experiment, in 1979). One of the critical factors favouring formal co-ordination was the need for satellite observations as an essential ingredient of the overall observing programme in GATE and FGGE. Although the specification and design of each satellite observing system, and the scientific analysis of the resulting data, all depend critically on the contributions of individual scientists, the need to create a case sufficiently powerful to convince governments and space agencies to allocate resources to meteorological rather than, say, astronomical satellites demanded a strong central lobby. The case presented by the lobby would be convincing only if its scientific objectives were simple and supported by the meteorological community as a whole. The task of the Joint Organizing Committee (JOC) for GARP was to help crystallize scientific objectives and to translate them into simple experimental plans, involving satellite observations, that would be widely accepted by the international meteorological community. Then, having prepared a strong case for satellites for GARP, the JOC had to act as the lobby to make sure that they were launched in time for the major experiments. The successful accomplishment of these tasks by the JOC for GARP sets a precedent for the new Joint Scientific Committee (JSC) for the WCRP and, for the oceanographic aspects, their partner, the Committee for Climate Change and the Ocean (CCCO), which is sponsored jointly by ICSU (through SCOR, the Scientific Committee for Ocean Research) and the Intergovernmental Oceanographic Committee (IOC, of Unesco).

If it becomes feasible, climate prediction will involve not only the atmosphere but also the other elements of the planetary climate system. The WCRP requirements for satellites will therefore involve missions dedicated to observing the atmosphere, the land surface, the cryosphere and the oceans. Progress is being made in all these elements. The successors of the GARP generation of meteorological satellites, together with novel meteorological missions designed to support the Earth Radiation Budget Experiment (ERBE) and the International Satellite Cloud Climatology Project (ISCCP), are now established. So is a new generation of satellites to observe the land surface: the successors of the Landsat series, and the new SPOT series (Eagleson 1982). The cryosphere (in particular the sea ice, which exhibits large seasonal and inter-annual variation) has been routinely monitored for many years by satellites carrying microwave radiometers (Untersteiner 1983). The case for meteorological, land surface and sea-ice missions for the WCRP rests securely on a great deal of experience gained in the 1970s. By contrast, the case for satellite missions to observe the oceans is newer, and therefore less secure. Nevertheless, oceanographers have made considerable progress during recent years, and a strong case can now be made for dedicated WCRP-O satellites. The experience comes from three main sources:

(1) analysis of data from meteorological satellites to estimate sea surface temperature, insolation and surface wind stress;

(2) the Coastal Zone Colour Scanner on the Nimbus-7 mission;

(3) the first dedicated ocean-observing mission, Seasat, which carried a variety of novel instruments, including radars and passive radiometers in the microwave, infrared and visible wavebands.

Cracknell (ed.) (1981), Stewart (1982) and Gower (ed.) (1982) have reviewed the state of the art of satellite oceanography at the start of the 1980s. My aim in this paper is to summarize the case that is being developed for a new generation of dedicated ocean-observing satellites to be used as central elements of WCRP oceanographic experiments during the remaining years of this century. The next section discusses why satellites will be crucial to the success of WCRP-O experiments. The subsequent sections look in more detail at the experiments planned for the three streams of the WCRP, identifying the role of satellite observations in each.

THE IMPORTANCE OF SATELLITES FOR WCRP OCEANOGRAPHIC EXPERIMENTS

Traditionally the ocean has been observed from ships, and ship measurements will play a key role in the WCRP-O experiments, especially for the establishment of the three-dimensional distributions of temperature, salinity and chemicals used as tracers in circulation studies. Satellites can only observe the surface of the ocean, and therefore only compete with surface observations from ships. But the WCRP-O specifications for surface observations cannot be satisfied by ship data alone. Satellites do not satisfy all the requirements either, but they offer a number of crucial advantages. It is doubtful whether the JSC and CCCO would proceed with the experiments if satellite observations were not going to be available. The advantages can be grouped into four categories: (1) global coverage, (2) accuracy and consistency, (3) novel products, and (4) tracking and communications. These will now be considered in turn.

Global coverage

Whereas it is possible to make quite good weather forecasts by using observations and a model that covers only part of the globe, that will not be true for climate prediction, even on the shortest timescales (stream 1). Empirical studies (Horel & Wallace 1981; Wallace & Gutzler 1981; Keshavarmurty 1982; Shukla & Wallace 1983) and modelling studies (Pan & Oort 1983) both show that the atmospheric climate responds remotely to anomalies in the surface fluxes of energy and water from the ocean. It is only meaningful to discuss the climate in terms of the *global* pattern of fluxes from the ocean (g.p.f.o.). Recent theoretical studies by Webster (1981) and Hoskins (1983) have helped to explain the mechanism by which the atmosphere responds remotely to anomalies in the g.p.f.o. Their theories make interesting predictions about seasonal and regional variation in the sensitivity of the response, predictions that have influenced the design of WCRP-O experiments, as we shall see later. Nevertheless, it is essential to measure the *global* pattern of ocean fluxes. They also serve as upper boundary conditions for ocean circulation models, which are needed to predict changes in the contribution of the ocean to the global circulations of energy and water in the planetary climate system. Global observations are a *sine qua non* for the WCRP. The sampling density must be sufficient to give statistically significant data with a spatial resolution of one megametre† and temporal resolution of one month. The distribution of ship observations (figure 1) cannot meet that specification, especially in the Southern Hemisphere. But, given appropriate orbits, satellites sample the whole globe systematically and predictably. They do not suffer from the kind of biases found in data bases derived from ships, which are likely to have avoided typhoons, for example. On the other hand, satellite-derived data may have biases of a different kind, for example in favour of cloud-free regions; so care must be taken in using them, too. Nevertheless one of the great attractions of

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† A higher meridional resolution is needed in the Tropics (see table 5).

satellite observations is their potential for complete, systematic, global coverage. A recent example is shown in figure 2.

Accuracy and consistency

Climate prediction will demand a very high order of accuracy in ocean surface data. The specification depends on the aims of the forecast; during the research phase it depends on

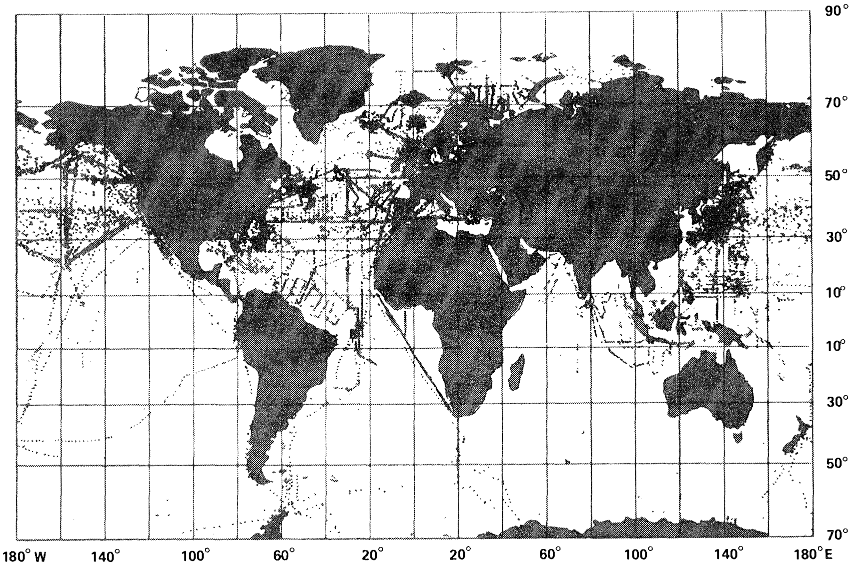

FIGURE 1. Distribution of ship observations reported during 1978 through IGOSS.

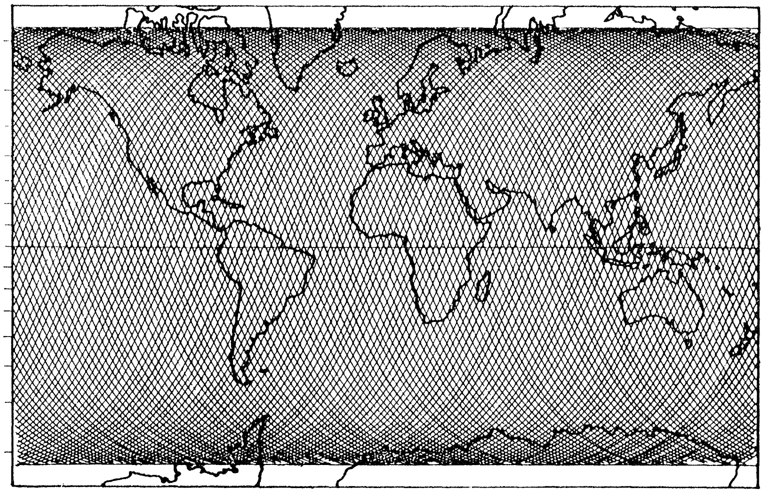

FIGURE 2. Coverage of the ocean by Seasat in an 8 day repeat orbit.

which stream of the WCRP is being pursued. As a rule of thumb we can specify the required accuracy as, say, 20% of the relevant signal, which might be the synoptic global range, the annual range at one place, the range of short-term inter-annual variability, or the secular change expected over a given period. The existing data base and predictions based on simple climate models give some idea of what these ranges are (table 2), but it must be admitted that there are large uncertainties due to measurement error and inadequate sampling, especially in the Southern Hemisphere. Examining table 2, we note that the uncertainty in existing data severely limits the areas of the World Ocean in which our climatological knowledge meets the 20% criterion. In many places the error is greater than 100% of the climatological signal, making it difficult to be sure even of the sign of the variation. One of the most urgent tasks of the WCRP-O is to collect a new data base that will meet the 20% specification for the megametre-monthly average values of the variables listed in table 2, everywhere around the globe.

TABLE 2. RANGES OF CLIMATOLOGICAL VARIABLES AND MEASUREMENT ERRORS AT THE OCEAN SURFACE

		range				measurement error		
		regional	seasonal	inter-annual	secular		satellite	
variable	qualification	Mm	month		(2 × CO_2)	ship	1985	1990
temperature	Tropics	10	3	6	2	0.5	1	0.3
K	mid-latitude	20	10	1	8			
	polar	5	5	1	10			
energy flux	Tropics	150	100	90	15	50	50	50
$W m^{-2}$	mid-latitude	200	100	30	15			
	polar	400	100%	100%	?			
precipitation	Tropics	50	100%	100%	?	50%(?)	50%(?)	10%(?)
cm $month^{-1}$	mid-latitude	10	30%	?	?			
pressure gradient	Gulf Stream	2	30	30	?	0.1	0.1	0.02
m $(100 km)^{-1}$	gyre	0.1	?	?	?			
	eddies	1	—	—	—			
Ekman pumping	Tropics	1	100%	50%	?	1(?)	0.2	0.2
m day^{-1}	mid-latitude	0.1	50%	30%	?			
heat content	Tropics	0.5	0.1	0.3	?	0.02†	0.1	0.02
m elevation	mid-latitude	—	0.1	0.01	?			

† Tide gauge.

The contribution of satellite measurements can be assessed by comparing their accuracies with these specifications. Some recent estimates of the uncertainties in existing satellite data are listed in table 3. In many cases the data are so new that algorithms used to produce the required variables are still under development; we can look forward to further hardware improvements in the new 'WCRP-generation' of ocean-observing satellites.

Although it may take some time before the accuracy of satellite observations exceeds that of the best ship observations, they will from the start offer consistency of data quality, which has always been a worry with routine observations from ships of opportunity. For example, there is evidence of systematic differences between sea-surface temperature measurements made by different methods (bucket, plate and engine intake thermometers), as discussed by Tabata (1978). Subjective estimates of rainfall rate from ships and islands present special problems of consistency (Mintz 1981). There are obvious advantages of a data set collected from carefully inter-calibrated sensors on a small number of satellites, each sampling the whole globe (Tabata & Gower 1980).

Novel products

Novel instruments on satellites and their systematic high-resolution scanning of the ocean opens the door to monitoring variables that are of great importance to modellers, but whose global patterns are known only sketchily from the existing ship observations. The highest priority for any dynamicist is the vertical motion due to Ekman convergence and synoptic-scale development. Saunders (1976) has discussed the problems of calculating the mean wind-stress curl over various averaging areas and intervals from ship data that are incoherent with respect to the atmospheric weather events controlling wind stress. Guymer *et al.* (1983) have produced the first synoptic map of wind-stress curl from Seasat radar scatterometer measurements, which are coherent with respect to the weather (figure 3). The annual vertical displacement due to Ekman pumping lies in the range ± 100 m. Similar vertical displacement is achieved in a month by transient 'synoptic-scale' motions (eddies & Rossby waves) in the ocean. The energy of the synoptic-scale motions exhibits considerable regional (Dantzler 1976) and seasonal (Dickson *et al.* 1982) variability. The dimpling of the sea surface by these (order 100 km) ocean synoptic-scale motions can be measured by satellite altimeter (figure 4). The sampling is unlikely to be coherent, so it will not be possible to measure the vertical velocity associated with these transient motions; but monitoring the regional and seasonal variation of the statistics of the surface dimpling will provide an invaluable product for comparison with the predictions of eddy-resolving ocean circulation models. The surface of the ocean also rises and falls (relative to the geoid) due to thermal expansion, so the altimeter can be used to monitor variations in the upper ocean's heat content; the maximum range of surface elevation, several decimetres, occurs in the Tropics (figure 5). To monitor these changes of eddy motion and heat content it will be necessary for the satellite to cover the same ground track to within 1 km every week or so. Less precise repetition would introduce contamination from spatial variation of the geoid, which is an order of magnitude bigger (Wunsch (ed.) 1982). A more ambitious goal is to use the satellite altimeter to measure the steady hydrostatic pressure distribution on the geoid, and

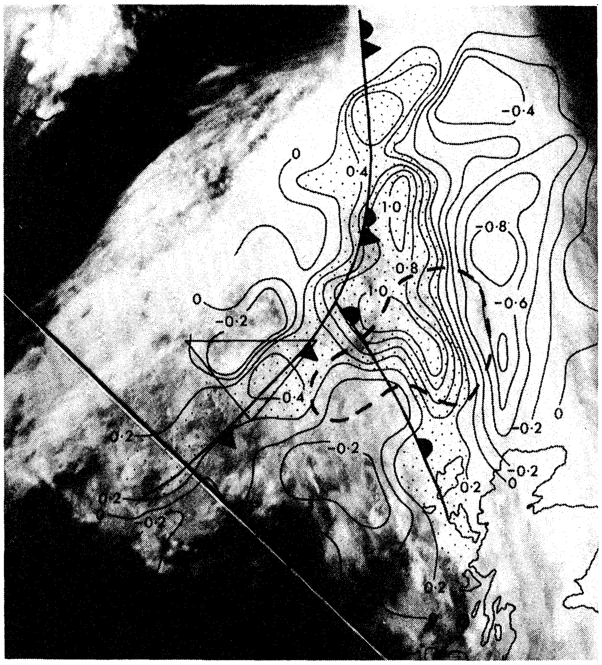

FIGURE 3. The first map of wind stress curl that resolves the variation with atmospheric weather. From the Seasat scatterometer during JASIN analysed by Guymer *et al.* (1983). The weather is shown in three ways: (i) by conventional synoptic analysis (the lines marking an occluded front), (ii) by contours of rainfall rate estimated from the Seasat scanning multichannel microwave radiometer, and (iii) by a cloud image from the NOAA-5 weather satellite which passed overhead 5 h earlier. (Reproduced by kind permission of the Director, Institute of Oceanographic Sciences, Wormley, and Dundee University.)

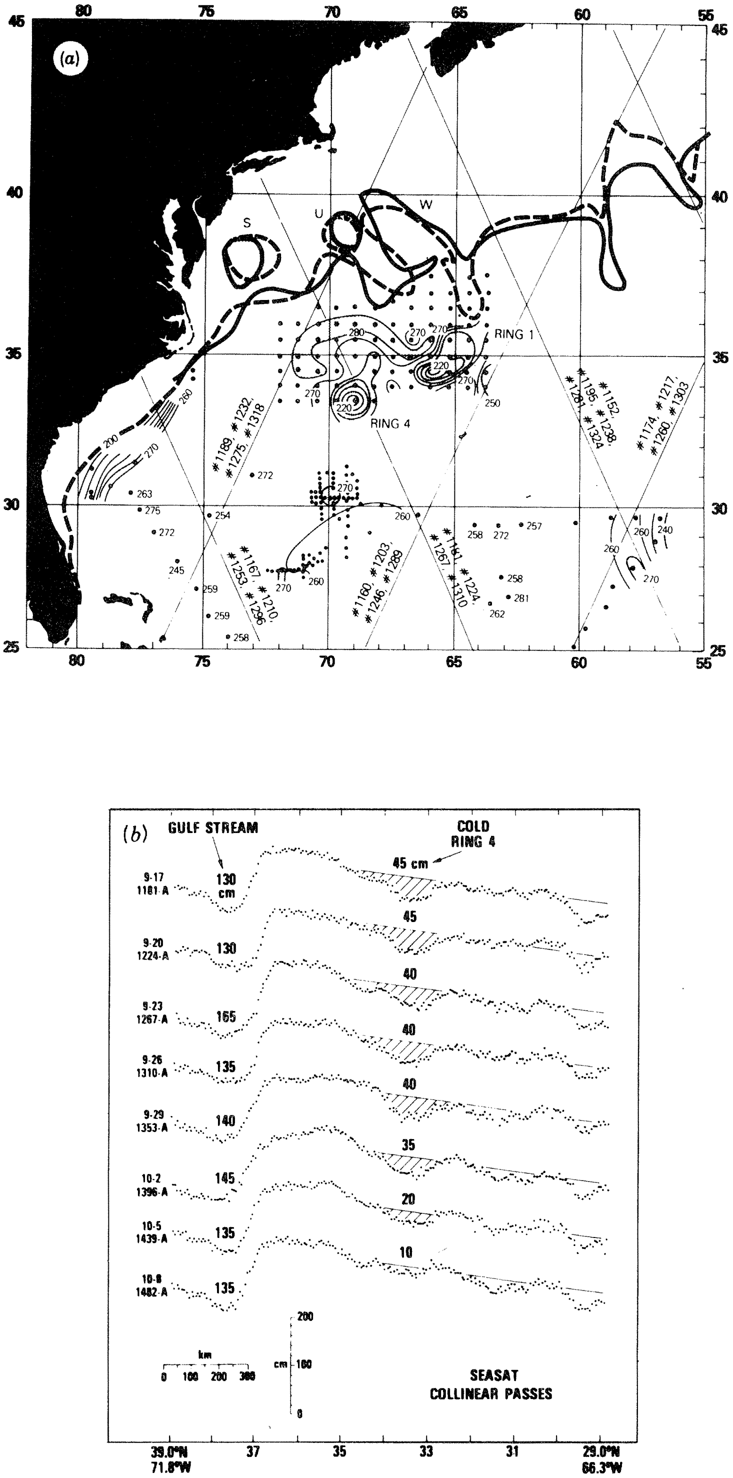

FIGURE 4. Observations of transient dimpling of the sea surface due to oceanic weather systems monitored by the Seasat altimeter during successive passes at 3-day intervals. (*a*) Seasat ground tracks in the vicinity of the Gulf Stream, 14–27 September 1978; (*b*) successive altimetric measurements along the set of tracks shown in (*a*) passing through ring 4, showing the evolution of more than 21 days of the Gulf Stream and a large, strong ring. (From Cheney & Marsh (1981); reproduced with permission.)

hence to calculate the surface geostrophic velocity field. Wunsch (ed.) (1982) has discussed a dedicated satellite mission for that purpose, and the supporting measurements needed to measure the geoid to the required accuracy (a few centimetres). These are the novel products uppermost in the minds of oceanographers planning WCRP-O experiments. Others are under development, including methods of subsurface profiling (Schwiesow 1980; Leonard 1980), but experience with GARP suggests that planning must proceed on the basis of methods that have been first tested on a satellite a decade beforehand.

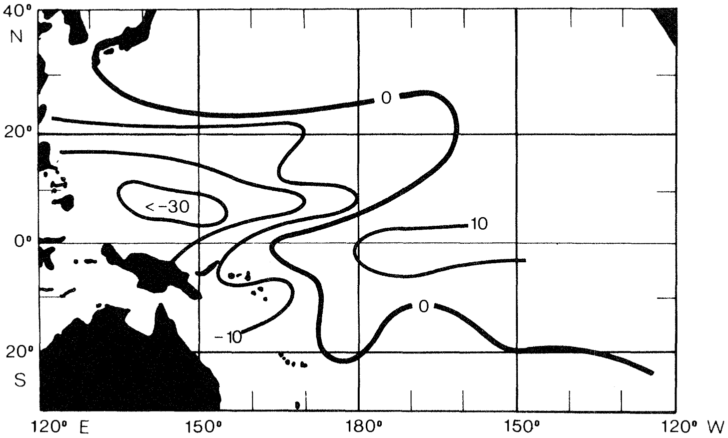

Figure 5. Inter-annual variation (October 1975 minus October 1976) of sea level (centimetres) due to changes in upper-ocean heat content in the western Pacific Ocean. This map is based on tide gauge measurements; satellite altimeter measurements will permit similar mapping around the World Ocean. (From Wyrtki (personal communication 1982); reproduced with permission.)

Tracking and communication

Although not strictly within the terms of reference of this paper, it would be a serious omission to neglect the supporting role of satellites in WCRP-O experiments. Precise navigation has always been a vital matter for oceanographers, and it has become even more important now that we try to take account of synoptic-scale 'weather' systems in the ocean. Conventional satellite navigation is the standard method of fixing the positions of ships and buoys. The forthcoming Global Positioning System (GPS), which will offer much higher accuracy and effectively continuous fixes (as against every hour or so at present), will greatly simplify ship surveys of intense currents on the high seas. It also opens the way to precision measurement of upper ocean velocity structure by shipborne doppler acoustic profiler, a major tool for the future. GPS may also play a key role in monitoring the orbits of satellites carrying radar altimeters.

Interrogation of drifting buoys (position and atmospheric pressure) by the Argos system was a crucial ingredient of FGGE. It is now possible to hang thermistor chains under drifting buoys to measure the temperature profile, which is also routinely extracted and transmitted to shore by the Argos system. Automatic satellite communication of meteorological and expendable-bathythermograph data from ships of opportunity is now a practical proposition and may supersede some aspects of the existing real-time system, IGOSS, which is based on manual h.f. telemetry via the meteorological global trunk system. Ships of opportunity and drifting buoys offer cost-effective platforms for monitoring the ocean, and will be used intensively during the WCRP-O experiments.

The principal satellite measurements for WCRP ocean monitoring

Table 3 lists the principal measurements required for WCRP-O experiments, with an indication of the expected accuracy.

TABLE 3. SATELLITE MEASUREMENTS OF THE OCEAN FOR WCRP EXPERIMENTS

name	estimated error	product for WCRP	comments and references
radar scatterometer (SCAT)	(wind velocity) ± 1.7 m s^{-1}, ± 17°	wind stress wind stress curl	Guymer, this symposium Guymer *et al.* (1983)
radar altimeter (ALT)	(surface elevation)		
class *b*	± 10 cm	ocean heat content eddy dimpling statistics intense current variability	large, non-dedicated satellite, in low orbit (e.g. ERS-1)
class *a*	± 2 cm†	ocean circulation (i) varying component (geoid not known) (ii) steady component (geoid known)	Wunsch & Grant (1982) dedicated mission (e.g. TOPEX) from geoid mission
infrared radiometer (IR)	± 0.3 K†	sea-surface temperature (cloud-free only)	Harries *et al.*, this symposium
visible radiometer (VR)	± 17 W m^{-2}	insolation (from cloud analysis)	Gautier (1982)
	(wind velocity) ± 4 m s^{-1}, ± 20°	wind stress (from cloud drift)	Krishnamurti & Krishnamurti (1980) Wylie & Hinton (1982)
colour scanner (CS)	?	seawater turbidity depth distribution of solar heating	Robinson, this symposium
microwave scanner (MS)	?	sea ice cover	Untersteiner (1983)
	± 1.2 K (*a*) ± 0.5 K (*b*)	sea-surface temperature (through cloud)	(*a*) Hofer *et al.* (1981) (*b*) Bernstein (1982)
	?	precipitation	Atlas & Thiele (eds) (1981)

† Design target.

TABLE 4. OCEAN-OBSERVING SATELLITES PLANNED FOR THE NEXT DECADE

		instruments and comments									status
launch	satellite	SCAT	ALT*a*	ALT*b*	IR	VR	CS	MR	SAR	sponsor	(7 Aug. 1982)
1984	DMSP	—	—	—	—	—	—	×	—	U.S.A.F.	approved
1984	Geosat	—	—	×	—	—	—	—	—	U.S.N.	approved
1986	NOSS	×	—	—	×	×	×	×	—	U.S.N./N.O.A.A./ N.A.S.A.	cancelled
1986	MOS-1	—	—	—	×	×	×	×	—	Japan	approved
1988	ERS-1	×	—	×	×	—	—	×	—	E.S.A.	approved
1987	NOAA-H	—	—	—	×	—	—	—	—	N.O.A.A.	approved
		—	—	—	—	—	×	—	—	N.A.S.A.	proposed
1987?	SPOT-2	—	—	×	—	×	—	—	—	C.N.E.S.	proposed
1988?	TOPEX	(×)	×	—	—	—	—	—	—	N.A.S.A.	proposed
1988?	ROSS	×	—	×	—	—	—	×	—	U.S.N.	proposed
		(NOAA-D bus)								N.O.A.A.	proposed
		×	—	—	—	—	—	—	—	N.A.S.A.	proposed
1988?	ERS-1	—	—	—	—	—	—	—	×	Japan	proposed
1989?	Gravsat	(supports TOPEX by determining geoid)								N.A.S.A.	proposed
1989	ERS-2	×	—	×	—	—	—	—	×	E.S.A.	proposed
1990	Radarsat	—	—	—	—	—	—	—	×	Canada	proposed
		×	—	—	—	—	—	—	—	N.A.S.A.	proposed
1990?	MOS-2	×	—	×	—	—	×	×	—	Japan	tentative

Ocean-related satellite missions planned for the 1980*s*

The information in table 4 comes from Goody (ed.) (1982). The lead time for planning a new satellite mission is about 10 years, so oceanographers already have a reasonable idea of what, all being well, will be available for WCRP oceanographic experiments. There seems a reasonable prospect of achieving global monitoring of the ocean by a number of satellites from different agencies during the period 1987–93. That period will therefore be designated an 'intensive observing period' for the WCRP-O experiments. Measurements *in situ* would be centred on the intensive period, but also start earlier and end later. Some ship and buoy programmes have already begun.

OCEANOGRAPHIC EXPERIMENTS IN THE WCRP

The three streams of the WCRP pose different problems for the oceanographer. In this section, I summarize briefly the oceanographic experiments that are being planned for each, emphasizing the role to be played by satellite observations. An essential background task for all climate research is the collection of a new global data base that will yield greatly improved information about the climatology (i.e. the regular seasonal cycle and statistics of the interannual fluctuations) in the variables listed in table 2. Satellite observations will make a major contribution to the new data set. The new methods adopted in collecting it will provide experience relevant to future operational monitoring of the oceans for climate prediction. The WCRP Pilot Ocean Monitoring Study (POMS) seeks to encourage new cost-effective methods, including remote sensing by satellites.

WCRP stream 1: *extended-range weather forecasting*

In short-term weather forecasting it is assumed that the boundary conditions of the atmosphere remain constant. No attempt is made to take account of changes in the global pattern of surface fluxes of energy and water entering the atmosphere from the ocean during the period of the forecast, which is limited to about 10 days by error growth in the atmospheric general circulation model (AGCM) used to make the forecast. It is nevertheless desirable to make use of accurate initial conditions for the g.p.f.o. In practice that means knowing the sea-surface temperature (s.s.t.), either from the seasonal mean distribution available in standard climatologies (see, for example, Robinson 1976; Robinson *et al.* 1979), or from maps that have been recently updated by using ship, buoy and satellite data collected during the preceding week or month. Such updating is worth while if there are sufficient data available to resolve the interannual thermal anomalies.

The possibility of extended-range weather forecasting, essentially by the same kind of AGCMs as are used today for short-term forecasting, rests on the tendency of certain atmospheric circulation systems to persist for longer than the average limits of predictability. The hope is that some kind of forecast might be achievable on periods up to a month or even a season ahead. The g.p.f.o. changes significantly during the period of the forecast. The change must be allowed for either by assuming it proceeds at the climatological mean seasonal rate (starting from either the climatological mean distribution or from an updated initial condition) or, more ambitiously, by calculating the changing g.p.f.o. during the period of the forecast from information derived solely from the AGCM. The success of Denman & Miyake (1973) in using a one-dimensional model of the ocean mixed layer to calculate s.s.t. changes from Ocean

Weather Ship (O.W.S.) meteorological observations, has encouraged National Meteorological Centres around the World to add ocean mixed-layer subroutines to their AGCMs. The assumption is that on periods of 1–3 months the s.s.t. (and therefore the g.p.f.o.) is insensitive to inter-annual changes in the ocean circulation and oceanic planetary waves, and, more critically,

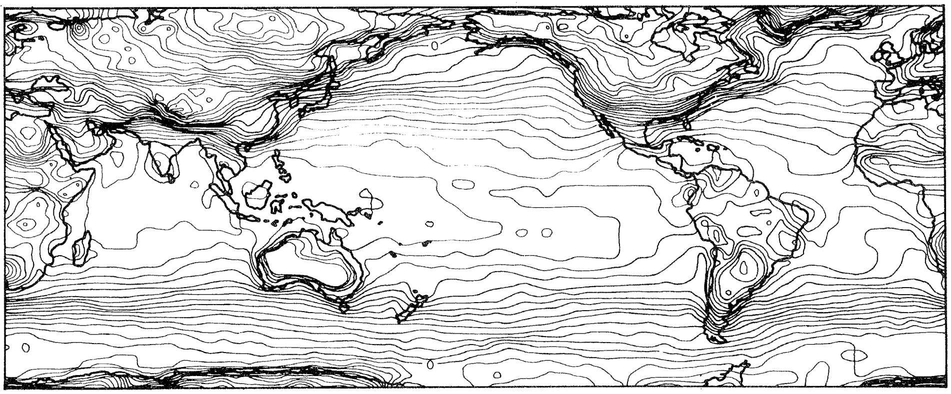

FIGURE 6. The first map of the surface temperature of the world based on satellite infrared observations made during January 1979. Contour interval is 2 K. (From Goody (1982); reproduced with permission.)

that the mixed layer subroutines can be made accurate enough to justify their use, i.e. they must predict the development of inter-annual anomalies of s.s.t. during the period of the forecast. That is a tough specification to meet: s.s.t. anomalies must be calculated to better than 1 K over 3 months. Recent studies of the accuracy of existing mixed-layer models suggest they cannot meet this specification; Thompson (1976) showed they have errors of more than 1 K at O.W.S.

Sensitivity studies by Hofmann (1982) showed that some, but not all, of the discrepancy could be attributed to random errors in the meteorological data used to drive the mixed layer model; the main consequence of which is that the mixed-layer subroutines cannot be tuned accurately to O.W.S. data. When used with an AGCM they will give consistent (consistently wrong?) results. To test the performance of mixed layer models in AGCMs it wil be necessary to compare the predicted s.s.t. anomaly development with the results of global monitoring by all available means, but especially by satellite infrared (figure 6). As we saw in table 2, the inter-annual deviations are small, only a kelvin or so over most of the World Ocean, so the specification for satellite monitoring of s.s.t. is around the $\frac{1}{3}$ K that Harries *et al.* (this symposium) believe may be possible by 1990.

What happens if the results of global tests with mixed-layer models in AGCMs prove discouraging? Extended-range weather forecasting will then have to proceed less ambitiously, using the climatological values for the seasonal progression of s.s.t., starting from the observed initial conditions. The emphasis will then fall on the collection of the best possible empirical description of the climatological mean seasonal development of the s.s.t. to the same accuracy.

WCRP stream 2: *short-term climate prediction*

Thermal anomalies occur spontaneously throughout the planetary climate system as the result of short-term fluctuations in the weather. The atmosphere has only a short memory for such anomalies (a few weeks at most), but other elements of the climate system, which can respond to this 'random' forcing by the atmosphere, have longer memories. Attention has been focused on the ocean because it not only has a longer thermal memory than the atmosphere, but it is also mobile, so thermal anomalies created in the ocean by atmospheric forcing might not stay where they are created (as do anomalies on land, for example deserts or forests), but they may move, creating feedback to the atmosphere that is both delayed and displaced. The creation of an oceanic thermal anomaly at one location followed by its emergence to the atmosphere elsewhere, where it may lead to significant climate response, is called an 'oceanic teleconnection'. If the detailed physics of these transient thermal anomalies in the ocean were understood, and if it were possible to calculate their residence time in the ocean and the subsequent response of the atmosphere when they emerge, then short-term climate prediction might become a possibility. Attention has been focused on a number of candidates.

1. The first, and best known, is that winters in Europe are influenced by the advection of warm water eastwards across the North Atlantic by the Gulf Stream. The idea can be traced back to a paper by Sabine (1846) who suggested that the mild winter of 1821/2 was due to the 'warm water of the Gulf Stream spreading itself beyond its normal bounds . . . to the coast of Europe, instead of terminating as it usually does about the meridian of the Azores'.

2. The second is that thermal anomalies created in mid-ocean, notably in the Pacific, as a Markov response to random forcing by the atmosphere relax slowly (over a period of months) modifying the climate. The generation of such anomalies has been studied by Hasselmann (1981), while Namias (1976) and Davis (1976, 1978) have produced statistical evidence that the atmospheric circulation in winter does show some correlation with the sea-surface temperature the previous autumn.

3. The third possibility is that anomalous growth of sea ice persists for several months, reducing the area of ocean available to create relatively warm, moist maritime air masses that are such a large factor in the climate at locations many hundreds of kilometres away from the ocean. Lemke *et al.* (1980) have examined the statistical evidence.

4. A fourth possibility, which is attracting great attention at present, is the transmission of thermal anomalies by planetary waves inside the ocean, just as anomalies are propagated around the globe by planetary waves in the atmosphere (Hoskins 1983). Wyrtki (1975) proposed that anomalies in the seasonal cycle of upper-ocean heat content in the western Pacific are transmitted eastwards at a predictable speed by an equatorial Kelvin wave, arriving on the American coast some three months later. Modelling studies (O'Brien *et al.* 1981) have simulated the phenomenon and shown how the Kelvin wave then travels poleward along the American coasts from where Rossby waves propagate the signal back out into the open ocean across a broad front, creating a massive winter anomaly in the sea-surface temperature, of the kind observed to occur every few years, the 'El Niño' years (figure 7). The anomalous thermal structure of the ocean created by these waves is important in its own right because of the crippling effect it has on the world's greatest fishery (Glantz & Thompson 1981), but also because it leads to a significant change in the rate of energy release to the atmosphere. Statistical analysis by Horel & Wallace (1981), Wallace & Gutzler (1981) and Shukla & Wallace (1983) have shown that the atmosphere responds vigorously to such tropical energy flux anomalies, demonstrating globally what Walker (1923) and Bjerknes (1969) had previously shown in selected locations, the famous 'southern oscillation'. Recent theoretical studies by Webster (1981) and Hoskins (1983) have revealed the sensitive manner in which the atmosphere responds to the El Niño. The response occurs in winter when the Westerlies are close enough to the Equator to overlap

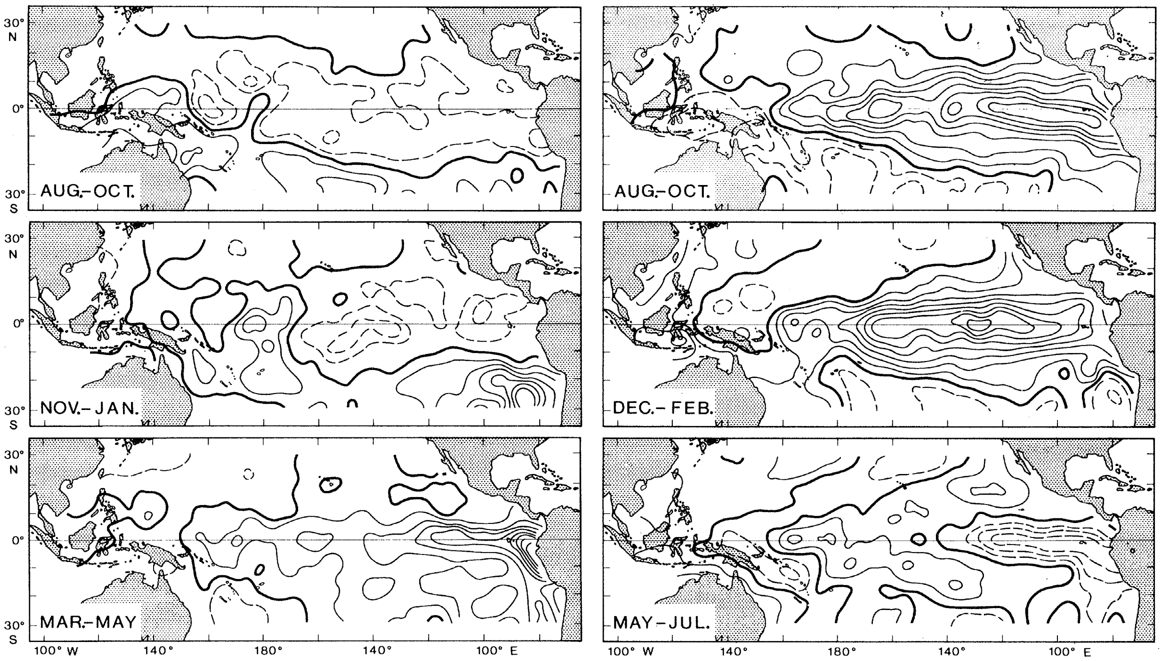

Figure 7. A sequence of sea-surface temperature anomaly maps showing the development and decay of an El Niño event. (Based on the ensemble analysis of Rasmussen & Carpenter (1982); reproduced with permission.)

s.s.t. anomalies that have been radiated beyond the Equator by the coastal Kelvin waves and Rossby waves. Thus a combination of planetary waves, first in the ocean, then in the atmosphere, collaborate at one season every few years to radiate climatic disturbances around the globe. The last major event occurred in 1972. Recent measurements off the Pacific coast of America suggest that an El Niño event is also under way this year (1982/3). The Northern Hemisphere winter has exhibited strong anomalies, with spring flowers blooming and birds nesting in northern Germany in December. Formal statistical analysis of this new event will be greatly aided by the advances in understanding made during the last decade. The prospects for climate forecasting based on coupled ocean–atmosphere teleconnections seem promising, but a great international investment in observations and modelling is now needed to set the subject on a sound scientific basis.

The relative importance of these four candidates is now being actively studied by modellers. The method is to use an atmospheric general circulation model to calculate the response of the global climate to simulated anomalies of sea-surface temperature or sea-ice extent. The aim is to discuss which, if any, of the observed ocean surface anomalies produce atmospheric climate anomalies that are statistically significant, i.e. that contain a significant fraction of the total climate variance, most of which is *not* correlated with the test ocean anomaly. Early results suggest that mid-latitude s.s.t. anomalies can produce significant climate response, but only if they are several kelvins (Haney 1979), whereas the observed anomalies are rather smaller, only about 1 K (Barnett & Davis 1975; Weare 1977). On the one hand, significant global climate response has been found to sea-ice anomalies by Warshaw & Rapp (1973), Newson (1973) and Herman & Johnson (1978), and potentially useful responses to equatorial anomalies of the El Niño type, described by Rasmussen & Carpenter (1982), have been revealed by modelling studies by Pan & Oort (1983). The global atmospheric circulation models still contain worrying flaws (for example, in the distribution of the annual heat budget (Dobson *et al.* 1982)), so predictions based on them must be treated with caution. Nevertheless, the results so obtained suggest that the best prospects for short-term climate prediction lie in tropical sea-surface anomalies associated with the El Niño phenomenon. The WCRP stream 2 activity has therefore been focused onto that fourth candidate with a major international project called TOGA (Tropical Oceans and Global Atmosphere).

TABLE 5. REQUIREMENTS FOR TROPICAL OCEAN MONITORING FOR RESEARCH INTO INTER-ANNUAL VARIABILITY OF THE GLOBAL CLIMATE

(*a*) *coverage*

duration	at least 10 years
regional limits	the tropical ocean (half the surface area of the World Ocean)

(*b*) *sampling density*

temporal resolution	1 month
spatial resolution	2° latitude; 10° longitude

(*c*) *measurement accuracy*

		feasibility		
variable	accuracy	*in situ*	satellite	
			1985	1990
surface temperature	0.3 K	yes†	no	yes
surface salinity	$0.1\ \mathrm{kg\ m^{-3}}$	yes†	no	no
sea level	2 cm	yes†	no	yes
total energy flux	$15\ \mathrm{W\ m^{-2}}$	no	no	no
precipitation	$3\ \mathrm{cm\ month^{-1}}$	no	no	yes
surface wind speed	$2\ \mathrm{m\ s^{-1}}$	yes†	yes†	yes
surface wind direction	20°	yes†	yes†	yes

† Measurement accurate, but sampling inadequate.

The key factor in all four candidates is the development of anomalies in the global pattern of fluxes of energy and water from the ocean to the atmosphere, associated with anomalous heat content of the upper ocean, or anomalous ice cover. There is an urgent need to improve the documentation of the regular seasonal cycle and inter-annual variability of the g.p.f.o. It is needed both as the raw material for further statistical studies designed to reveal new aspects of global air–sea interaction on a period of a few years, and as time series to be used in testing models of short-term climate change. The specification for such measurements depends on region and season and whether or not an El Niño event is occurring. The values given in table 5 can be treated as a rough guide. They are based on Gill (ed.) (1983), who suggested, as a criterion, values that are 20% of the Rasmussen & Carpenter (1982) El Niño ensemble analysis, which is being widely used in modelling studies. Although most of the required measurements could in principle be made *in situ*, it would be unrealistically expensive to do so with the specified sampling density, which must be sustained over a period of at least a decade if the measurements are to capture the important, but relatively rare, El Niño events. Monitoring by satellite is already making significant contributions, especially with regard to solar heating of the ocean and the surface wind stress derived from cloud drift (figure 8), but the accuracies achieved in other variables (temperature, precipitation) are not yet good enough. The situation could change dramatically by 1990 as the result of improvements in algorithms used to extract the required variables and a new generation of satellites. Most of the requirements should then be achieved. But the most important measurement of all, the energy flux at the surface, will still remain beyond the reach of measurements both *in situ* and by satellite. At present there seems no alternative to filling the gap by an expensive programme of aircraft measurements of the kind made during GATE and JASIN (Nicholls *et al.* 1983).

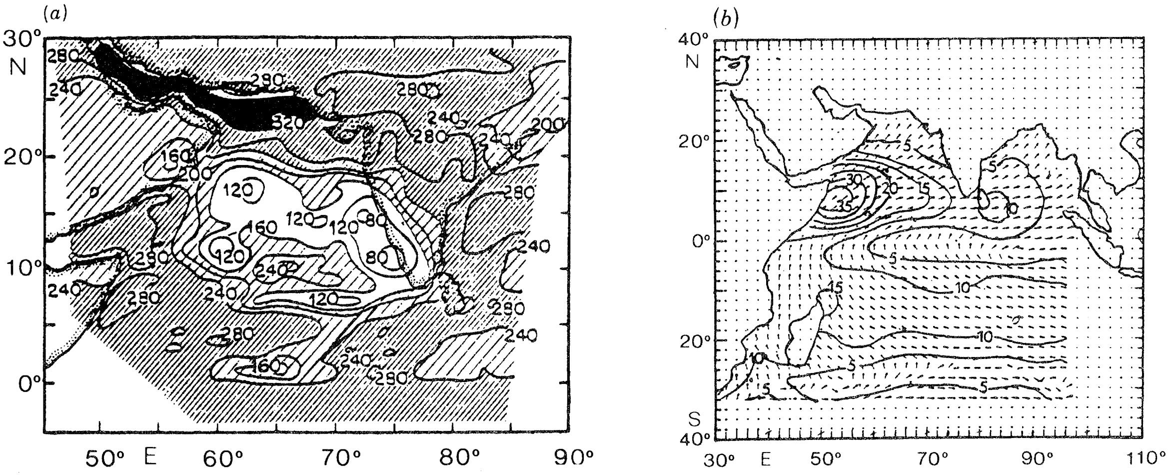

FIGURE 8. Maps of (*a*) solar energy flux into the sea (watts per square metre) from Gautier (1982), and (*b*) wind stress (centinewtons per square metre) from the cloud drift analysis of Wylie & Hinton (1982). These distributions for the Indian Ocean during the period 10–19 June 1979 illustrate the potential of existing meteorological satellites (in this case GOES-1) to yield oceanic products useful for climate research.

WCRP stream 3: *longer-term climate prediction*

The third stream of the WCRP is concerned with decadal timescales. The major preoccupation is climate change due to pollution of the atmosphere by CO$_2$ and other radiatively active gases, or changes land or river use, or a change in the solar constant. How would the climate respond to such changes in the boundary conditions of the planetary climate system? The response is best studied by considering the slow changes that will occur in the global circulations of energy and water. In the atmosphere these lead to changes in mean temperature and precipitation and in the regional distributions of temperature and rainfall over the continents, with consequences for agriculture, energy consumption, transport and other factors that influence the habilitability and economy of our planet. The decadal scale is important because major decisions are made by government and industry that are based on assumptions about the pattern of life decades ahead. Climate change is one factor in that pattern; it would be attractive to make reliable forecasts of decadal climate change, rather than assuming as at present that the present climate will persist. The first stage is to predict how the boundary conditions will change over coming decades. So far nothing can be done about predicting future changes in the solar constant, but fairly realistic predictions can be made about the rate at which man will pollute the planet (Bach *et al.* (eds) 1979). The second task is to calculate how the global circulations of energy and water will be altered by a given scenario for future pollution.

Most attention has been focused on CO$_2$ pollution, which is observed to be increasing in the atmosphere (Kellogg 1981) and which is expected to reach double the present concentration in the next century. The CO$_2$ acts as a steadily thickening blanket that allows the Earth to reach a higher temperature before regaining thermal equilibrium with solar heating. The thermal capacity of the planetary climate system introduces a lag between the increase in CO$_2$ and attainment of the new climate equilibrium. The question for climatologists are:

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

(*a*) How much will the concentration of atmospheric CO_2 change?
(*b*) How long will the global climate change lag behind the CO_2 change?
(*c*) What will the new equilibrium temperature régime be like?
(*d*) What will the new water régime be like?
(Water and energy circulation are linked through latent heat.)

The ocean is the key element in solving these problems, for two quite distinct reasons: (1) its ability to remove some of the extra CO_2 from the atmosphere, and (2) its thermal lag to increased heating caused by the extra CO_2 that remains in the atmosphere. A little more will be said about each of these below; the reader is referred to extended discussion in Bretherton (1982) and Woods (1983) for further information.

1. The rate of increase of atmospheric CO_2 depends both on the anthropogenic sources and on the rate at which some of the excess is accommodated in the ocean. So far only about half of the CO_2 pollution since the start of the Industrial Revolution remains in the air: the rest has been accommodated by the ocean, where it does not affect the climate. The processes of oceanic accommodation of CO_2 involves a complex chain of physical, chemical, biological and sedimentological processes that need not detain us here (see, for example, Bolin *et al.* (eds) 1979). But the effect of those processes depends significantly on physical processes in the upper boundary layer of the ocean, and on the circulation of the ocean. Models used by geochemists to calculate changes in the oceanic carbon cycle do not include a detailed description of ocean circulation based on the laws of ocean dynamics (Bolin (ed.) 1981), and are therefore not entirely satisfactory.

2. Although it is not certain exactly when it will occur, there seems little doubt that eventually the CO_2 left in the atmosphere will reach double its present concentration. When that occurs, the net surface flux of infrared radiation at the sea surface will differ from the present flux on average by 1.2 $W\,m^{-2}$ due to the CO_2 alone, plus 2.3 $W\,m^{-2}$ because the CO_2 will have directly warmed the air, and (when the new global thermal equilibrium is reached) by another 12 $W\,m^{-2}$ due to increased water vapour in the atmosphere, making a total of 15.5 $W\,m^{-2}$ (values from Ramanathan 1981). In equilibrium, the ocean loses heat by infrared radiation, evaporation and conduction at the same rate as it gains heat from the Sun and atmosphere. The extra CO_2 disturbs this balance, which is only regained when the sea-surface temperature has risen sufficiently. On these timescales, the atmospheric temperature and precipitation are slave to the sea-surface temperature. The thermal aspect of the CO_2 problem is therefore to calculate how rapidly the sea-surface temperature rises in response to the modified net infrared balance at the surface. The key question is how much of the oceanic water column is warmed. The lag in climate response to CO_2 pollution will be a few years if only the top 50 m 'mixed layer' is involved; it will be several decades if the whole of the 'warm-water sphere' has to heat up; and it will be centuries if the 'cold-water sphere' must heat up too. Existing ocean models have been used to predict climate response to doubled atmospheric CO_2 (Bryan *et al.* 1982). But it is generally agreed that more has to be learnt about the global circulation of the ocean and the processes of water mass formation before we can have confidence in such calculations.

The availability of reliable, quantitative models of the circulation of the ocean and the transformation of water mass temperature and salinity are a *sine qua non* for prediction of climate change over a period of decades in response to pollution by CO_2 and other changes in the

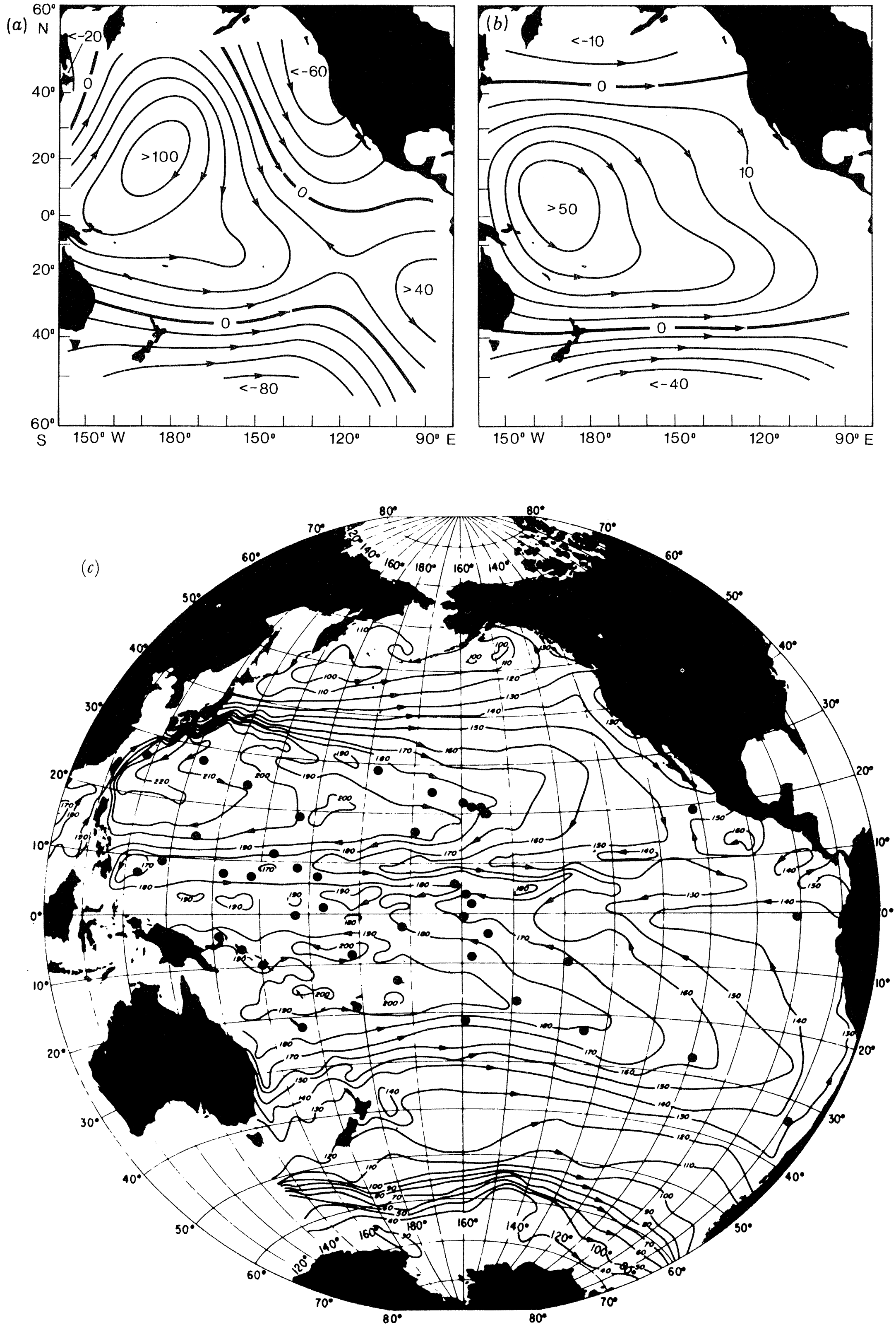

FIGURE 9. A comparison of two estimates of the distribution of sea-surface elevation in the Pacific Ocean: (*a*) from the Seasat altimeter, (*b*) from the classical dynamical method, as used by Wyrtki (1979), after spatial filtering to permit comparison. (From Wunsch (1983); reproduced with permission.) The unfiltered Wyrtki map (*c*) is shown for comparison (reproduced with permission). One of the central aims of the World Ocean Circulation Experiment (WOCE) is to collect a satellite altimeter data set that will permit the production of surface elevation maps with spatial resolution similar to that of Wyrtki's, but not dependent on the assumption inherent in the classical dynamical method that there is a level of no motion at a depth of 1 km.

boundary conditions of the planetary climate system. Existing models of the global ocean, such as that of Bryan & Lewis (1979), have succeeded in describing the principal features of the observed three-dimensional distributions of temperature, salinity and currents, and they have yielded estimates of the meridional heat flux similar to values derived by other methods (Bryden 1982). Nevertheless they are based on simplifications of unresolved processes that give cause for worry (see Wunsch 1983). For example, the parametrization of energetic eddies and waves with scales of about 100 km, the oceanic equivalent of weather systems in the atmosphere, has been shown to be important in a series of studies by Holland (1977). Also, Worthington (1981) has expressed the general feeling of unease about our ability to parametrize water mass formation in such global models. And Garrett (1979) has argued that the representation of mixing across density surfaces in the interior of the ocean is not all that it should be. The general feeling in the oceanographic community is that a new generation of ocean models will be needed to tackle the decadal climate problem. The expectation is that the general rise in computer power should make it possible by the end of the century to do what the meteorologist does with regard to the weather systems in atmospheric climate models; namely to resolve them. But the key processes of water mass transformation, both in the upper boundary layer and in the deep interior of the ocean, will have to be parametrized in ocean climate models for the foreseeable future, as clouds are in atmospheric climate models.

As work proceeds on new climate models of the World Ocean, there will develop an increasingly urgent need for a description of the ocean circulation and scalar distributions with which the model results can be compared. The construction of such an empirical description of the World Ocean is not easy. Oceanographers cannot follow the approach of meteorologists in the Global Atmospheric Research Programme (GARP) who designed the 1979 Global Weather Experiment to serve a similar purpose. The meteorologists could base their description on measurements of directly relevant variables (wind velocity, temperature, pressure, etc.), according to a sampling schedule that resolved the weather systems. The oceanographer must base his description on measurements that are less directly relevant (e.g. chemical tracers) and which under-sample the energetic weather systems. Consequently the empirical description of the ocean circulation that emerges is itself heavily dependent on a diagnostic model. The potential for uncertainties in the description of the ocean is much greater than in the GARP description of the atmosphere.

The description of the World Ocean that we have at present is based largely on hydrographic data collected over the past 100 years, but especially during a small number of major expeditions (notably the German *Meteor* expedition of 1925–7 and the International Geophysical Year expedition of 1958). There have recently been significant advances in the methodology of diagnostic models used to estimate the circulation from those data (Wunsch & Grant 1982). New types of data have also been added to the inventory, notably a wide range of chemical tracers surveyed by the Geosecs expeditions of the 1970s (Broecker 1981), satellite-tracked drifting floats used extensively for the first time in 1979 (Richardson 1983), deep-drifting, acoustically tracked floats used widely in the exploration of the ocean 'weather' in the 1970s (Rhines 1977), and the new range of satellite measurements listed in table 3.

The planners of the WCRP have now decided that the major oceanographic activity in stream 3 should be to seek a new description of the World Ocean circulation and water mass transformation in readiness for the coming generation of climate-related ocean models. Plans are now being prepared for a World Ocean Circulation Experiment (WOCE) intended to produce that description by the end of the century. The aim will be to bring together the new observing techniques and the new diagnostic modelling techniques in a coordinated experiment that will for the first time study the World Ocean as a whole.

The commitment to a global approach, echoing the GARP Global Weather Experiment, puts the satellite observations at the centre of the design. They alone offer the necessary global coverage and without them there would be no WOCE. The following systems are seen as demanding highest priority:

(1) the *altimeter*, to measure the surface pressure distribution and therefore the surface geostrophic current, for (i) statistics of the ocean weather systems, (ii) the varying component of large currents or gyres, and (iii) the steady large-scale circulation;

(2) the *scatterometer*, to measure surface wind stress and hence the Ekman transport and Ekman pumping;

(3) the *infrared radiometer*, to measure sea-surface temperature.

The first two of these are vital for the first goal of WOCE, namely to determine the ocean circulation. The third is added to them as the barest minimum contribution (from satellites) to the second goal of WOCE, namely to determine water mass conversion. In practice all the other systems listed in table 3 will contribute to the second goal, too. The experiment will also involve a major programme of measurements *in situ*. The preliminary list drawn up by the steering group for WOCE includes the following items:

(1) a global ship programme of coast–coast sections of top-to-bottom hydrographic and light (i.e. requiring small samples) chemical profiles;

(2) a sparser global sampling programme of 'heavy' chemicals (i.e. those requiring larger samples);

(3) large numbers (perhaps thousands?) of deep drifting neutrally buoyant floats, with pop-up capability to permit satellite tracking and data communication;

(4) basin-scale acoustic tomographic arrays;

(5) a global network of tide gauges or pressure gauges (to support the altimetric programme);

(6) current-meter arrays at special regions (e.g. overflow regions between ocean basins).

It would be premature to present detailed specifications for the WOCE measurements, whether by satellite or *in situ*. But the experiment is being designed with careful regard to the planned ocean-observing satellites listed in table 4. In particular it is hoped that there can be an intensive observing period lasting for about 5 years starting about 1988. The value of the satellite measurements will be greatly enhanced if they coincide (e.g. cross-calibration of altimeter measurements) and the measurements *in situ* may prove crucial for extracting the full information from them, as the happy coincidence of JASIN and Seasat showed (Guymer *et al.* 1983). These points will be clarified by meetings of the WOCE steering group over the coming years. Meanwhile, it is clear that WOCE is a very ambitious project offering to make a major contribution to solving a key issue in climate research and demanding a major commitment of resources over a period of about 5 years.

CONCLUSION

Satellite monitoring of the ocean will be a central ingredient of all three streams of the World Climate Research Programme, and it will be an essential for the major experiments WOCE and TOGA.

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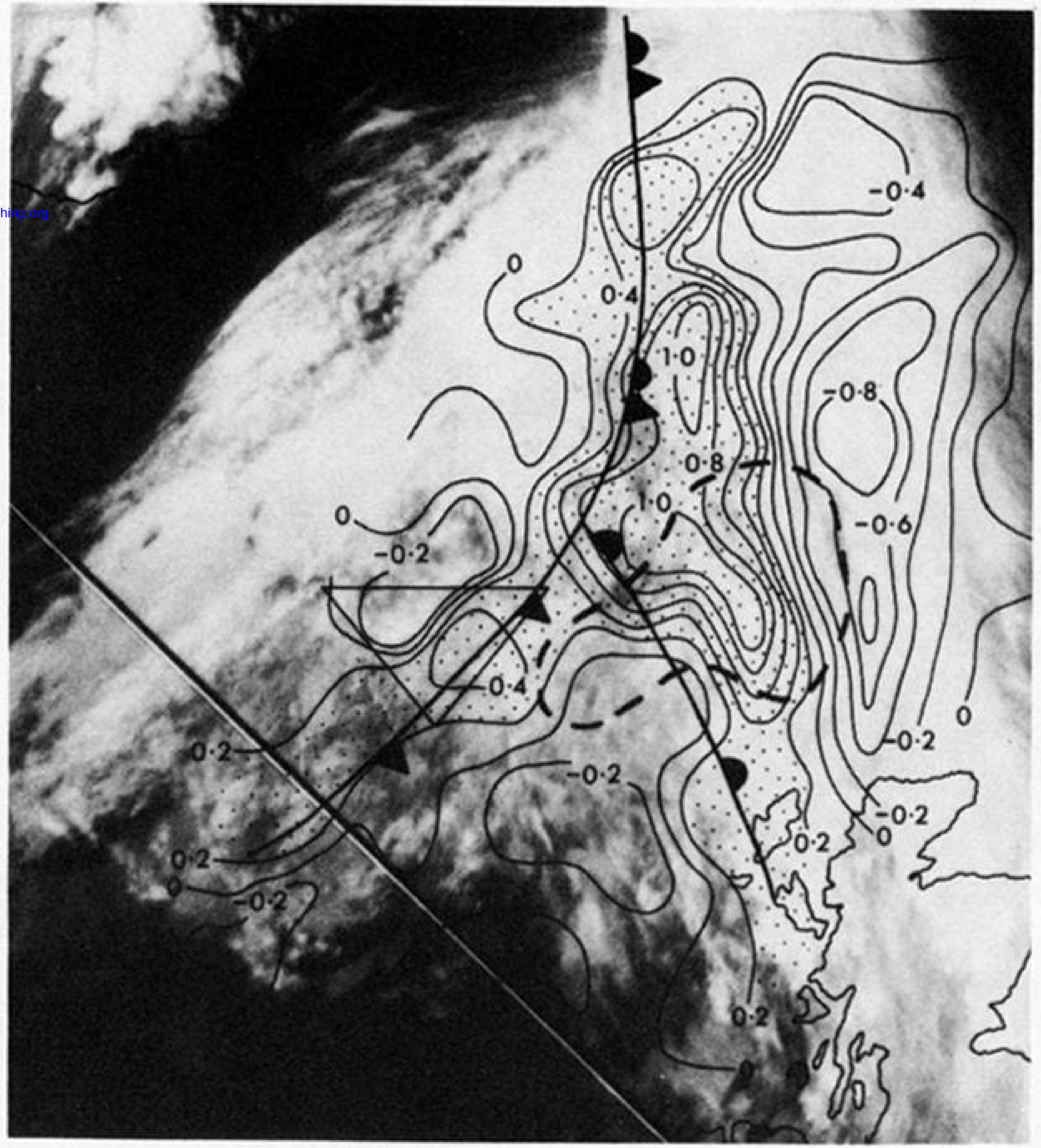
Discussion

P. K. TAYLOR (*Institute of Oceanographic Sciences, Wormley, U.K.*). The accuracy of the measurements of surface winds *in situ* quoted by Professor Woods, ± 5 m s^{-1}, sounds surprisingly poor. What is the source of this estimate, and should greater effort and resources be devoted to increasing the accuracy, and temporal and spatial distribution, of observations *in situ*?

J. D. WOODS. The estimate of ± 5 m s^{-1} was based on evidence from a combination of sources. First, my observations at sea: I have noted that sporadic malfunction of anemometers on ships (for example, at particular headings to the wind) can introduce such errors. Second, visual estimates of sea state are unlikely to be better than one point on the Beaufort scale, which rises in steps of 5 m s^{-1} in the upper part of the range, which is particularly important for global climatology. Third, comparisons of wind fields derived independently from the altimeter and scatterometer on Seasat, and from merchant ship observations exhibit differences as large as 5 m s^{-1}. Of course, some of the difference can be attributed to inadequate sampling by ships; only part is due to measurement error. I agree with Dr Taylor that *in situ* measurements by anemometers on purpose-built buoys can yield data with errors much smaller than

± 5 m s^{-1}, and that careful analysis of research ship anemometer records can also yield excellent results, as he and his colleagues showed in the Royal Society JASIN expedition (*Phil. Trans. R. Soc. Lond.* A**308**, 221–449). However, such high-quality data are seldom available, and do not have the coverage needed to produce wind fields used in global climate research. Such wind fields depend on the analysis of either patchy and less accurate merchant ship data, or satellite data. Experience with Seasat encourages us to believe that the latter will not only solve the sampling problem, but that the data will also have superior accuracy (± 2 m s^{-1}). The European ERS-1 mission, due to be launched in 1988, will be particularly important for the WCRP. Meanwhile, efforts to improve the coverage and quality of *in situ* wind measurements are being focused onto regions like the Tropical Pacific, where there is an urgent need to support WCRP projects, such as TOGA, that have already begun.



IGURE 3. The first map of wind stress curl that resolves the variation with atmospheric weather. From the Seasat scatterometer during JASIN analysed by Guymer *et al.* (1983). The weather is shown in three ways: (i) by conventional synoptic analysis (the lines marking an occluded front), (ii) by contours of rainfall rate estimated from the Seasat scanning multichannel microwave radiometer, and (iii) by a cloud image from the NOAA-5 weather satellite which passed overhead 5 h earlier. (Reproduced by kind permission of the Director, Institute of Oceanographic Sciences, Wormley, and Dundee University.)